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Petroleum and natural gas industries — Arctic offshore structures (ISO 19906:2010)

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National foreword

This British Standard is the UK implementation of EN ISO 19906:2010.

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A list of organizations represented on this committee can be obtained on request to its secretary.

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Foreword

This document (EN ISO 19906:2010) has been prepared by Technical Committee ISO/TC 67 "Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries" in collaboration with Technical Committee CEN/TC 12 “Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries” the secretariat of which is held by AFNOR.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by June 2011, and conflicting national standards shall be withdrawn at the latest by June 2011.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN [and/or CENELEC] shall not be held responsible for identifying any or all such patent rights.

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and the United Kingdom.

Endorsement notice

The text of ISO 19906:2010 has been approved by CEN as a EN ISO 19906:2010 without any modification.

Contents

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 19906 was prepared by Technical Committee ISO/TC 67, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, Subcommittee SC 7, *Offshore structures*.

ISO 19906 is one of a series of International Standards for offshore structures. The full series consists of the following International Standards.

- ISO 19900, *Petroleum and natural gas industries — General requirements for offshore structures*
- ISO 19901 (all parts), *Petroleum and natural gas industries — Specific requirements for offshore structures*1)
- ISO 19902, *Petroleum and natural gas industries — Fixed steel offshore structures*
- ISO 19903, *Petroleum and natural gas industries — Fixed concrete offshore structures*
- ISO 19904-1, *Petroleum and natural gas industries — Floating offshore structures — Part 1: Monohulls, semi-submersibles and spars*
- ISO 19905 (all parts), *Petroleum and natural gas industries — Site-specific assessment of mobile offshore units*2)
- ISO 19906, *Petroleum and natural gas industries — Arctic offshore structures*

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1) ISO 19901-3, *Topsides structure,* to be published.

2) All parts are under preparation.

Introduction

The series of International Standards ISO 19900 to ISO 19906 addresses design requirements and assessments for all offshore structures used by the petroleum and natural gas industries worldwide. Through their application, the intention is to achieve reliability levels appropriate for manned and unmanned offshore structures, regardless of the type of structure and the nature or combination of the materials used.

It is important to recognize that structural integrity is an overall concept comprising models for describing actions, structural analyses, design rules, safety elements, workmanship, quality control procedures and national requirements, all of which are mutually dependent. The modification of one aspect of design in isolation can disturb the balance of reliability inherent in the overall concept or structural system. The implications involved in modifications, therefore, need to be considered in relation to the overall reliability of all offshore structural systems.

The series of International Standards applicable to the various types of offshore structure is intended to provide wide latitude in the choice of structural configurations, materials and techniques without hindering innovation. Sound engineering judgment is, therefore, necessary in the use of these International Standards.

This International Standard was developed in response to the offshore industry's demand for a coherent and consistent definition of methodologies to design, analyse and assess arctic and cold region offshore structures of the class described in Clause 1.

Structures capable of resisting ice have been in use in temperate regions for well over a century. These include bridge piers and navigation aids in ice-covered rivers and estuaries. In fact, bridge codes in cold countries have included methods for ice loads dating back many decades. In more severe arctic and cold regions, ice resistant structures are more recent. But much experience has been gained commencing in the 1960s, and this knowledge is incorporated into this International Standard. Where uncertainties still exist, conservative approaches and methods have been recommended.

This International Standard also addresses issues such as topsides winterization, and escape, evacuation and rescue that go beyond what is strictly necessary for the design, construction, transportation, installation and decommissioning of the structure. These issues are essential for offshore operations in arctic and cold region conditions and they are not covered in other International Standards. When future editions of ISO 19906 and other International Standards are prepared, efforts will be made to avoid duplication of scope.

Annex A provides background to and guidance on the use of this International Standard and it is intended that it be read in conjunction with the main body of this International Standard. The clause numbering in Annex A is the same as in the normative text to facilitate cross-referencing.

Annex B provides regional information on the physical environment of specific offshore areas in arctic and cold regions.

To meet certain needs of industry for linking software to specific elements in this International Standard, a special numbering system has been permitted for figures, tables, equations and bibliographic references.

Petroleum and natural gas industries — Arctic offshore structures

1 Scope

This International Standard specifies requirements and provides recommendations and guidance for the design, construction, transportation, installation and removal of offshore structures, related to the activities of the petroleum and natural gas industries in arctic and cold regions. Reference to arctic and cold regions in this International Standard is deemed to include both the Arctic and other cold regions that are subject to similar sea ice, iceberg and icing conditions. The objective of this International Standard is to ensure that offshore structures in arctic and cold regions provide an appropriate level of reliability with respect to personnel safety, environmental protection and asset value to the owner, to the industry and to society in general.

This International Standard does not contain requirements for the operation, maintenance, service-life inspection or repair of arctic and cold region offshore structures, except where the design strategy imposes specific requirements (e.g. 17.2.2).

While this International Standard does not apply specifically to mobile offshore drilling units (see ISO 19905-1), the procedures relating to ice actions and ice management contained herein are applicable to the assessment of such units.

This International Standard does not apply to mechanical, process and electrical equipment or any specialized process equipment associated with arctic and cold region offshore operations except in so far as it is necessary for the structure to sustain safely the actions imposed by the installation, housing and operation of such equipment.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 19900, *Petroleum and natural gas industries — General requirements for offshore structures*

ISO 19901-1, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 1: Metocean design and operating considerations*

ISO 19901-2, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 2: Seismic design procedures and criteria*

ISO 19901-3, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 3: Topsides structure*[3)]

ISO 19901-4, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 4: Geotechnical and foundation design considerations*

[3)] To be published.

ISO 19901-6, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 6: Marine operations*

ISO 19901-7, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 7: Stationkeeping systems for floating offshore structures and mobile offshore units*

ISO 19902, *Petroleum and natural gas industries — Fixed steel offshore structures*

ISO 19903, *Petroleum and natural gas industries — Fixed concrete offshore structures*

ISO 19904-1, *Petroleum and natural gas industries — Floating offshore structures — Part 1: Monohulls, semi-submersibles and spars*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 19900, ISO 19901-1, ISO 19901-2 and ISO 19901-4 and the following apply.

3.1
abrasion
effect of ice grinding against the surface of a structure removing paint, surface protrusions and coatings, oxidized material, or concrete particles and aggregate

3.2
accidental situation
exceptional condition of use or exposure for the structure

NOTE Exceptional conditions include fire, explosion, impact or local failure.

3.3
action
external load applied to the structure (direct action) or an imposed deformation or acceleration (indirect action)

3.4
action combination
design values of the different actions considered simultaneously in the verification of a specific limit state

3.5
action effect
effect of actions on the structure or its components

3.6
adfreeze
freezing of ice to the surface of a structure

3.7
alert
prescribed reaction to specific ice conditions, which in time can become hazardous to the operation of a structure

NOTE Several different levels associated with the time proximity of the hazard are normally recognized.

3.8
aspect ratio
ratio of structure diameter or width to ice thickness

3.9
broken ice
loose ice consisting of small floes, broken up as a result of natural processes, or active or passive intervention

3.10
characteristic value
value assigned to a basic variable associated with a prescribed probability of being exceeded by unfavourable values during some reference period

NOTE For actions, the characteristic value is the main representative value. In some design situations, a variable can have two characteristic values, an upper and a lower value.

3.11
companion environmental action
environmental action applied simultaneously with the principal environmental action

3.12
consequence category
classification system for identifying the environmental, economic and indirect personnel safety consequences of failure of a platform

NOTE For offshore structures, three consequence categories are defined; see 7.1.3:

- C1: high consequences;
- C2: medium consequences;
- C3: low consequences.

3.13
consolidation
process of freezing of pore water in voids within ice rubble, between floes, or between soil particles

NOTE For soils, this involves drainage of pore fluid as a result of overburden pressures.

3.14
consolidated layer
portion of an ice ridge keel, rubble pile, rubble field or stamukha below the waterline formed by the ice consolidation process

3.15
design action
action combination resulting from factored representative actions associated with an AL or EL event

3.16
design resistance
resistance calculated from factored characteristic material properties or from factored resistance based on unfactored characteristic material properties

3.17
design service life
assumed period for which a structure or a structural component will be used for its intended purpose with anticipated maintenance but without substantial repair being necessary

3.18
design value
value derived from the representative value for use in the design verification procedure

3.19
disconnection
planned separation of the risers (and mooring, if applicable) from a floating structure

3.20
ductility
ability of a material to deform and absorb energy beyond its elastic limit or ability of a component to sustain load beyond yield

NOTE See also **system ductility** (3.79).

3.21
dynamic action
action that induces acceleration of a structure or a structural component of a magnitude sufficient to require specific consideration

3.22
dynamic positioning
technique of automatically maintaining the position of a floating vessel within a specified tolerance by controlling onboard thrusters to counter the wind, wave, current and ice actions

3.23
emergency disconnection
planned separation of the risers (and mooring, if applicable) from a floating structure, without depressurization of the risers

3.24
escape
act of personnel moving away from a hazardous event to a place on the installation where its effects are reduced or removed

3.25
evacuation
planned precautionary and emergency method of moving personnel from the installation (muster station or TR) to a safe distance beyond the immediate or potential hazard zone

3.26
exposure level
classification system used to define the requirements for a structure based on consideration of life-safety and of environmental and economic consequences of failure

For offshore structures, three exposure-level categories are defined; see 7.1.4:

- L1: highest exposure level;
- L2: intermediate exposure level;
- L3: lowest exposure level.

3.27
first-year ice
FY
sea ice formed during the current or prior winter that has not survived one summer melt season

3.28
floe
relatively flat piece of sea ice greater than 20 m across

NOTE There are typically sub-categories: small (20 m to 100 m across), medium (100 m to 500 m across), big (500 m to 2 000 m across), vast (2 km to 10 km across) and giant (greater than 10 km across).

3.29
flowline
piping on the sea floor linking one or more subsea wells to the production system

NOTE Functions may include production, injection, subsea systems control and export of produced fluids.

3.30 Freeboard

3.30.1
freeboard
vertical distance from the water surface to the top of the ice

3.30.2
freeboard
vertical distance from the mean water surface at a given draught to the deck level, measured at the lowest point where water can enter the structure or ship

3.31
freeze-thaw
possible degrading effect on concrete of repeated temperature changes causing frost cycles at the surface

3.32
glory hole
man-made areal excavation in the seabed used to protect a subsea installation or its components from ice damage

3.33
ice alert
alert related to encroaching hazardous ice features or conditions, generally requiring specific changes to production operations

3.34
iceberg
glacial or shelf ice (greater than 5 m freeboard) that has broken (calved) away from its source

NOTE Icebergs can be freely floating or grounded, and are sometimes defined as tabular, dome, pinnacle, wedge or block shaped.

3.35
ice detection
discrimination of ice features or associated conditions from the surrounding environment

3.36
ice gouge
ice scour
incision made by an ice feature in the seabed, having the form of either an areal incision (i.e. pit) or a linear incision (i.e. furrow)

3.37
ice island
large tabular shaped ice feature that has calved from an ice shelf or glacier

3.38
ice management
active processes used to alter the ice environment with the intent of reducing the frequency, severity or uncertainty of ice actions

3.39
ice management plan
detailed plan outlining the objectives, active procedures involved and individual responsibilities for the implementation of the ice management system

3.40
ice management system
ice management, and associated ice detection and threat evaluation tools used for its implementation

3.41
ice ridge
linear feature formed of ice blocks created by the relative motion between ice sheets

NOTE A pressure ice ridge is formed when ice sheets are pushed together and a shear ice ridge is formed when ice sheets slide along a common boundary.

3.42
ice scenario
combination of circumstances involving the presence of ice, resulting in actions or action combinations on a structure

3.43
infill
material deposited in an ice gouge, excavation or trench through natural processes

3.44
landfast ice
fast ice
ice that remains attached to a shoreline, island or grounded ice feature

3.45
level ice
sheet ice
region of ice with relatively uniform thickness

3.46
life-safety category
classification system for identifying the applicable level of life-safety for a platform

NOTE For offshore structures, three life-safety categories are defined; see 7.1.2:

- S1: manned non-evacuated;
- S2: manned evacuated;
- S3: unmanned.

3.47
local failure
localized damage to the structure with the potential for escalating to partial or complete failure

3.48
lowest anticipated service temperature
LAST
minimum hourly average extreme-level (EL) air temperature

NOTE The EL temperature is described in 7.2.2.6.

3.49
mat
man-made weighted sheet used for the stabilization of soils or subsea components

3.50
material factor
partial safety factor applied to the characteristic value of a material property

3.51
multi-year ice
MYI
MY
sea ice that has survived at least one summer melt season

NOTE When the term "multi-year ice" is used in conjunction with the term "second-year ice", the former should be interpreted as ice that has survived at least two summer melt seasons.

3.52
offshore installation manager
OIM
person responsible for the installation and all operations on and around a structure

3.53
owner
representative of the company or companies that own, hold a licence for or hold a lease for the development

3.54
pack ice
sea ice consisting of discrete floes that is not landfast

3.55
pack ice driving actions
actions exerted by the surrounding sea ice on the structure or to an ice feature in contact with it

3.56
permafrost
ground (soil or rock) remaining at or below 0 °C for at least two consecutive years

3.57
place of safety
area outside the hazard zone in which personnel safety is no longer at risk due to the installation hazard

3.58
polynya
area of open water surrounded by sea ice, caused by persistent winds, currents or upwelling of warm water

3.59
rafted ice
ice feature formed from the superposition of two or more ice sheet layers

3.60
recognized classification society
RCS
member of the International Association of Classification Societies (IACS), with recognized and relevant competence and experience, and with established rules and procedures for classification/certification of arctic and cold region structures or ice class vessels used in petroleum and natural gas activities

3.61
recovery
transfer of evacuees to a rescue vessel, helicopter, etc.

3.62
reliability target
specified average annual probability associated with failure

3.63
representative value
value assigned to a basic variable for verification of a limit state

3.64
rescue
process by which persons entering the sea or reaching the ice surface, directly or in an evacuation craft, are subsequently retrieved to a place where medical assistance is typically available

3.65
ridge keel
portion of an ice ridge that extends below the waterline

NOTE A ridge keel can consist of a consolidated layer and an unconsolidated layer.

3.66
ridge sail
portion of an ice ridge that extends above the waterline

3.67
rubble field
region of broken ice blocks floating together as a continuous body

3.68
rubble pile
ice feature of areal, rather than linear, extent, composed of blocks of broken ice

NOTE See also **stamukha** (3.76), the term for a grounded rubble pile.

3.69
safety-critical element
SCE
item of equipment, procedure or structure whose failure can lead to a major accident or whose purpose is to prevent or limit the consequences of a major accident

3.70
scour
soil erosion caused by wave, ice or current action

3.71
seabed
material below the elevation of the sea floor or ocean floor

3.72
sea floor
mudline
interface between the sea and the seabed and referring to the upper surface of all unconsolidated material

3.73
seasonal operation
operation of a structure during a selected period during the course of the year, generally to avoid particular ice conditions

3.74
second-year ice
sea ice that has survived one summer's melt season

NOTE "Second-year ice" is sometimes referred to as "multi-year ice"; see 3.51.

3.75
shelf ice
sea ice formed adjacent to a glacier terminating in the ocean

3.76
stamukha
grounded ice feature composed of broken ice pieces or rubble

3.77
station bill
posted list showing the duties and duty stations of designated personnel on the installation with emergency response organization roles and responsibilities

3.78
strudel scour
incision in the seabed caused by a natural water jet draining through holes in the ice

NOTE Strudel scours are usually found in river deltas when freshwater flows on the surface of sea ice.

3.79
system ductility
ability of a structure to deform and dissipate energy, taking into account material ductility, the ability of structural components to maintain inelastic load-carrying capacity and structural redundancy

3.80
temporary refuge
TR
place provided on the installation where personnel can take refuge for a specified period while investigations, emergency response and evacuation preparations are undertaken

3.81
unconsolidated layer
part of an ice ridge keel or ice rubble found below the consolidated layer that consists of unbonded or very weakly bonded ice blocks

NOTE The unconsolidated layer is also called the unconsolidated rubble layer.

3.82
upheaval buckling
buckling of a conductor or buried pipe due to soil deformations

NOTE Upheaval buckling is generally induced by changes to the permafrost.

4 Symbols and abbreviated terms

4.1 Symbols

A	Accidental action
E	Environmental action
F	Repetitive action
f_c	Concrete compressive strength
f_y	Characteristic yield strength
G	Permanent action
G_1	Dead permanent action
G_2	Deformation permanent action
Q	Variable action
Q_1	Long-duration variable action
Q_2	Short-duration variable action
γ_s	Steel resistance factor
γ_c	Concrete resistance factor
η	Concrete efficiency factor

4.2 Abbreviated terms

AL	abnormal level
ALARP	as low as reasonably practicable
ALE	abnormal-level earthquake
ALIE	abnormal-level ice event
ALS	abnormal (accidental) limit state
EER	escape, evacuation and rescue
EL	extreme level
ELE	extreme-level earthquake
ELIE	extreme-level ice event
FE	finite element
FLS	fatigue limit state
FY	first-year, with reference to ice
GBS	gravity base structure
HAZID	hazard identification
HSE	health, safety and environment

HVAC	heating, ventilating and air conditioning
IMO	International Maritime Organization
LAST	lowest anticipated service temperature
MY	multi-year, with reference to ice
ND	no data
NDT	non-destructive testing
OIM	offshore installation manager
POB	personnel on board
PPE	personal protective equipment
QRA	quantitative risk analysis
RCS	recognized classification society
SAR	search and rescue
SCE	safety-critical element
SLIE	serviceability-level ice event
SLS	serviceability limit state
TR	temporary refuge
ULS	ultimate limit state
WMO	World Meteorological Organization

5 General requirements and conditions

5.1 Fundamental requirements

Offshore structures for use in arctic and cold regions shall be planned, designed, constructed, transported, installed and decommissioned in accordance with ISO 19900 supplemented by this International Standard.

Physical environmental parameters shall be determined in accordance with ISO 19901-1 and the further requirements of this International Standard. Seismic actions shall be determined in accordance with ISO 19901-2, foundation behaviour shall be determined in accordance with ISO 19901-4, and actions and resistances for steel, concrete and floating structures shall be determined in accordance with ISO 19902, ISO 19903 and 19904-1 respectively, and according to the further requirements of this International Standard. Requirements for marine operations, stationkeeping and topsides in arctic and cold regions are provided to complement the requirements of 19901-6, 19901-7 and 19901-3 respectively. This International Standard provides requirements, recommendations and guidance on ice related parameters, as well as actions for the above structure types and for particular structures such as man-made islands. The above documents should be used jointly to develop appropriate physical environmental parameters, actions, resistances and designs.

Clause 5 provides general requirements and conditions applicable to all types of offshore structures.

5.2 Design methods

For designs performed in accordance with the design process and equations provided in this International Standard, levels of safety and performance are established in Clause 7.

An alternative rational design method based on theory, analysis, and recognized engineering practice may be used in lieu of the design process and equations provided in this International Standard, provided that it establishes levels of safety and performance that are at least equal to those established in Clause 7.

Where possible, data from full-scale measurements of ice actions shall be used to verify new designs. Appropriately scaled physical models and mathematical models may also be used to determine the response of structures to ice actions, in combination with current, wind and wave actions. Where possible, such models shall be calibrated using data from full-scale measurements.

5.3 Site-specific considerations

5.3.1 General

Identification, investigation and determination of site-specific conditions for sea ice and icebergs shall be made with due consideration to the phenomena and effects described in 6.5 and 8.2.

The structure and all its subsystems shall be operated in an environmentally sound manner. Conditions that can influence the functional and operational requirements shall be identified. Appropriate procedures for matters concerning health, safety and the environment shall be established and maintained.

The evaluation of possible hazard scenarios shall include potential occurrences of abnormal-level ice events, the local and global consequences of impacts from ice features, and arctic-specific geohazards.

5.3.2 Long-term climate change

Changes in storm frequency and magnitude, ice conditions, ocean circulation, air temperatures, permafrost, wave heights and water levels can occur during the design service life of the structure. Consideration for such changes should be included in the design.

5.3.3 Structural configuration

The configuration of the structure should consider the following:

- protection of risers and conductors;
- concept for oil storage and export;
- wet or dry storage system;
- layout of facilities and separation distances from hazards;
- potential for future expansion under phased development;
- potential for platform removal;
- environmental constraints;
- capability of local construction facilities and materials; and
- available construction season for offshore operations.

Different structural shapes, orientations and profiles for the structure and the topsides should be considered for resisting sea ice or iceberg actions.

In defining the orientation of the structure at the site, consideration should be given to the ice conditions, prevailing ice drift directions and ice rubble build-up. The topsides should be arranged with respect to the functional and operational requirements, such as re-supply, offloading, flaring and EER, and with respect to wind and ice encroachment.

The reliability of EER, platform supply and offloading systems can potentially be improved through

a) ice management to prevent ice rubble accumulation;

b) duplication of facilities on opposite sides of the platform; and

c) large crane booms to reach over accumulated rubble.

5.3.4 Winterization

Winterization measures should be considered to ensure the safe operation of all systems and equipment, thereby ensuring the safety of personnel. Such measures shall also ensure that personnel can conduct the required tasks in an ergonomically sound way, with respect to temperature, wind, visibility and restrictions imposed by personal protective equipment. Selected options should not result in adverse environmental consequences.

5.4 Construction, transportation and installation

5.4.1 General

The construction, transportation and installation of offshore structures shall be planned to minimize the risks to personnel and equipment due to adverse environmental conditions associated with cold regions.

5.4.2 Construction planning

The planning of construction activities shall include adequate consideration for periods of extreme low ambient temperatures. Materials and equipment shall be adequately protected by the provision of heating or insulation.

5.4.3 Transportation and installation

Evaluation of minimal draft limitations shall be performed for all regions through which the structure can be transported in order to reach its final destination.

Consideration shall be given to the specification of all marine spread equipment and the ability of personnel to safely perform the required transportation and installation activities during periods of low ambient temperature, low visibility and other relevant environmental conditions. Limiting environmental conditions shall be specified for all critical offshore activities and the associated weather windows shall be included in the planning and execution of such work. Contingency planning for all critical offshore activities shall be included to ensure safe transportation and installation.

Marine operations associated with the transportation and installation of the structure shall be in accordance with ISO 19901-6.

5.5 Design considerations

The combinations of actions and partial factors for determining action effects applicable to the different limit states shall be in accordance with the provisions of Clause 7.

5.6 Environmental protection

Arctic and cold region environments can be more sensitive and vulnerable to pollution than other environments. A structure intended for such environments shall be designed to minimize the potential for polluting the environment as far as is reasonably practicable. Structural systems requiring active operations to avoid pollution should be kept to a minimum. Harmful environmental impacts should also be minimized in the construction, transportation, installation and decommissioning phases.

Fluids and materials that, if released, can pollute the environment shall be contained in tanks having double barriers. A careful strategy should be followed as far as practically possible for inspection, maintenance and repair of any tanks containing fluids or materials that possibly can pollute.

Means for the containment and clean-up of polluting fluids shall be available at the site and be proven to operate under the expected physical environmental conditions.

In the case of permafrost or freezing conditions, provision should be made to ensure the integrity of ballast tanks.

5.7 Vibrations and crew comfort

Measures should be taken to ensure that structural vibrations do not cause crew discomfort during normal operations.

6 Physical environmental conditions

6.1 General

6.1.1 Physical environment requirements

The owner shall be responsible for selecting appropriate physical environmental design parameters and operating conditions. The owner shall take regulatory requirements into account, where they exist. These requirements can include a minimum duration of site-specific data (according to country regulations), the type of data and a definition of extreme design parameters.

General guidelines on metocean information are given in ISO 19900 and specific requirements in ISO 19901-1.

A realistic assessment of the physical environmental parameters affecting the proposed offshore structure shall be made. All relevant environmental data, as well as applicable physical, statistical, mathematical, and numerical models, shall be used to develop the appropriate information.

The following information shall be determined:

a) normal environmental conditions that are required to carry out checks for serviceability limit states, to develop actions and action effects to determine when particular operations can safely take place, and to plan construction activities (fabrication, transportation and installation) or field operations (e.g. drilling, production, offloading, underwater activities);

b) long-term distributions of physical environmental parameters, in the form of cumulative conditional or cumulative marginal statistics that are used to define design situations and to perform design checks for the fatigue limit state, or to make evaluations of downtime/workability/operability during a certain period of time for the structure or for associated items of equipment;

c) extreme and abnormal physical environmental parameters that are required to develop extreme and abnormal environmental actions and/or action effects, which are used to define design situations and to perform design checks for ultimate limit states and abnormal limit states;

d) regional environmental oscillations, cycles, and long-term trends associated with the parameters in a) through c).

The relevant physical environmental parameters can be dependent on the chosen structural form.

To obtain reliable and appropriate physical environmental parameters, experts in the field of metocean and ice technology shall be involved with the analysis of data and its interpretation for developing appropriate design situations and design criteria.

6.1.2 Physical environmental data monitoring programmes

Appropriate physical environmental parameters shall be monitored and forecast during the design service life of the structure to ensure safe operational procedures.

6.1.3 Relationship with remainder of this International Standard

Physical environmental parameters described in 6.2 through 6.6 shall be obtained for use in the calculation of global and local action values, as described in the appropriate subclauses of this International Standard.

Data shall be analysed in a format appropriate for use in the determination of relevant environmental actions (e.g. 8.2 for ice actions).

6.2 Daylight hours

The varying amount of daylight hours in arctic regions is a consideration for initial data collection and for the operations of offshore facilities. Due consideration of the effect of this parameter should be incorporated in operational planning.

6.3 Meteorology

6.3.1 Air temperature

Estimates shall be made of the probability distributions of air temperatures that a structure is likely to encounter during its design service life. The lowest anticipated service temperature (LAST) shall be defined in accordance with 3.48.

The effects of temperature shall be accounted for in the selection of structural materials, machinery lubrication, sealants and topsides winterization. The effects of thermal changes on structural behaviour and human capability shall be considered as part of the design and operation of the structure.

The air temperature affects ice properties and ice conditions. Air temperature changes, combined with wind and snow depth, control thermal expansion and associated actions in landfast ice. Low air temperatures, combined with winds, waves and sea spray, can also lead to marine icing events.

6.3.2 Wind

Wind related parameters shall be determined in accordance with ISO 19901-1.

6.3.3 Wind chill

The combined effect of air temperature and wind shall be used to calculate wind chill. The effect of wind chill upon human capability, machinery heat loss and topsides winterization shall be considered.

The importance of PPE, heated shelters, appropriate work procedures and other actions should be considered when workers are exposed to outdoor conditions.

6.3.4 Precipitation and snow

Estimates shall be made of the probability distributions of precipitation and snowfall that a structure is likely to encounter during its design service life. The extent to which snow can accumulate, and its possible effect on the structure and machinery, shall be considered. The effect of snow cover should be considered when evaluating ice properties, e.g. friction and ice strength, in determining ice actions and assessing vessel operations.

As snow accumulation can affect platform operations, considerations for snow removal should be made at the design stage.

6.3.5 Ice accretion

The extent of ice accretion from sea spray, freezing rain or drizzle, freezing fog or cloud droplets shall be considered in the design and operability of the structure. Ice accretion can increase the diameter of structural components and can lead to a substantial increase of actions caused by wind and self-weight, particularly for long slender structures such as flare towers. Ice accretion also affects operations and personnel safety.

6.3.6 Visibility

Information on factors affecting visibility (e.g. fog, blowing snow, daylight hours) particular to the site of the offshore structure shall be obtained. Its effect upon operations and physical environmental monitoring shall be considered.

6.3.7 Polar lows

Polar lows can affect the sub-arctic and arctic. Due to their small size and the lack of an extensive ground observation system in these regions, polar lows are difficult to observe and forecast. The waves and winds associated with these features are generally not in the extreme range, but can affect operations. When activities take place, the use of satellite remote sensing to seek out these features should be considered as part of the normal meteorological forecast service.

6.4 Oceanography

6.4.1 Water depth

The water depth at the site, including its variation, shall be determined. The range of water levels and its effect on ice action location shall be used to determine the most adverse effect on the foundation or structural component under consideration. For shallower water depths, ice can ground around a structure and cause changes in ice design scenarios for the structure and transportation systems, create operational problems and affect EER procedures.

For the purpose of design or assessment, water depth can be considered to consist of a more or less stationary component relative to a reference datum (e.g. lowest astronomical tide or mean sea level) and a variable component being the variations in time relative to this level. The variations are due to astronomical tide, storm surges caused by wind and atmospheric pressure, long-term variations, sea floor subsidence and tsunamis. The design implications of positive and negative storm surges should be considered in the specification of actions on the structure, in the operation of the structure and for vessel operations planning.

6.4.2 Waves

Wave parameters for open water shall be determined in accordance with ISO 19901-1.

Ice coverage on the sea surface affects wave growth, propagation and decay. The effect of ice cover should be considered when determining extreme and operational wave parameters, especially when numerical models are employed to determine these parameters.

The effect of increased speed and elevation of ice features due to waves shall be taken into account in determining the combined wave-ice actions upon the structure.

6.4.3 Ocean currents

Parameters related to currents, including tidal effects, shall be determined in accordance with ISO 19901-1.

6.4.4 Other oceanographic factors

6.4.4.1 Marine growth

Marine growth shall be determined in accordance with ISO 19901-1.

When calculating the effect of marine growth in ice covered regions, consideration should be given to local conditions and their effect on the periodic cleaning of marine growth on the parts of the structure exposed to ice. Increased marine growth near areas of warm water discharge should be considered.

6.4.4.2 Tsunamis

The design implications of tsunamis shall be determined in accordance with ISO 19901-1.

Consideration should be given to the effect of ice cover on tsunami wave parameters.

6.4.4.3 Dissolved oxygen

Higher dissolved oxygen content can be encountered in cold water regions. Since higher oxygen levels can enhance corrosion, local data should be collected to assess this hazard when relevant for the structural materials used.

6.4.4.4 Water temperature and salinity

The temperature at which water freezes is a function of water salinity. At normal ocean water salinity, considered to be 35 ‰, water freezes at −1,9 °C. This shall be considered as the coldest water temperature that can be found in regions affected by sea ice.

6.5 Sea ice and icebergs

6.5.1 General

Information required to characterize site-specific ice criteria shall be determined for the location of the structure under consideration. This information should consider all phases of the structure's design service life.

Data can be obtained from direct observations at a location, interpretation of satellite imagery, or historical information at the geographic region of the installation. Where local ice data are unavailable or are not representative of relevant severe ice conditions, or where ice incursions are infrequent, data from nearby sites or geographical regions with similar ice environments may be used. Numerical or statistical modelling may be used to extend these data sets, with due account for uncertainties. Long-term trends shall be taken into account. Interrelationships between the various parameters listed in 6.5.2 through 6.5.5 shall be considered, where relevant for the development of design criteria.

6.5.2 Ice types

The types of ice expected, i.e. first-year, second-year, multi-year, shelf or glacial, shall be determined. Statistics, such as probability distributions and parameters thereof, shall reflect the occurrence and concentration of all relevant ice types.

Inter-annual and seasonal variations in the presence of ice types shall be considered.

6.5.3 Ice morphology

The occurrence and geometry of specific ice features, such as icebergs, ice islands, rafted ice, rubble fields, leads or polynya, pressure and shear ridges, stamukhi, landfast ice, pack ice, shelf ice and glacial ice, shall be determined on the basis of field measurements at the site and historical data from nearby sites. Statistics, such as probability distributions and parameters thereof, and appropriate ice feature frequency, dimensions, as well as ridge and stamukha consolidated layer thickness, sail height and keel depth shall be determined.

The occurrence of grounded ice features, such as grounded rubble piles and beach pile-ups, shall be determined to obtain appropriate ice feature frequency, extent, size, potential gouge depth and stability. This information shall be used in the determination of ice actions, design of flowlines and their burial depth, access to facilities, logistics, and evacuation systems.

Inter-annual and seasonal variations in ice morphology shall be considered.

6.5.4 Ice movement

Wind, waves, current and thermal expansion affect ice movement and pack ice pressure. Statistics, such as probability distributions, means and extremes, of movement rates for pack ice, ice floes and discrete features such as icebergs and ice islands, shall be determined on the basis of field data. Ice movement rates affect the number of ice features encountered, ice actions, and operations. Ice pressure can affect vessel traffic, ice management and evacuation procedures.

If field data do not exist for these parameters, numerical modelling or analysis of the interaction of winds, waves, ocean currents and ice may be performed to obtain this information, with due account for uncertainties in the data and modelling procedures.

Inter-annual and seasonal variations in ice presence, polynyas and physical parameters shall be considered.

6.5.5 Ice properties

Appropriate mechanical and physical properties of ice shall be used for design and operational procedures. The considerations of 8.2.8 shall apply.

6.5.6 Ice monitoring

Ice conditions shall be considered as part of the physical environmental data monitoring programme. Real-time information on ice conditions should be used, for example, to operate ice management systems, and escape, evacuation and rescue (EER) procedures for the installation. Coupled with a management plan for shutdown and possible removal during the operational phase of the structure, ice monitoring can help to reduce the ice criteria used for structural design of both floating and bottom-founded mobile structures.

6.6 Seabed considerations

6.6.1 Earthquake

The complexity of a seismic action evaluation and the associated design procedure for an arctic offshore structure depends on the structure's seismic risk category as determined in accordance with ISO 19901-2. Acceleration levels taken from the maps provided in ISO 19901-2 define the seismic zones, which can be used to determine the appropriate seismic design procedure. The selection of the procedure depends on the structure's exposure level as well as the severity of ground motion.

Where seismic events are a design concern, appropriate analyses shall be carried out (see 9.10).

6.6.2 Permafrost

An investigation into the extent of permafrost from the shore and the presence of permafrost at platform locations shall be performed. Offshore structures founded on permafrost require special studies in order to understand the performance of the soil under time-varying actions induced by earthquakes, waves or sea ice (refer to Clause 9). The potential effects of thaw consolidation of ice-rich permafrost as a result of producing warm hydrocarbons should be considered in the design of all structure foundations.

6.6.3 Ice gouge

Seabed gouging occurs due to the interaction of ridges, icebergs, and stamukhi with the seabed. Data on ice-induced gouging shall be obtained to determine the frequency of gouge occurrence and its depth, width, length, and direction. Gouge statistics shall be used in regions of seabed utilization for the design and burial of flowlines and umbilicals, subsea facilities and platform tie-ins. See 9.2 for survey requirements and 14.2.2 for effects on subsea structures.

6.6.4 Strudel scours

Strudel scouring shall be investigated for structures in regions near the mouths of rivers. See 9.2 for survey requirements, and 14.2.3 and 14.3.5 for effects on subsea structures.

7 Reliability and limit states design

7.1 Design philosophy

7.1.1 Governing principles

The structure and its components shall be designed so that they function with adequate reliability for all physical environmental, accidental and operational actions and conditions to which the structure can be subjected during all phases of the design service life, including construction, transportation, installation and removal. The required reliability depends on the exposure level, which is determined by the life-safety category and the environmental and economic consequence category of the structure or component.

Design shall be in accordance with the limit states approach as specified in 7.2. This requires that action effects arising from factored action combinations shall not exceed factored resistances. Resistances and their relevant partial factors shall be determined in accordance with this International Standard and its referenced documents. Actions shall include, but not be limited to, ice, seismic, oceanographic, meteorological, permanent and variable actions. Partial factors for action combinations associated with ULS and ALS shall be in accordance with 7.2.4.

7.1.2 Life-safety categories

The life-safety category of a structure and its components is a ranking of its exposure in relation to the safety of personnel on the platform and the likelihood of successful evacuation before a design environmental event occurs during its design service life, and shall conform to the life-safety categories defined in ISO 19902, ISO 19903 and ISO 19904-1 as relevant for the type of structure. Since the life-safety category of a structure can change during its design service life, the structure shall be designed to meet the applicable life-safety category during each phase of its design service life or shall meet the most stringent category occurring during the design service life.

For offshore structures, three life-safety categories are defined:

- S1: manned non-evacuated;
- S2: manned evacuated;
- S3: unmanned.

7.1.3 Consequence categories

The consequence category of a structure and its components is a ranking of its hazard potential with respect to the safety of personnel brought in to react to any incident, the potential risk of damage to the environment and the potential risk of economic losses, and shall conform to the consequence categories defined in ISO 19902, ISO 19903 and ISO 19904-1.

For offshore structures, three consequence categories are defined:

— C1: high consequences;

— C2: medium consequences;

— C3: low consequences.

7.1.4 Exposure levels

Exposure level depends on the life-safety and consequence categories in accordance with Table 7-1. All manned, non-evacuated structures (S1) and high consequence structures (C1) are designated L1; unmanned (S3), low consequence (C3) structures are designated L3; while other structures are designated L2.

Table 7-1 — Determination of exposure level

Life-safety category		Consequence category		
		C1 High consequence	C2 Medium consequence	C3 Low consequence
S1	Manned non-evacuated	L1	L1	L1
S2	Manned evacuated	L1	L2	L2
S3	Unmanned	L1	L2	L3

The exposure level applicable to a structure or a component shall be determined by the owner prior to the design of a new structure or the assessment of an existing structure, and be agreed by the regulator where applicable. Where more than one exposure level can apply to a structure or component, the most stringent exposure level matching the specification is applicable. Some components or sub-structures can be categorized differently from each other and from the overall structure, in which case their exposure level can be different.

Categorization may be revised over the design service life of the structure as a result of changes in factors affecting life-safety or consequence category.

7.1.5 Limit states

For the limit states design method, the reliability relevant to the exposure level is achieved with respect to ultimate limit states (ULS) and abnormal limit states (ALS). These limit states are critical because their violation can directly result in loss of human life, environmental damage, or asset loss.

Fatigue limit states (FLS) shall be satisfied.

Serviceability limit states (SLS) are only assigned quantitative reliability targets under specific circumstances in this International Standard. Such limit states shall be satisfied as appropriate.

7.1.6 Alternative design methods

Alternative design methods may be used if the reliability of the structure and its components is shown to be equivalent to or better than that of the limit state design approach as set out in 7.2.

7.2 Limit states design method

7.2.1 Limit states

7.2.1.1 Categories of limit states

Limit states are divided into the following four categories:

a) ultimate limit states (ULS) that generally correspond to resistance to extreme applied actions;

b) serviceability limit states (SLS) that correspond to criteria governing normal functional use;

c) fatigue limit states (FLS) that correspond to the accumulated effect of repetitive actions;

d) abnormal (accidental) limit states (ALS) that correspond to accidental events and abnormal environmental events.

The structure shall be designed for ULS for strength and stiffness, for ALS so it has adequate reserve capacity and energy dissipation capability, for FLS so it has adequate endurance under dynamic action effects, and for SLS so it performs adequately under normal use.

7.2.1.2 Ultimate limit states

The ULS requirement ensures that no significant structural damage occurs for actions with an acceptably low probability of being exceeded during the design service life of the structure. The ULS design condition for ice shall be the extreme-level ice event (ELIE). Both local and global actions shall be considered.

7.2.1.3 Serviceability limit states

Exceedance of SLS results in the loss of capability of a structure to perform adequately under normal use. The specification of actions for SLS is generally the owner's responsibility, except for considerations that can lead to long-term structural degradation, such as corrosion of reinforcement in concrete.

7.2.1.4 Fatigue limit states

Exceedance of FLS for offshore structures results from cumulative damage due to repeated actions. All actions over the design service life shall be considered, including the transportation phase to the site. For ice actions, cyclic variations are generally associated with compressive and flexural ice failure.

7.2.1.5 Abnormal (accidental) limit states

The ALS requirement is intended to ensure that the structure and foundation have sufficient reserve strength, displacement or energy dissipation capacity to sustain large actions and other action effects in the inelastic region without complete loss of integrity. Some structural damage can be allowed for ALS. The ALS design condition for ice shall be the abnormal-level ice event (ALIE). Both local and global actions shall be considered.

7.2.2 Actions

7.2.2.1 General

Permanent actions (G), variable actions (Q), environmental actions (E), repetitive actions (F) leading to fatigue, and accidental actions (A) are defined in ISO 19900. Further details on their specification are found in ISO 19902, ISO 19903 and ISO 19904-1.

For structures in arctic and cold regions, the design shall be based on both extreme-level (EL) and abnormal-level (AL) events, which include ice actions arising from ELIE and ALIE.

Representative values shall be assigned to each action. The main representative value is the characteristic value, which is a value associated with a prescribed probability of being exceeded by unfavourable values during a reference period, which is generally one year.

In arctic and cold regions, there can be additional accidental events that should be evaluated, such as ice-driven ship impacts on a structure.

7.2.2.2 Serviceability-level ice events

For SLS, the structure should satisfy the requirements of this International Standard when structural members are subjected to localized ice damage. Examples include: concrete cracking and shrinkage, for which action factors are provided in ISO 19903; loss of concrete cover due to ice abrasion, removal of paint and removal of corroded steel from ice abrasion; and localized damage as a consequence of vibrations induced by ice and other physical environmental factors. The structure shall also satisfy serviceability limits for vibrations and deflections.

Unless the owner has specified otherwise, the characteristic value of the SLIE used for SLS shall be determined based on an annual probability of exceedance not greater than 10^{-1}.

7.2.2.3 Extreme-level ice events

For ULS, the design procedures shall be based primarily on linear elastic methods of structural analysis. Some localized inelastic behaviour is acceptable, for example, as permitted in Clause 11 for fixed steel structures.

The representative value for actions arising from extreme-level ice events (ELIE) shall be determined based on an annual probability of exceedance not greater than 10^{-2}. The ELIE is not applicable for discrete events with an annual probability of occurrence of less than 10^{-2}.

7.2.2.4 Abnormal-level ice events

For ALS, non-linear methods of analysis may be used. Structural components are allowed to behave plastically, and foundation piles are allowed to reach axial capacity or develop plastic behaviour. The design is based on a combination of static reserve strength, ductility and energy dissipation to resist the ALIE conditions.

The representative value for actions arising from the ALIE shall be determined based on an annual probability of exceedance related to the exposure level. For L1 structures, this shall be determined based on an annual probability of exceedance not greater than 10^{-4} or shall be derived from events with an annual probability of occurrence not greater than 10^{-4}. For L2 structures, these probabilities shall be not greater than 10^{-3}. Abnormal-level events need not be considered for L3 structures.

Iceberg and ice island impact events with an annual probability of occurrence between 10^{-4} and 10^{-5} for L1 structures (between 10^{-3} and 10^{-4} for L2 structures) and with high consequences should be considered for ALIE to ensure adequate reliability of the structure (see A.7.2.4 for reliability targets).

7.2.2.5 Dynamic ice actions

If relevant, dynamic ice actions and ice-induced vibration shall be characterized with respect to the FLS, and with respect to other effects on structures and foundations including potential for soil liquefaction.

7.2.2.6 Other environmental actions

Characteristic values for all other environmental actions shall be determined at the extreme-level (EL), with an annual probability of exceedance not greater than 10^{-2}, and at the abnormal-level (AL), with an annual probability of exceedance not greater than 10^{-4} for L1 structures and 10^{-3} for L2 structures. It is not necessary to consider abnormal-level events for L3 structures. For seismic actions, the extreme-level earthquake (ELE) and abnormal-level earthquake (ALE) event probabilities shall be as specified in ISO 19901-2.

It is not necessary to consider actions from environmental events other than ice if the action arising has an annual probability of exceedance less than 10^{-4}.

Effects due to temperature differences within the structure or component are to be considered in all relevant limit states.

7.2.2.7 Accidental actions

Accidental situations shall be addressed in accordance with ISO 19902, ISO 19903 and ISO 19904-1 depending on the structure type. For man-made islands, the provisions of ISO 19902 shall be applied.

7.2.3 Principal and companion environmental actions

Action combinations for each environmental action shall be derived by considering each EL and AL representative value of the action, in turn, as the principal action. These values shall be accompanied by companion environmental actions.

Potential combinations of principal and companion environmental actions are given in Table 7-2.

Table 7-2 — Companion EL environmental actions

Principal action (EL or AL)	**Companion EL environmental action**		
	Stochastically dependent	**Stochastically independent**	**Mutually exclusive**
Waves	Wind, wind-driven current	Tidal and background current	Sea ice (for ice concentration ⩾ 8/10)
Waves	Wind, wind-driven current, ice (for ice concentration < 4/10)	Sea ice (for ice concentration < 8/10)	—
Swell	—	Waves, wind, wind-driven current, tidal and background current, sea ice (for ice concentration < 8/10)	Sea ice (for ice concentration ⩾ 8/10)
Tsunami	—	Waves, wind, wind-driven current, tidal and background current, sea ice	—
Wind	Waves, wind-driven current, sea ice	Swell, tidal and background current	—
Wind	Wind-driven current, sea ice	Tidal and background current	Waves, swell (for ice concentration ⩾ 8/10)
Current (tidal and background)	Sea ice	Waves, swell, wind, wind-driven current	Waves, swell (for ice concentration ⩾ 8/10)
Current (wind-driven)	Sea ice, waves, wind	Swell, tidal and background current	Waves, swell (for ice concentration ⩾ 8/10)
Sea ice	Wind, wind-driven current, tidal current	—	Waves, swell (for ice concentration ⩾ 8/10)
Sea ice	Wind, wind-driven current, tidal current, waves (for < 4/10 sea ice concentration)	Waves, swell (for ice concentration < 8/10)	—
Earthquake[a]	—	Waves, swell, wind, wind-driven current, tidal and background current, persistent ice cover	—
Large icebergs or isolated ice features	Wind, wind-driven current, tidal and background current	Waves[b], swell[c]	—

[a] For the AL earthquake, it is normally sufficient to consider only ice likely to be present when an earthquake occurs.

[b] The principal action from small icebergs or ice floes and the companion wave actions can be stochastically dependent.

[c] It can be necessary to assess the swell-driven motion of large icebergs.

The effect of water level changes shall be considered in the specification of companion actions. Storm surges should be considered as stochastically dependent on the wind if the principal action depends on the wind. Tidal elevations should be considered as stochastically dependent where the principal action depends on tidal currents.

Where data are available, the joint probability distribution of the principal and relevant companion actions should be used to determine the magnitude of combined EL or AL environmental action. In the absence of specific consideration of joint probabilities, the combination factors provided for companion EL actions in Table 7-3 shall be used. In this case, the representative EL value of each relevant companion action shall be multiplied by the relevant factor from Table 7-3 and added to the value of the EL or AL principal action. The values specified in Table 7-3 are conservative to account for a wide variety of possibilities. Consequently, site-specific data should be used and joint probabilities calculated whenever possible.

The principal and companion EL actions for ice are extreme-level ice events (ELIE). The principal AL action for ice is the abnormal-level ice event (ALIE).

Table 7-3 — Combination factors for companion EL environmental processes

Principal action	Factor for representative EL companion environmental action	
	Companion action is stochastically dependent on the principal action	Companion action is stochastically independent of the principal action
EL action	0,9	0,6
AL action	0,5	0,4

7.2.4 Combinations of actions and partial action factors

The action combinations specified in Table 7-4 shall be used in design. For each action combination, the representative value of an action or combined environmental action shall be multiplied by a partial action factor not less than that specified in Table 7-4, except that, alternatively, action factors for permanent and variable actions may be taken from ISO 19902, ISO 19903 or ISO 19904-1 for the respective structure types. These action factors apply to both local and global actions. ISO 19900 provides further information on the classification of types of action.

The combination of actions and the partial action factors for earthquakes shall be in accordance with ISO 19902 for fixed steel structures and in accordance with ISO 19903 for fixed concrete structures. Further guidance is provided in 8.4.

Action factors and action combinations for SLS and FLS shall be in accordance with ISO 19902, ISO 19903 or ISO 19904-1 as relevant to the structure type.

For action combinations where an abnormal or accidental action is the principal action (action combinations 4 and 5 in Table 7-4), the action effects shall be checked for ALS only.

The partial action factors for environmental actions other than earthquakes specified in Table 7-4 have been calibrated to the reliability targets given in Table A.7-1. When these partial action factors are applied to ULS and ALS action combinations for arctic offshore structures and their components within the scope of this International Standard of exposure levels L1 and L2, the reliability targets given in Table A.7-1 are deemed to be achieved.

As an alternative to Table 7-4, the partial action factors may be derived from a calibration analysis using a full probabilistic description of actions if this analysis demonstrates that the reliability targets of A.7.2.4 are achieved.

Table 7-4 — Exposure levels L1 and L2 — ULS and ALS action factors and action combinations

Action combination		Limit state action factors						
		Permanent action G		**Variable action** Q		**Environmental action** E		**Accidental action** A
		Dead G_1	**Defor-mation** G_2	**Long duration** Q_1	**Short duration** Q_2	**EL**	**AL**	
Ultimate limit states								
1	Gravity and deformation – long and short duration	1,30[a] or 0,90[b]	1,00	1,50[a]	1,50[a]	0,70[c]	—	—
2	Extreme environmental	1,10 or 0,90[b]	1,00	1,10 or 0,80[b]	—	1,35 (L1)[c,d] 1,10 (L2)[c,d,e]	—	—
3	Damaged condition[f]	1,10 or 0,90[b]	1,00	1,10 or 0,80[b]	—	1,00	—	—
Abnormal (accidental) limit states								
4	Abnormal environmental	1,00	1,00	1,00	—	—	1,00[c]	—
5	Accidental	1,00	1,00	1,00	—	—	—	1,00

[a] For the gravity and deformation action combination, a partial action factor of 1,20 may be used for permanent hydrostatic pressure and for physically limited variable actions.

[b] The lower partial action factor applies for permanent G_1 actions when the permanent action resists overturning or uplift, and for variable Q_1 actions when there is a reversal of variable action effects.

[c] The representative value of the environmental action to which the action factor applies shall be calculated as described in 7.2.3.

[d] The limit state partial action factor for the extreme-level seismic action (ELE) shall be as defined in ISO 19902 for steel structures and shall be as defined in ISO 19903 for concrete structures. The partial action factor for the ELE shall be 1,0 for all other structures.

[e] For L2 exposure level, all action factors for all action combinations are as for L1 except for the EL factor in the extreme environmental action combination.

[f] Damaged condition or progressive collapse limit states are defined generally for structures in ISO 19900 and for particular types of structures in ISO 19902, ISO 19903 and ISO 19904-1.

7.2.5 ULS and ALS design

For the ULS, the characteristic resistances shall be divided by resistance factors to obtain the design resistances. Alternatively, the characteristic material properties shall be divided by material factors to obtain the design material properties. The safety for each ultimate limit state shall be verified by ensuring that the effect of factored actions does not exceed the factored resistance.

For the ALS, the resistances shall be derived such that failure or collapse does not occur, and therefore structure and foundation resistance or safety factors may be reduced from their ULS values, or set to unity, as permitted by this International Standard and its referenced documents. However, components may be allowed to behave inelastically (i.e. design resistance may be exceeded) if there is sufficient ductility and if the overall structural design is adequately robust and provides alternative load-paths to distribute and resist the action effects and dissipate the energy.

8 Actions and action effects

8.1 General

The actions and action effects necessary to consider for design depend on the physical environment into which the structure will be placed, as well as the reliability expected of the structure. Guidance on actions and action effects is found in ISO 19900, ISO 19901-1, ISO 19901-2, ISO 19902, ISO 19903 and ISO 19904-1.

Wave actions, wind actions, current actions, ice actions, and seismicity are considered in ISO 19901-1, ISO 19901-2, ISO 19902, ISO 19903 and ISO 19904-1. Provisions for the treatment of ice actions and their combination with other types of actions are given in 7.2.4 with the further requirements of Clause 8.

The design of arctic offshore structures shall include consideration of global actions, relating to the overall integrity of the structure, foundation and stationkeeping system, and local ice actions for specific components or portions of the structure.

The actions used for design shall consider all phases of the design service life, including construction, transportation, installation and removal. Allowance for possible weight increase and shift in the centre of gravity due to ice accretion during fitting out (if performed in arctic or cold regions) and transportation shall be considered. The allowance shall reflect the time of year and geographical area. Differential strains or lock-in stresses due to temperature changes between construction and permanent locations shall be considered in the design.

Structures or components subjected to ice interaction events with an annual probability exceeding the value specified in 7.2.2.4 appropriate to the exposure level shall be designed for ice actions. In the absence of data to quantify the potential for ice events, ice actions shall be assessed if there is a reasonable probability of interaction. All realistic interaction scenarios with potentially adverse consequences should be considered in this respect. Reference should also be made to 8.3.1.4 for wave-induced ice motion.

8.2 Ice actions

8.2.1 General principles for calculating ice actions

Direct ice actions and actions arising from the interaction between the ice and the structure shall be considered for both global and local scales. Such actions can include

a) static, quasi-static, cyclic and dynamic actions (EL and AL);

b) cyclic and dynamic actions that can cause structural fatigue, liquefaction and personnel discomfort; and

c) spatial actions such as rubbling, pile-up, ride-up and similar ice behaviour that can hinder operations.

The magnitude of global ice actions and their point of action shall be determined in accordance with 8.2.4 so that the required integrity of the structure can be assessed. This includes resistance to sliding and overturning, capacity of the foundation, fatigue and foundation liquefaction. Local actions shall be considered in accordance with 8.2.5.

Methods based on full-scale action and response data from measurements on instrumented structures shall be used for the determination of design ice actions on offshore structures, with due account of their applicability, and for the uncertainties in the data and the methods used in their interpretation. Where no data are available at the location of interest, measurements from other regions may be extrapolated using knowledge of the ice regimes, metocean aspects, climate, brine volume and strength parameters. Small-scale ice strength data obtained locally, preferably *in situ*, can be of assistance in the extrapolation. Physically based models and scale model tests may also be used to complement the full-scale data, with due account for uncertainties in their application.

Further requirements relating to ice actions are found in 10.3 for man-made islands, in 13.4 for floating structures and in 14.3 for subsea structures.

8.2.2 Representative values of ice actions

The design shall be carried out for extreme-level ice events (ELIE) and abnormal-level ice events (ALIE), as defined in 7.2.2.3 and 7.2.2.4.

Representative values for ice actions shall be calculated using probabilistic methods or deterministic methods for ELIE and ALIE.

8.2.3 Ice action scenarios

Design ice actions shall reflect

- the relevant ice scenario, limiting mechanisms and ice failure modes for the geographical location of the structure, with reference to the provisions of 8.2.4, 8.2.5, 8.2.6 and 8.2.8; and
- the structural configuration and the relevant operational scenarios, including seasonal operation, ice detection, physical ice management, manoeuvring of the structure and disconnection, with reference to the provisions of 8.2.7.

The ELIE and ALIE shall be determined for each relevant ice loading scenario. When several ice and operational scenarios are relevant for a particular structure, those resulting in the largest ice actions for each limit state shall be considered in the design.

Where applicable, scenarios for consideration shall include structures interacting with

a) first-year ice features (level ice, rafted ice, landfast ice, floes, ridges, rubble fields, refloated stamukhi);

b) multi-year ice features (level ice, floes, ridges, rubble or hummock fields);

c) icebergs; and

d) ice islands (ice shelf fragments).

The basis for determining the scenarios is given in Annex B, which outlines the various ice regimes present in offshore waters. The relative importance of potential scenarios shall be determined based on the structural configuration.

Subsidiary conditions that can act in combination with the ice features or can influence the nature of the interaction include

- seasonality;
- ocean currents including tidal effects;
- wind;
- waves;
- water depth.

8.2.4 Global ice actions

The determination of global ice actions shall be based on methods that incorporate relevant full-scale measurements, model experiments if they can be scaled reliably, or theoretical methods (analytical or numerical) that have been calibrated using experiments or full-scale measurements. Each of the following conditions shall be considered, and the governing ones shall be used to determine ice actions:

a) quasi-static actions due to level ice (first-year, rafted or multi-year), where inertial action effects within the structure can be neglected;

b) dynamic actions due to level ice (first-year, rafted or multi-year), where inertial action effects within the structure are influential and a dynamic analysis is required;

c) quasi-static actions due to ice rubble and ridges, where inertial action effects within the structure can be neglected;

d) impacts from discrete features such as icebergs, ice islands and large multi-year or first-year ice features;

e) quasi-static actions from features lodged against the structure, driven by the surrounding ice or directly by metocean actions;

f) adfreeze action effects, including the frozen-in condition; and

g) thermal action effects;

The following limiting mechanisms shall be considered.

- Limit stress, which is the mechanism that occurs when there is sufficient energy or driving force to envelop the structure and generate ice actions across its total width. Limit stress actions include direct ice failure against the structure, ice failure within rubble lodged against the structure, floe buckling or floe splitting.

- Limit energy, which is the mechanism that occurs when the interaction is limited by the kinetic energy of the ice feature and is generally characterized by the absence of surrounding ice. Such actions are likely to arise due to impacts of icebergs, refloated stamukhi, multi-year floes or ice islands.

- Limit force, which is the mechanism that occurs when the interacting feature is driven against the structure by metocean actions, and the actions are insufficient for the ice to fail locally and envelop the structure. Such actions are likely to arise where large ice features interact with a structure under the action of wind, current or pack ice pressures, or a combination of these actions.

Ice crushing, shear, flexure, splitting and buckling failure modes should be considered in the calculation of global actions for each of the above failure mechanisms. Where relevant for the scenario, ice conditions and limiting mechanisms, the following factors shall be considered in determining ice actions:

- event frequency;

- geometry of the ice or ice features;

- geometry of the structure;

- mass and added mass of the ice feature;

- mechanical properties of the ice or ice feature;

- adfreeze bond between ice and the structure;

- inertial effects (and added inertia) for both the ice and the structure;

- velocity and direction of movement of the ice features;
- pressured ice conditions;
- ice rubble build-up, and implications for encroachment, structure freeboard requirements and actions transmitted to the structure;
- clearing of ice around the structure;
- ice jamming between the members of a multi-leg structure;
- compliance and damping of the structure and stationkeeping system;
- dynamic and hydrodynamic effects;
- degree of contact between the ice and the structure;
- friction between the ice and the structure;
- thermal effects in the ice;
- environmental actions of wind, current and pack ice pressure available to drive the ice and their persistence;
- surface morphology and the presence of snow on the ice; and
- influence of shoals and other barriers.

8.2.5 Local ice actions

Local ice actions shall be based on relevant full-scale measurements or established theoretical methods. Due account shall be taken of geographical differences and water level changes in their specification.

Local ice actions shall be considered for all parts of the structure contributing to its overall integrity and stability or that, if damaged, can lead to progressive failure as required in 7.2.2.3 and 7.2.2.4. For steel structures, local actions shall apply to the design of sheet piling, plates, stiffeners, frames and bulkheads. For concrete structures, local actions shall be considered for wall thickness, steel reinforcement and abrasion (see Clause 12). Regardless of structural material, local actions shall be applied to corners, structural discontinuities and appendages where these contribute to overall structural integrity.

Design contact areas shall be considered based on the local structural configuration, including frame spacing, plate thickness and appendage dimensions. The size and placement of the local contact areas shall be selected to ensure that the most critical cases are addressed.

Local ice actions shall be considered in the context of background actions on adjacent panels or areas of the structure.

8.2.6 Dynamic ice actions

The time-varying nature of ice actions and the corresponding ice-induced vibrations shall be considered in the design. The potential for dynamic amplification of the action effects due to lock-in of ice failure and natural frequencies shall be assessed. Particular attention shall be given to dynamic actions on narrow structures, flexible structures and structures with vertical faces exposed to ice action.

Structural fatigue and foundation failure as a consequence of dynamic ice actions shall be considered.

8.2.7 Operational procedures to reduce ice actions

Operational procedures may be used to mitigate ice actions on fixed, floating and subsea structures provided that it can be shown that, in combination with structural resistance, the intended level of reliability is achieved. Operational procedures include ice management, disconnection and removal, clearing of snow and ice accumulations, rubble and spray ice barriers, and seasonal operation. Ice management can be used to alter the ice regime, through decreases in floe size and the destruction or removal of potentially hazardous ice features, and through local reduction in ice coverage.

Ice action calculations for managed ice shall be performed when appropriate.

Reduction in design actions for ELIE and ALIE shall be demonstrated through changes to the magnitude and frequency of ice actions for all applicable scenarios. The effectiveness of operational procedures shall be founded on documented experience, where applicable, and the approach shall reflect the uncertainty inherent in the input data and modelling techniques.

8.2.8 Physical and mechanical properties of ice

Appropriate physical and mechanical properties of ice shall be used in the calculation of ice actions. The following provisions apply.

- Ice properties shall be appropriate to the geographical location and season under consideration.
- Appropriate full-scale test data shall be used, when available, with due account of their applicability.
- Ice property tests should follow accepted practice (see A.8.2.8).
- When reliable methods exist to predict the mechanical properties from physical properties, these may be used.
- Small-scale field and laboratory test data should be used with caution.

The following parameters may be used in adjusting and interpreting full-scale ice load data for the calculation of ice actions:

a) compressive and shear strength;

b) flexural strength;

c) tensile strength;

d) fracture toughness;

e) friction;

f) adfreeze strength;

g) internal cohesion and friction of fragmented ice;

h) elastic modulus; and

i) density.

8.3 Metocean related actions

8.3.1 Metocean actions on structures

8.3.1.1 General

Metocean actions on structures are discussed in ISO 19901-1. Additional requirements are provided in 8.3 for structures located in arctic and cold regions. These requirements fall in three categories:

a) effects of ice accumulation on the structure, its members and decks above the waterline;

b) particular forms of structures employed in such environments;

c) wave-induced local ice loading.

8.3.1.2 Ice accumulation on the structure

8.3.1.2.1 General

The expected effects of icing shall be accounted for in the ELIE and ALIE analyses of the structure. Icing of structures or structural members can result from fog, freezing rain, green water trapped on decks, wind- and wave-driven seawater spray, or tidal variation. Icing modifies the aerodynamic and hydrodynamic properties, static stability and dynamic responses of the structure. Icing can also modify the buoyancy and stability of floating structures.

Icing can be measured in terms of the thickness, volume or mass of ice adhering to the structure. Such estimates may be obtained from observations of icing on similar existing structures in the same area or from available theoretical models. When theoretical models are used, they should be suitably calibrated against observations.

8.3.1.2.2 Wave and current actions

The effect of icing on wave and current actions shall be determined. Icing can significantly raise the levels of wave and current actions on a structure due to changes in projected area, volume and surface roughness.

Accumulation of ice on a structure can cause large increases of projected area and volume around and above the mean waterline. It can also make circular cylinders effectively rough. Where these effects are present in the design situation, they should be accounted for in the areas, volumes and drag coefficients used in the calculation of environmental actions. Any of these effects can cause large action increases on a member above that in the absence of ice. Advice on the selection of drag coefficients for the Morison equation is given in ISO 19902. Advice on the use of diffraction analysis for large volume structures is given in ISO 19903, ISO 19904-1 and ISO 19902. Where computational fluid dynamics are used, the method should be verified against good quality model tests.

8.3.1.2.3 Wind actions

Wind actions shall reflect the presence of icing. The effect of icing on drag actions due to wind shall be analysed in the same way as Morison drag actions due to waves and currents are treated in 8.3.1.2.2.

8.3.1.2.4 Dynamic and static responses

Icing can affect the dynamic and static responses of structural members, appurtenances and complete structural systems and, consequently, the following factors shall be considered.

a) Actions exciting dynamic responses shall be modified as described in 8.3.1.2.1 and 8.3.1.2.3.

b) Strouhal numbers for the assessment of vortex-induced vibrations of members shall be similarly modified.

c) Masses of members and systems and any added masses shall be adjusted and moved in accordance with the icing. Consequences for additional vertical actions, stability, static position, reductions of structure freeboard and righting moments of floaters shall also be considered.

8.3.1.3 Particular considerations for large volume structures

The non-linear effects that control water surface elevation beneath a structure standing on large columns are not easily treated theoretically. In the case of fixed arctic offshore structures, wave focusing due to the presence of large caissons and/or earth mounds can further complicate the wave-structure interaction. Model testing should be carried out to assess the required air gap under the deck of a platform.

Wave actions shall be assessed for ice resisting structures with sloping faces and conical forms.

8.3.1.4 Freeboard and deck elevation

Deck elevations, structure freeboard and bow wall or ice deflector height shall account for the wave-induced vertical motion of the water surface and incident ice features. Account shall be taken of ice accumulations on the structure, the underside of the topsides deck or the substructure. The routing of all risers, caissons, J-tubes and other appurtenances shall minimize the risk of impact by such ice features. Further guidance is provided in 15.1.1.3.

Non-linear wave-structure interaction tends to increase water surface elevations around the structure. Consequently, ice can impact the structure at levels higher than most numerical schemes predict. The area of ice strengthening shall take this into account.

8.3.2 Wave-induced velocity of ice features

The incident wave and current determine the velocities of ice features impacting a structure and shall be considered. Methods to estimate the velocities depend on the ratio of the wavelength of the incident wave to the dimensions of the ice and the structure.

Pieces of ice with maximum dimension less than 1/15 of the incident wavelength can be conservatively assumed to follow the water particle velocity. For larger ice pieces, velocities can be obtained by solving their equation of motion accounting for wind, wave and current actions. For ice with horizontal dimensions less than 1/5 of the incident wavelength, actions may be derived from the relative velocity formulation of the Morison equation. For larger pieces, diffraction analysis can be used to calculate wave actions. Computational fluid dynamics or model testing may also be applied to estimate actions and velocities induced.

Slopes and changes in water depth can focus and steepen incident waves through refraction. If the tops of underwater mounds or caissons are less than half a wavelength below the free surface, the possibility of their influence shall be considered.

NOTE 1 Where the dimensions of the ice or the structure are 1/15 of the wavelength of the incident wave or greater, the approach described above becomes less accurate and generally overestimates the velocity of the ice induced by the incident wave field.

NOTE 2 Small ice features can impact structures with an accelerated velocity due to breaking or near-breaking waves. Such situations can also arise in cases of shallow water near shore due to shoaling waves. In addition, these situations can arise for gently sloping structures such as man-made islands and extended berms.

8.4 Seismic actions

8.4.1 General

Offshore structures in arctic and cold regions shall be designed for extreme-level earthquakes (ELE) and abnormal-level earthquakes (ALE) in accordance with the provisions of ISO 19901-2. In addition, steel structures shall comply with ISO 19902 and concrete structures shall comply with ISO 19903.

This International Standard contains specific provisions for seismic actions and effects for foundations in 9.4.4, for man-made islands in 10.4, for steel structures in 11.7, for concrete structures in 12.3.6, for subsea structures in 14.4 and for topsides in 15.3.

Ice and seismic events may be considered as stochastically independent. The combination of ice and seismic events should be made through an assessment of their joint probability, in which the duration of events is reflected.

8.4.2 Companion seismic actions

Probabilities associated with the simultaneous occurrence of extreme-level and abnormal-level ice actions of short duration and seismic actions can be very low. In such cases, it is not necessary to consider companion seismic actions for ELIE and ALIE.

8.4.3 Companion ice actions

When offshore structures in arctic and cold regions are designed for extreme-level earthquakes (ELE) and abnormal-level earthquakes (ALE), appropriate companion ice actions shall be included.

There is a very low probability for the simultaneous occurrence of extreme- or abnormal-level seismic events and ice events of short duration. Accordingly, the specification of companion ice actions is likely to involve ice conditions of long duration only. The companion actions provided in Table 7-2 may be disregarded when the joint probability of seismic and ice events has been established.

8.4.4 Factors influencing seismic actions and effects

The relative speed of the structure and the ice shall be considered in the specification of companion ice actions.

Ice accretion and landfast ice or grounded ice rubble adhering to the structure shall be considered when calculating the mass of the structure used for seismic analyses. The local restraint can result in changes to the natural modes of the system, and potentially induce large local and global actions.

The presence of a surrounding ice sheet shall be considered in the calculation of hydrodynamic added mass.

8.4.5 Seismic isolation and damping systems

Seismic isolation and damping systems may be used for arctic offshore structures to meet the requirements of this International Standard, provided they are designed to operate reliably under the expected environmental conditions. Further requirements for seismic isolation and damping systems are provided in 15.3.5.

9 Foundation design

9.1 General

Foundations for structures in arctic and cold regions require consideration of several factors beyond usual offshore geotechnical practice that can influence the reliability of foundations. The ice loading environment can be such that high horizontal actions can occur. Depending on the shape of the structure, these high actions can be eccentric and cyclic with magnitudes, frequencies and durations of loading that are different from those caused by other environmental conditions such as waves and earthquakes. These same ice action conditions and resulting action combinations can result in structural forms different from those that are designed for temperate waters, so that the experience base for overall performance of arctic offshore structure foundations can be limited.

Climate (past and present) has resulted in occurrence of widespread permafrost even in deep water in some arctic and cold regions. Identification and characterization of permafrost becomes a particular task of the soils investigation and can require specific sampling procedures and expertise. Stability of frozen soils through the design service life of the structure shall be considered. Hydrocarbon exploration and production activities, as well as structures, can result in permanent or cyclic thermal changes to permafrost. Lower ground temperatures also increase the probability of the presence of frozen gas hydrates at relatively shallow depths in cold climates.

Furthermore, soils in arctic and cold regions are likely to have been affected by glacial episodes in recent geological history. There can, therefore, be a greater likelihood of the occurrence of boulders and gravels in certain geological environments. Current geological processes such as gouging of the seabed by moving ice keels can change sea floor topography and can affect the properties of soils and loading for buried structural components and flowlines.

Quick clays, or highly sensitive clays, can be encountered in certain nearshore arctic locations. A characteristic of quick clays is a natural moisture content that is considerably in excess of the liquid limit, as a result of which the soil possesses negligible remoulded shear strength.

9.2 Site investigation

9.2.1 Purpose and scope of the investigations

9.2.1.1 Site investigations — General

Site investigations shall be performed for all offshore structures in arctic and cold regions. The purpose of the investigation shall be to provide relevant bathymetric, geophysical and geotechnical data necessary to characterize the site conditions and for the determination of characteristic material properties.

Site investigations shall take the following into consideration:

- type of structure and foundation actions;
- size of structure;
- nature of the sea floor;
- types of seabed materials;
- near-field and far-field conditions;
- data available from previous investigations in the area;
- available performance data from existing structures in the area;
- liquefaction susceptibility.

The investigation shall be performed utilizing the skills of professional personnel in the fields of geology, geophysics, ice engineering, seismology and geotechnics, and should include an evaluation of all relevant existing data.

Potential geohazards such as ice gouges, sand waves, boulder beds, submarine slope instability, faults, shallow gas, subsidence, mud volcanoes, gas hydrates, permafrost and over-pressurized geological strata shall be considered and investigated as necessary.

Soil studies in arctic and cold regions require additional data gathering to ensure that the structure foundation can be adequately designed, especially in terms of dynamic soil properties. This includes special geophysical as well as geotechnical studies with guidance as provided in A.9.2.4.

Investigations shall consider both far-field and near-field seabed conditions.

9.2.1.2 Site investigations — Far-field

The far-field investigations shall determine the impact of the following on the design of the structure:

- bathymetry;
- surficial geology;
- bedrock geology;
- risk of seismic events;
- slope stability and the potential for mass movements;
- presence of ice gouges;
- present sedimentary environment and erosional processes.

9.2.1.3 Site investigations — Near-field

The near-field investigations shall address the local issues related to

- a detailed sea floor bathymetry;
- a detailed soil/rock seabed stratigraphy;
- the foundation stability and displacement;
- the local slope stability;
- sediment movements adjacent to the structure;
- the presence and influence of ice gouges, boulders, permafrost and gas hydrates and shallow faults.

The near-field conditions shall be evaluated to provide detailed quantitative and qualitative data on relevant bathymetric and geomorphological features, geological processes and geotechnical parameters that can affect the design of the structure. The lateral and vertical extent of the near-field investigation shall be consistent with the size, zones of influence, and placement tolerances of the intended structure and with the complexity of the site conditions.

The near-field investigation shall include as a minimum

a) a bathymetry survey;

b) a geophysical survey, including ice gouge delineation where applicable;

c) a geotechnical investigation.

9.2.2 Bathymetry survey

Bathymetric data shall be obtained to provide information about the relief and elevations of the sea floor, and can assist in determining the likely draught of ice features reaching the structure.

Bathymetry shall be determined by methods that account for vessel heave, tidal fluctuations, and other factors that can influence the establishment of local and relative datums. The precision of the methods and accuracy of the survey shall be compatible with the design requirements of the structure.

The areal extent, spacing, and orientation of the survey lines shall be compatible with the purpose of the investigation and the type (near-field or far-field), and shall adequately define bathymetry and morphology.

9.2.3 Geophysical survey

Geophysical data shall be obtained to assist in the identification and delineation of relevant geological features as set out in 9.2.1. The geophysical data shall be interpreted in conjunction with available bathymetric and geotechnical data to permit cross-checking and verification.

High-resolution geophysical survey methods and equipment shall be chosen with due consideration for site conditions and the intended purpose. The capabilities of the equipment with regard to the depth of penetration and resolution shall also be considered.

The areal extent, spacing and orientation of the geophysical survey lines shall be compatible with the purpose and the type (near-field or far-field) of the investigation, and with the nature of the sea floor and seabed features.

Additional features pertinent to arctic and cold regions include the depth, frequency and distribution of ice gouges and the presence or otherwise of shallow permafrost and gas hydrates. In areas of shallow permafrost, consideration shall be given to the use of special geophysical investigation techniques such as the incorporation of shorter receiver arrays or the application of resistivity methods.

9.2.4 Geotechnical investigation

The geotechnical investigation programme shall be established on the basis of the geological and geophysical data. The investigation should include borehole drilling and sampling, *in situ* testing and laboratory testing.

The investigation shall cover the area and the soil/rock layers of significance to the structure. Particular attention shall be given to determining the disposition and properties of shallow soils/rocks, as relatively thin layers of weak soils/rocks near the seabed can have a significant influence on foundation stability of gravity structures. It shall also cover the zone of expected thermal disturbance for locations where permafrost is present. Special attention shall be given to minimizing both thermal and mechanical sample disturbance when sampling permafrost.

9.3 Characteristic material properties

Characteristic strength and deformation parameters shall be determined for all relevant soil layers, and for the relevant temperature ranges and stress ranges, taking due account of stress history, anisotropy and soil disturbance effects.

In these evaluations, caution should be exercised in the utilization of a strength value that depends on the dilatancy of the foundation soils and hence foundation movement.

NOTE Dilatancy is the tendency of a soil to increase its volume with change in shear stress.

Similarly, post-peak strength reduction and the possibility of progressive failure shall be considered.

The selected characteristic material properties shall be appropriate to the particular issues/situations to which they are applied. Limitations of the validity of the parameters, or conditions for their application, shall be clearly stated.

The effect of cyclic stresses on soil strength and stiffness induced by hydrodynamic and ice actions on the structure and applied to the foundation soils, shall be determined when such effect is of relevance to the particular issues under consideration.

The effect of stress paths and load periods on soil characteristic properties shall be accounted for in the design.

The effects of thermal conditions prior to and during the operation of the structure shall be considered.

9.4 Design considerations

9.4.1 General

The following additional factors shall be taken into consideration in the design of foundations for offshore structures in arctic and cold regions:

- potential for permafrost or gas hydrates in the seabed;
- potential variation in sea floor relief and soil properties due to ice gouging;
- potential for grounding of ice in shallow water;
- potential for gouging around structures due to stamukhi or movement of grounded ice.

The design shall consider the limit equilibrium between driving and resisting actions using the method of partial factors. Both the material factor and the resistance factor approaches for calculation of the resisting actions are acceptable within this International Standard as appropriate to the safety format and methodology contained within the particular referenced code relating to each foundation type.

Geotechnical foundation engineering depends on the extent and reliability of the basic soils data, their interpretation, method of analysis, type of structure, type of loading, and monitoring and maintenance. All of these considerations influence the choice of action, resistance, material factors and combinations of actions.

The transfer of actions between the structure and the adjacent soil shall be analysed with respect to all limit states and all phases in the design service life of the structure, including the removal of the structure, when required.

The sensitivity of the calculated results should be analysed making due allowance for reasonable variations of the assumptions made in the computation models, and variations in material properties and static and cyclic actions and effects.

In the analysis of the interaction between soil and structure, consideration shall be given as to whether the stiffness of the structure should be taken into account. The analysis should be based on appropriately selected characteristic deformation properties of the soil.

All significant effects of ice and companion environmental actions shall be considered, including the stability of adjacent seabed slopes. Possible interaction effects between structures should be considered.

Representative drainage conditions shall be determined for the designs under consideration.

Where permafrost or gas hydrates are anticipated or proven to exist, the design of the foundation shall make appropriate allowance for these conditions. Locations where soil deposits include gas hydrates that can affect the integrity of the structure should be avoided. The effects of thawing of permafrost and gas hydrates on soil strength and foundation stability shall be considered.

In areas with subsea permafrost or where development can induce freezing of soils, the design process shall involve analysis to evaluate the influence of the structure, its storage, and wells on the soil. Such analyses can include: evaluation of thawing and freezing; deformation analyses of the creep characteristics of permafrost; and deformation analysis to evaluate the extent and time dependence of foundation settlements and the ramifications of the time-dependent reduction in foundation shear strength as a result of thawing.

The potential for the development of grounded ice rubble around the structures that can impose ice actions, influence the path of the actions and create seabed gouges shall be considered.

The design shall consider the potential influence of ice gouging on the variability in sea floor relief and the requirement for site preparation. Ice gouging can also affect the strength and compressibility of near-surface sediments.

Physical testing complemented by numerical modelling should be considered where there is uncertainty in the mode of resistance of new foundation solutions and/or the ground conditions differ from those where there is precedent for a particular foundation type.

9.4.2 Action factors

Action effect combinations that give the most unfavourable result shall be selected in each of the stability mechanisms and deformation analyses performed.

In order to demonstrate that the design resistance is equal to or greater than the design action effect and that large cyclic and permanent displacements cannot occur due to the cyclic action effects, the ultimate limit state shall be analysed with the appropriate cyclic action effect history.

9.4.3 Material and resistance factors

Either the material factor or the resistance factor approach may be used. Designers are encouraged to use sound engineering judgment, precedent cases and their own experience, as well as relevant industry experience and due diligence, to investigate which method is more suitable to a particular application. Wherever feasible, designers are encouraged to investigate the applicability of both methods to determine which approach best meets the geotechnical design requirements.

While the material factor or resistance factor should not generally be lower than 1,25, it may be modified with regard to the consequences of failure, the failure mechanism, and the way in which the characteristic strength of the soil material is determined and expressed. Recognized practice should be considered in the selection of the computation procedures and stability mechanisms.

Consideration should be given to increasing the material factor or resistance factor for new types of structures and foundations and/or soil conditions with which no experience has been gained. An increased factor should also be considered when site variability is greater than usually encountered.

In the serviceability, fatigue and progressive collapse limit states, the material and resistance factors shall be 1,0.

9.4.4 Dynamic action effect analysis

In cases where the structure is subjected to cyclic actions due to waves, seismic or ice, the effects of cycling and dynamic amplification shall be considered. For dynamic studies, the soil-structure interaction behaviour shall take into account the dynamic response of the foundation, unless it can be shown that the frequency is such that the foundation can be treated in a quasi-static manner.

Dynamic analysis should be considered for certain types of structures where the action frequency is such that foundation design cannot be treated in a quasi-static manner under wave or ice action. It should be noted that the results can be sensitive to variations of stiffness and damping properties of the soil and the structure. A probable range of variation of soil properties should, therefore, form the basis of such analysis.

Soil parameters and calculation methods shall be selected in accordance with the action history included in the analysis of the structure and the stress and strain levels resulting from the calculations.

The effects of cyclic actions on the generation and accumulation of pore pressures and deformations in the soil, and the consequential potential reduction in shear strength shall be analysed. The combined effects of cyclic actions during several design events and subsequent consolidation over a period of time should be considered.

Earthquake response shall be calculated on the basis of dynamic properties of all soil layers likely to influence the response of the structure. The effect of interaction between soil and structure shall be taken into consideration.

Offshore structures in arctic and cold regions shall be designed for cyclic loading from ice in addition to cyclic loading from waves. Ice failure against the structure can generate cyclic loading at multiple frequencies, depending on the stiffness of the structure and its foundation.

9.4.5 Ultimate limit state

It shall be demonstrated that the design resistance of the soil under and around the foundation is sufficient to resist the design action effects. The development of the design resistance over a period of time shall be assessed.

Displacements of the foundation due to design action effects should be considered when checking the ultimate limit state of the structure or vital equipment, such as conductors, casings and risers.

9.4.6 Serviceability limit state

Settlements, differential settlements and horizontal displacements of the structure, and their development over the design service life of the structure shall be calculated. The settlements and displacements calculated shall not exceed specified limits that are established in advance for each structure and its equipment.

Assessment of settlements and displacements shall include but not be limited to

- immediate settlement, consolidation settlement, secondary compression and creep;
- differential settlement across the appropriate footprint of the structure;
- dynamically and cyclically induced settlements and deformations;
- lateral displacements and tilt;
- potential subsidence of the foundation due to reservoir depletion or depressurization;
- potential subsidence of the foundation due to local thaw in the permafrost layer.

The methods of analysis shall be compatible with the anticipated deformation modes and mechanisms and shall be appropriate for the intended structure, founding materials and loading conditions. Methods of calculating the magnitude of deformations may be based on numerical modelling, empirical relationships or physical model tests, or combinations thereof.

In predicting the evolution of the settlements with time, the drainage conditions and the uncertainties related thereto shall be considered, including possible assumptions regarding watertight structural components and draining soil layers.

The effect of cyclic actions on the deformation properties of the soil shall be taken into account.

In permafrost regions, thermal effects of hydrocarbon drilling and production should be included in deformation analyses to take into consideration the consequences of thaw and consolidation of permafrost and gas hydrates. These effects can also impact other design cases. The possibility of corrosion, erosion or other deterioration of the foundation and soil during the presumed design service life shall be considered.

The consequences of seepage or compression of shallow gas should be considered.

9.4.7 Fatigue limit state

Where structures are exposed routinely to ice crushing actions, fatigue behaviour of foundations and slopes shall be considered. Fatigue analyses shall be based upon unfactored characteristic soil properties, with due regard for cyclic effects on soil stiffness and strength. Methods of analysis and design considerations as presented in 9.4.6 apply.

9.4.8 Abnormal limit state

Abnormal-level ice events are defined in 7.2.2.4.

The foundation, as well as any skirts or other structural components for the transfer of actions to the soil, shall be designed so as to prevent local yield in the components or in the soil spreading, which can lead to collapse.

In dynamic analysis for the progressive failure limit, a range of probable values of all soil properties shall be considered to account for soil-structure interaction effects.

9.4.9 Stabilized soils

If it is intended to stabilize foundation soils, sufficient testing and analysis shall be carried out to prove the effectiveness and durability of the treatment and to verify the *in situ* properties of the stabilized material.

9.4.10 Construction and installation

The construction and installation procedures shall be compatible with the geotechnical parameters used and the design assumptions.

The construction and installation phases shall be inspected and recorded. If at any time the inspection reveals any foundation condition that differs from that assumed in the design, revision or remedial work shall be carried out as necessary to satisfy the requirements of this International Standard.

9.5 Gravity base structures

9.5.1 General

Foundations of gravity base structures shall be designed in accordance with ISO 19901-4 and ISO 19903 as applicable, with due account taken of the following particular considerations for offshore arctic and cold regions:

- eccentricity of loading;
- alteration of action path due to ice rubble build-up;
- gas hydrate dissociation and gas accumulation under foundations, the consequential effects on long-term capacity and methods to mitigate the risks;
- presence of, influence of and changes to permafrost.

9.5.2 Stability

General theories of bearing capacity and sliding should be used with caution and should be considered only for geologic settings where it can be demonstrated that the soil conditions are relatively homogeneous and isotropic, where loading conditions are simple and where loading rates are such that the pore water pressures can be clearly defined. In such cases, theories of general bearing capacity such as are presented in ISO 19901-4 can be applied.

Theories of general bearing capacity are not applicable to large area foundations subjected to combined horizontal, vertical, moment and torsion loading, or supported on layered, anisotropic soils of varying strength. Analyses of such combined actions/soil conditions require numerical or physical modelling.

Stability analyses should consider the limit equilibrium of kinematically admissible modes of displacement and deformation of the soil.

All potential rupture surfaces in the soil mass shall be investigated, with special consideration given to the influence of weak layers or zones. Sliding resistance can be improved by the use of a suitable arrangement of skirts on the underside of the foundation, which transmit the actions through the weaker soils into underlying stronger soils.

In the drained condition of the soil, the horizontal and vertical actions should be assumed to be acting on the effective foundation area only for limit equilibrium methods. The effective foundation area is the reduced foundation area having its centre of area at the point of application of the resultant action.

It may be assumed that the action effects for the undrained condition are distributed over a greater part of, or over the total foundation area. In this case, there should be documentation to show that this stress distribution is possible and does not lead to new forms of failure with a lower safety level.

Wave pressures acting on the sea floor around the structure shall be included in the analyses.

The potential for destabilization of the foundation due to liquefaction or pore pressure build-up in seabed soils under wave, seismic or ice actions shall be assessed.

9.5.3 Actions from the soil on structures

Soil action effects on all foundation structures that either bear on or penetrate into the seabed shall be calculated. The foundation and the structure shall be designed for these action effects.

Design values of action effects and material properties and characteristic soil properties shall be used in determining the distribution of the soil reactions. The action effects should be considered for those combinations that give the most unfavourable results with respect to the various limit states. An assessment shall be made of reasonable alternative distributions of the soil reactions that follow from the uncertainties in the computation models used and in the properties of the soil and the foundation.

Distributions of the soil reactions can differ for different parts of the foundation and structure.

Account shall be taken of the potential extent and distribution of partial contact between the seabed and the base of the structure due to seabed irregularity and/or the structural form.

The potential for uplift pressures and horizontal actions due to hydraulic gradients arising under the base in permeable soils shall be considered.

The potential for downward frictional forces or down-drag on skirts and/or conductors shall be assessed. Down-drag can arise on foundation skirts due to differential settlement between the foundation and the surrounding consolidating soil. Down-drag on conductors can arise from the soil settlement under the imposed weight of the structure, relative to the conductor.

Installation effects, changes in soil properties over a period of time, properties of grout below the foundation as well as local effects of pipes or other structures carried through the foundation or placed in the ground shall be taken into account.

The analysis of the ultimate limit state of the structure should also include the soil reactions distributed according to the assumptions made in the calculation of bearing capacity.

9.5.4 Installation and removal

The seabed shall be prepared to receive the platform, and this can include the following, as appropriate:

- removal of obstacles, debris, boulders, etc.;
- dredging and removal of unsuitable materials;
- levelling the sea floor, i.e. by placement of a rock/gravel/sand bed of suitable materials.

Installation should be planned to ensure that the base of the structure can be properly seated at the intended site without excessive disturbance to the supporting soil and excessive contact stresses against the base. The design of gravity base structures shall include consideration of the possibility of non-uniform soil reactions that can cause hard spots acting on the base of the structure. Underbase grouting, differential ballasting and/or site preparation may be used to mitigate the effects of such actions.

When the design requires that dowels, skirts or ribs penetrate into the seabed during installation, it shall be demonstrated that the planned penetration can be achieved, and that the maximum moment due to uneven penetration resistance is less than the available ballasting moment. Special attention shall be given to penetration into permafrost.

The soil resistance against skirts or other penetrating components shall be analysed with respect to its upper and lower characteristic values. These values shall be used in the evaluation of the installation process.

The consequences of heave of the seabed resulting from soil displaced during skirt installation should be considered.

It shall be demonstrated that the structure is stable during touchdown as well as before and during any foundation grouting.

The stability during installation shall be calculated on the basis of planned progress of the operations and the expected setting time of grouts, if used.

Consideration shall be given to the risk of scour to surface soils during installation and, in particular, where large caisson GBSs cause a local increase in current velocities at the seabed due to the blockage effects.

If an underpressure is required during installation, the geotechnical and hydraulic stabilities should be analysed.

Where removal is anticipated, an analysis shall be made of the likely upper bound action effects on the underbase and the skirts to ensure that removal can be achieved with the means available.

In the calculation of the extraction action effects, the effects of soil adhering to the foundation shall be considered.

If an overpressure is used under the base, the geotechnical and hydraulic stability should be analysed.

NOTE Foundations overlying ice-gouged areas can be subject to non-uniform pressures due to differences in shear strength (short-term) and compressibility (long-term) of ice gouge infill and surrounding sea floor sediments.

9.6 Piled structures

Piles that are driven or drilled and grouted shall be designed in accordance with ISO 19902, with due account taken of the following particular considerations for offshore arctic and cold regions:

- downdrag due to thaw subsidence;
- adfreeze of soil to shaft;
- creep;
- frost heave;
- installation in frozen ground.

The pile penetration design shall be sufficient to resist design compressive and tensile action effects for all actions including down-drag caused by thaw subsidence of permafrost.

9.7 Floating structures

9.7.1 General

Anchors for floating structures shall be designed in accordance with ISO 19901-7, with due account taken of the following particular considerations for offshore arctic and cold regions:

- installation and removal difficulties in frozen soil;
- gas hydrate dissociation and accumulation under anchors, and consequential effects on long-term holding capacity;
- thawing and freezing of the permafrost;
- creep and strength changes in the permafrost zone under sustained actions.

For permanently moored systems, the design value of the resistance to failure in the soil surrounding anchors should normally exceed the breaking strength of the anchor and/or chain line. The design resistance should be calculated on the basis of site-specific geotechnical data.

For temporary moored systems where the structure is not subjected to ice actions, the design resistance can be less than the breaking strength of the anchor and/or chain line.

9.7.2 Drag anchors

Consideration shall be given to the effect of permafrost on anchor penetration during installation. Consideration shall also be given to potential for slacking in the mooring line catenary due to

a) thawing and freezing of the permafrost;

b) creep and strength changes in permafrost zone under sustained actions.

The holding capacity of a drag embedment anchor in a particular soil condition represents the maximum horizontal steady pull that can be resisted by the anchor at continuous drag. For an embedded anchor, this pull shall include the resistance to the chain or wire rope as it moves through the soil, but shall exclude the friction of the chain or wire rope moving on the sea floor.

9.7.3 Suction anchors

9.7.3.1 Installation

Suction anchors are installed by means of actions generated by the weight of the anchor and an underpressure applied inside the anchor. This action shall exceed the maximum anticipated side shear resistance and the bearing capacity of skirt tip and stiffeners.

The penetration analysis shall consider both the intact and remoulded shear strength of permafrost. In cases with internal stiffeners, higher strength in permafrost zones can cause the soil plug to stand under its own weight over a larger height than in non-frozen soils, leading to reduced shear strength along the inside of the skirt wall. It can also lead to a larger soil heave, for which compensation should be made by an anchor height in excess of the target penetration depth.

In sand, penetration resistance is normally reduced by the gradients from the flow of water in the sand inside the anchor when underpressure is applied. In cases with permafrost, it should be recognized that the drainage through the permafrost layer can be lower, potentially blocking the drainage inside the anchor. In this case, the penetration resistance is not reduced and larger underpressures are required. It should also be checked that the underpressure does not draw water into the sand layer beneath the permafrost layer, with the consequence that the soil plug moves up inside the anchor.

The high underpressures that can be required for anchor penetration shall be taken into account in the structural design of the anchors.

9.7.3.2 Capacity

Suction anchors achieve their vertical capacity from their weight, shear strength along the outside skirt wall and reverse bearing capacity of the soil plug at skirt tip level.

The shear strength along the outside skirt wall normally increases with time after installation, due to increased effective stresses and thixotropy. Special consideration shall be given to the effect of permafrost on this set-up, since permafrost can influence the stress and drainage conditions in the soil outside the anchor after installation, the thixotropy and the reconsolidated strength parameters.

In cases where the shear strength along the inside skirt wall is relevant, consideration shall be given to inside skirt friction in permafrost. This includes the potential for increase in the height over which the soil plug can stand under its own weight.

Consideration shall be given to the effect of permafrost on the potential for gapping at the active side of the anchor.

Consideration shall be given to potential for slacking in the mooring line catenary due to

a) thawing and freezing of the permafrost;

b) creep and strength changes in the permafrost zone under sustained load.

9.7.4 Piled anchors

Piled anchors shall be designed in accordance with ISO 19902, with due account taken of the particular considerations for offshore arctic and cold regions listed in 9.6.

Consideration shall be given to the potential for slacking of the mooring line catenary through the soil due to

a) thawing and freezing of the permafrost;

b) creep and strength changes in the permafrost zone under sustained actions.

Consideration shall also be given to possible gapping in permafrost zones for laterally loaded piled anchors.

Special attention shall be given to fatigue design of the padeye, including the effects of pile driving.

9.7.5 Removal

Consideration shall be given as to whether increased set-up and break-out resistance can develop in permafrost zones compared to non-frozen soils.

9.8 Scour

The possibility of seabed sediment transport shall be considered as well as the effects of the structure in modifying the flow and transportation regime during installation and in-place conditions. If there is a risk of scour due to wave or current effects or ice gouging occurring around and within the foundation footprint, precautions shall be taken based on one of the following principles.

- The foundation shall be designed so as to tolerate the scour of material from the seabed.
- Adequate scour protection shall be placed during installation.
- The foundation shall be regularly observed, and scour-resistant materials immediately placed where necessary to ensure stability with respect to ultimate limit states.

9.9 Inspection and performance monitoring

An inspection programme should be considered as an integral part of the foundation design. Where it is deemed necessary, the inspection programme should include the use of instrumentation to monitor critical aspects of the foundation performance during installation and operation.

The scope of the inspection and the frequency of observation depend on the following:

- type of structure;
- anticipated and observed performance of the structure;
- documented behaviour of similar structures in the area;
- physical environmental conditions.

If at any time during the design service life of the structure, the inspection programme reveals conditions or behaviour that are detrimental to the integrity of the foundation or structure, maintenance or remedial action shall be carried out as necessary.

9.10 Seismic analysis

Soil studies in seismic arctic and cold regions require additional data gathering to ensure that the structure foundation can be adequately designed, especially in terms of dynamic soil properties. This includes special geophysical as well as geotechnical studies with guidance as provided in A.9.2.4. These tests are in addition to the typical soil tests performed for structures in non-seismic regions.

Seismic design of pile foundations for seismic actions shall be performed in accordance with ISO 19901-2 and ISO 19902. Provisions for piled structures in arctic and cold regions are provided in 9.6.

Shallow foundation structures shall be analysed for dynamic soil-structure interaction (SSI). SSI analyses may be executed by the direct method or the impedance method. Some limited guidance is available in ISO 19903. Dynamic effects for foundations are also included in 9.4.4.

10 Man-made islands

10.1 General

Man-made islands are generally suited to shallow water arctic and cold regions. This International Standard covers all man-made islands, some of which are described in 10.2.1 through 10.2.9. Ancillary structures used for access and transport (causeways) or protection (ice barriers, breakwaters) are also included. The provisions of Clause 10 cover offshore man-made islands but do not address all the issues associated with islands constructed in rivers.

10.2 Island types

10.2.1 Sacrificial beach islands

Sacrificial beach islands use a buffer zone of sacrificial fill material to protect the topsides facilities against ice encroachment, wave run-up and erosion. The sacrificial fill material typically requires replenishment on multiple occasions during the design service life. Sacrificial beach islands typically are employed in shallow water or protected locations, where the anticipated replenishment rate is sufficiently low to be economical over the design service life.

10.2.2 Slope-protected islands

A slope-protected island employs armour units to protect the island fill and topsides facilities against wave and ice attack. In contrast to a sacrificial beach island, the intent is to prevent rather than accommodate wave-induced erosion. Representative armour types include, but are not limited to, quarry stone, pre-cast concrete units, linked concrete mats, gabions and geotextile containers (such as sand bags and tubes). Slope protection systems that use armour units also typically incorporate one or more filtration media to retain the island fill material.

10.2.3 Sheetpile-retained islands

Sheetpiles can be used to overcome the height difference between the sea floor and the island work surface. They are often used for quay walls and can also be used as a secondary line of defence behind an armoured slope. In arctic and cold regions, the fill behind sheetpile walls can be frozen and can provide resistance to local ice actions. A key consideration for sheetpile design is local ice actions and the possibility of a more global failure.

Another type of sheetpile structure is a cofferdam. Cofferdams can be used as a connection between two sites, for protection of vulnerable areas, or as a quay wall/mooring dock. Cofferdams are limited in width and more likely to undergo large deformations, rotational instability or overturning failure, and internal shear failure than other sheetpile structures.

Cellular sheetpiles use tensile action to maintain the interlock between pile components, thereby retaining fill and resisting external actions. Plan designs include closed configurations that rely on the tension ring created by the structure and open configurations that rely on soil restraint to anchor the sheets and maintain the tension.

10.2.4 Caisson-retained islands

Caisson-retained islands are similar to sheetpile-retained islands except that the retaining system is composed of pre-built caissons that are ballasted down onto the sea floor to create a retaining ring behind which interior fill can be placed. Caissons can be constructed of steel or concrete, have sloping or vertical faces and can incorporate ice and wave deflectors. Retained islands offer the potential advantages of occupying a smaller footprint, requiring less fill and having the retaining caissons serve as slope protection against waves and ice. Potential disadvantages include susceptibility to wave run-up and overtopping, and to scour at the base of the caisson.

10.2.5 Hybrid islands

A hybrid island is distinguished by a prefabricated core, such as a barge containing topsides facilities, which is surrounded by fill material. The core can be ballasted onto the natural seabed or placed on an underwater berm. The fill material is protected against wave and ice attack using sacrificial beaches, slope armour, sheetpiles, or caisson units.

10.2.6 Underwater berms

Underwater berms can be combined with sheetpile and caisson-retained islands to reduce the height of the retaining structures. Underwater berms can also be used to reduce the size of steel and concrete platforms.

The specification of the underwater berm shall include material selection, grading and surface level tolerance to avoid overstressing the bearing surfaces of the steel or concrete structure.

10.2.7 Barriers and breakwaters

Detached barriers and breakwaters can be used to protect an island from wave and ice effects. These structures can be constructed of fill material protected by slope armour, or as stand-alone caissons.

10.2.8 Causeways

A causeway connects an offshore structure (such as an island) to other offshore structures or to the natural shoreline. Causeways can be constructed of fill material and/or caissons, and can contain breaches to permit the passage of marine life and the mixing of water masses on opposite sides of the structure. If the causeway is constructed of fill material, protection against wave and ice attack can consist of sacrificial beaches, slope armour, sheetpiles, or caisson units.

10.2.9 Coastal pads

A coastal pad consists of fill material placed on or near a natural shoreline and protected against wave and ice attack by sacrificial beaches, slope armour, sheetpile or caisson units. Coastal pads can be constructed on natural islands as well as on mainland shorelines.

10.3 Design considerations

10.3.1 General design considerations

10.3.1.1 General

The design of each man-made island shall take into account all actions and action effects on the structure during construction, installation, and the operational and decommissioning phases of the design service life, according to the provisions of Clauses 8 and 9. Adaptive design may be used where long-term conditions are uncertain, provided that adequate monitoring is put in place.

10.3.1.2 Design requirements

The structure and its foundation shall be designed against failure or collapse to ensure safe operation and deformational response within the limits required for its intended purpose under the provisions specified in Clause 7.

The methods of analysis, the actions and action combinations and the soil response parameters selected for design shall be appropriate for the intended structure and the proposed site.

10.3.1.3 Multi-disciplinary approach

The distinguishing attributes of cold climates, low temperatures and ice impact the geotechnical and coastal engineering aspects of the design in unique ways. For example, pre-cast concrete armour units capable of providing protection against wave attack can be damaged or transported by ice, and the geotechnical properties of fill materials can be changed by freezing and the formation of permafrost. Man-made islands should be designed with due consideration of ice, structural, geotechnical and coastal engineering, with adequate knowledge of local conditions.

10.3.1.4 General considerations for man-made islands

10.3.1.4.1 General

The following should be considered in the design of man-made islands.

a) In shallow to medium water depths, ice pile-up can form around wide structures such as islands. Effects include impairment of accessibility and evacuation, encroachment onto the working surface, and alteration of subsequent ice interactions. The use of barriers or an ice encroachment zone can be used to address this problem.

b) Ice can ride up or pile up on island slopes until it encroaches onto the working surface. Island slopes and edge geometry should be designed to address this problem.

c) The general low freeboard of islands can lead to wave overtopping as well as ice encroachment onto the working surface. Critical facilities should be either separated from the perimeter of the work surface or protected against direct impact from wave overtopping and ice encroachment.

d) The porosity of granular fill material implies that anything spilled on the island surface can penetrate the fill. Geo-membranes can be required for spill containment and, if so, they shall be designed for arctic and cold regions.

e) The influence of regional climatological trends on the environmental actions and state of the materials should be assessed.

10.3.1.4.2 Shape and orientation

The plan view shape and orientation of a man-made island should be designed to accommodate the particular operational or service requirements.

Normal and extreme ice and oceanographic conditions shall be taken into consideration when designing the island orientation. Factors for consideration shall include: wave and ice actions; wave overtopping; and the prevailing and extreme winds, currents and ice movements. In some cases, particularly in river channels, deltas or nearshore locations, the actions of ice, waves and currents can vary significantly by direction, thereby requiring slope protection that varies around the structure. At other sites, natural actions can be omni-directional, thereby requiring omni-directional protection.

If the island is constructed of permeable fill material, measures to mitigate the consequences of an oil spill shall be incorporated into the design. Mitigative measures can include providing a fluid-impermeable surface with containment structures or providing a subsurface geomembrane. If a geomembrane is used, water levels, the freeze-front and decommissioning shall be taken into consideration in the design.

Normal and extreme wind, wave, current and storm directions shall be considered when designing the docking and evacuation facilities. In cases where storms or ice can arrive from multiple directions, it can be necessary to provide docking/evacuation facilities at more than one location on the island or to protect the docking/evacuation facilities with an offshore breakwater.

10.3.1.4.3 Facilities

In designing the layout of island facilities, care shall be exercised to minimize the potential for damage or disruption associated with environmental factors. Factors for consideration shall include ice actions, ice encroachment, wave actions, wave run-up and overtopping. In addition, the prevailing wind direction or wind directions shall be taken into consideration when determining the locations of facilities occupied by humans relative to facilities prone to the release of toxic gases.

10.3.1.4.4 Spill containment

Where possible, islands should be designed to contain spills that can result in release of contaminants to the environment. Spill containment shall be considered as part of the overall system design to meet environmental requirements. The environmental impact of surface operations and spills should be considered over the design life and abandonment of the structure.

10.3.1.4.5 Marine access

The installation should be designed with alternative marine access routes that facilitate access and evacuation under the anticipated ice and physical environmental conditions.

10.3.2 Design against ice

10.3.2.1 Ice-structure interaction scenarios

Actions associated with continuous ice crushing on steep and vertical faces shall be considered for the fill material design.

Ice interaction events for consideration in the design of a sloping interface shall include flexural failure, rubbling, confined ice sheets, ride-up over ice rubble, adfreeze/frozen-in effects, and ice actions on bare slopes. The effects of ice rubble accumulations on the side slopes shall be considered not only in terms of actions, but also in terms of possible impacts on structure operations.

Components of man-made islands subjected to direct ice interaction shall be designed for ice actions as specified in 7.2.2.3 and 7.2.2.4 for the appropriate exposure level. Reference should also be made to 8.3.1.4 and 8.3.2 for wave-induced ice motions.

In addition to the provisions of Clause 8, extreme and abnormal ice events can include river ice. Such events shall be considered in the design of the island to the extent that they are relevant to the prevailing ice regime.

10.3.2.2 Ice actions

See 8.2 for provisions relating to global ice actions. The effects of grounded ice rubble on ice failure modes and net actions on the structure should be recognized; see also 16.3.

Local ice actions and their effects shall be considered. Additionally, the overall stability of a damaged component shall be accounted for in the design by the use of sacrificial areas on non-critical sections.

The effects of dynamic and cyclic actions on fill material and foundations shall be considered, including drained, undrained and liquefied soils, and the frozen state.

10.3.2.3 Ice encroachment

Ice encroachment is the process whereby ice advances onto the surface of a structure. It can be due to two processes: ice ride-up and ice pile-up. Reference should be made to 16.3.3.2.

Actions caused by ice ride-up or ride-down in combination with storm surges shall be considered in the island design.

The design shall incorporate suitable defensive measures to prevent and/or accommodate ice encroachment.

Actions due to ice pile-up, including intentional ice pile-up, shall be considered in the island design.

Critical equipment shall either be protected from ice encroachment or be placed away from areas of the island subjected to ice encroachment.

Active ice defence systems, if employed, shall be used to detect, evaluate and respond to ice features that can pose a threat to critical equipment or personnel on the island.

Passive ice protection structures, if employed, shall be designed for the extreme and abnormal ice and wave conditions anticipated at the project site. The design of passive ice protection systems should incorporate knowledge gained from full-scale experience, theory and model tests.

10.3.3 Geotechnical considerations

10.3.3.1 Geotechnical investigations and surveys

Investigations shall be performed to obtain geological and geotechnical data compatible with the requirements of 9.2.

Seabed soil conditions shall meet all design and construction requirements.

Investigative methods and procedures used to characterize the site conditions and to define the relevant bathymetric, geological and geotechnical design parameters shall be undertaken in accordance with 9.4.

The geotechnical surveys for foundation design and design parameters developed for stability, deformation and thermal analyses shall be representative of all seabed materials within the zone of significant stress influence of the man-made island and within the zone of expected adverse thermal disturbance for locations where permafrost is present.

10.3.3.2 Fill characterization

Potential sources for fill material shall be confirmed to meet all design and construction requirements. Investigative methods and procedures used to determine the quality, quantity and relevant geotechnical properties of the fill material shall be undertaken in accordance with 9.2. Where key strength and deformation parameters of the fill can be expected to change following excavation, transport and island placement, those parameters shall be confirmed by *in situ* testing following construction. Key properties of the fill affecting strength and deformation include, but are not limited to, frozen state, density (void ratio), grain size and permeability.

10.3.3.3 Cyclic actions

Design and construction of fill used for man-made islands shall consider the strength reduction as a result of pore pressures arising from cyclic actions. The fill used shall resist all dynamic actions including, but not limited to, operational, ice, wave and seismic actions.

10.3.3.4 Thermal changes

Site investigations shall include data on the initial seabed thermal regime where permafrost is known to exist or is expected to form. The existing thermal condition and changes over the design service life shall be taken into account in the design of the island and in the stability and deformation analyses. Geothermal modelling may be used for this purpose.

10.3.3.5 Failure modes

Gravel slopes and man-made island foundations shall be designed for global sliding, decapitation, passive edge failure, slope failure and structural containment component failure (as applicable). The elevation of the island work surface should be sufficient to avoid passive edge failure and to restrict wave overtopping and ice encroachment to acceptable levels.

10.3.3.6 Deformation

Deformation of the island and the underlying seabed shall not exceed the tolerable limits established for serviceability, ultimate and abnormal limit states. Settlement and displacement during island construction and operation shall be addressed based on the actions defined in 8.2. The assessment of deformation shall include, but not be limited to,

- immediate settlement, primary consolidation, secondary compression and creep;
- thaw settlement, frost heave or permafrost degradation;
- actions that can be considered using static analysis, as well as dynamic and/or cyclic actions from ice and waves;
- lateral deformation;
- reservoir depletion or depressurization.

Selection of the method of analysis shall account for anticipated modes and mechanisms of deformation, intended island configuration, foundation materials and design situations.

10.3.3.7 Soil improvement

Improvements to the soil may be used to ensure that design criteria are met, including removal of layers of weak soil identified through field measurements.

10.3.4 Coastal engineering

10.3.4.1 Meteorological and oceanographic factors

10.3.4.1.1 Water levels

The elevation of the island work surface and marine access facilities shall be high enough to accommodate water level changes. Provisions for water level fluctuations are presented in 6.4.1.

10.3.4.1.2 Waves

The design of a man-made island shall take into account the effects of the local wave climate. Provisions for analysing the local wave climate are presented in 6.4.2.

10.3.4.1.3 Winds

Provisions for analysing the local wind climate are presented in ISO 19901-1.

10.3.4.1.4 Currents

Islands located near a river mouth or a region with large current velocities shall be designed with consideration given to the actions generated by the local currents. Provisions for analysing the local current climate are presented in 6.4.3.

10.3.4.1.5 Strudel scours

When an island is located in a riverine environment where strudel scours are likely to occur at the edge of the structure, the periodic monitoring activities noted in 9.9 shall be designed to identify damage caused by strudel scouring.

10.3.4.2 Side slope profile

The island side slope and its protection system shall be designed to account for the anticipated wave and ice actions at the site. Wave overtopping rates and ice encroachment potential shall be determined to ensure that the side slopes limit flooding and ice incursions on the island work surface to acceptable levels. Optimization of the island slope profile can be based on experience with similar installations in the region or through model testing.

10.3.4.3 Slope protection

10.3.4.3.1 General

The design of man-made islands shall address the various types of damage that can occur to the slope protection system, including loss of island fill, wave overtopping and ice encroachment. The island design should incorporate components that have redundant protection mechanisms and that fail progressively in a local sense rather than globally. Timely inspection and repair efforts shall be included in the operational plans to secure the long-term serviceability and security of the island.

10.3.4.3.2 Quarry stone

Large quarry stone revetments can be used to provide slope protection in ice environments. The design of such structures shall include actions from waves and ice, stone size, amour size, number of layers and armour stability. Stone size shall be sufficient to limit removal of individual stones by ice to an acceptable level.

10.3.4.3.3 Sand- or gravel-filled geotextile bags

Geotextile bags filled with sand or gravel can be used as slope protection in areas where they are capable of withstanding the anticipated wave and ice conditions with an acceptable level of damage. The bag fabric shall provide a service life that is compatible with the design service life, or a monitoring and maintenance programme shall be in place to replace damaged bags. In the design, damage due to exposure to ultraviolet radiation and the direct impact of ice, driftwood and construction equipment shall be assessed. Bag stability under direct wave impact shall be analysed through engineering methods, including the use of physical model studies.

10.3.4.3.4 Linked concrete mats

Linked concrete mats can be used to protect man-made island slopes. The design of slope armour systems with linked concrete mats shall consider the normal and extreme wave and ice climates and shall be closely aligned with the design of the island slope profile. Calculations shall be performed to determine the effects of local and global actions on the concrete blocks and links. The mats shall be restrained from downslope movement under wave and ice actions and shall not experience uplift of a sufficient magnitude to jeopardize the integrity of the underlying fill material or the mats themselves. A durable filtration medium shall be installed under the concrete mat to contain the island fill material.

10.3.4.3.5 Pre-cast concrete units

Pre-cast concrete armour units can be used to provide island slope protection. The design of pre-cast concrete armour shall consider the armour stability, underlayer design and the ability of the units to resist breakage under the anticipated wave and ice impact actions.

10.3.4.4 Wave run-up and overtopping

Wave run-up, impact and overtopping of the island slope shall be evaluated, given the selected slope protection system, side slope profile and extreme wave conditions. This may be performed using hydraulic model studies or engineering analysis.

10.3.4.5 Coastal stability

Coastal pads and facilities shall be designed for ice interaction and coastal processes unless they are positioned at a safe distance landward from the shore or bluff in order to allow coastal changes to occur over the design service life of the project without affecting the project facilities.

10.4 Seismic design

Seismic design shall conform to ISO 19901-2 and consider both global and local failures of the island fill materials and retaining system. The following issues shall be addressed in relation to earthquakes:

a) global design to prevent global failure due to an earthquake;

b) local design of components such as slope protection in order that local failure during an earthquake does not lead to global failure;

c) retaining systems, which, in general, are critical to the overall structure and should be designed to prevent local and global failure.

Man-made island fill material can freeze during winter or become permanently frozen. Both the frozen and unfrozen states shall be considered as appropriate.

Man-made Islands located on permafrost can cause permanent freezing of the island fill materials and this condition shall be considered, where applicable.

Seismic-induced liquefaction of soils within or below the man-made island shall be considered.

Man-made islands can be prone to tsunami run-up and this effect shall be considered.

10.5 Construction

Construction of man-made islands in ice covered regions shall be planned to include consideration of the limited construction windows and other logistical limitations.

10.6 Monitoring and maintenance

10.6.1 General

A comprehensive monitoring and maintenance programme shall be prepared as part of the design. Guidance is provided in 16.4.

10.6.2 Environmental monitoring

Sufficient data regarding physical environmental conditions should be acquired to support an evaluation of the actions to which the structure has been subjected and an assessment of the causes of damage (if any) which the structure has sustained. The environmental conditions that should be recorded over the design service life of the structure include

- wind speed and direction;
- temperature;
- water level and sea states;
- ice data, such as ice thickness, ice drift, ice feature types and frequency, and interactions with man-made and natural structures.

Data shall be applicable to the structure site. Provided that the applicability requirement is fulfilled, data acquired at one site may be used to fulfil the environmental monitoring requirements for multiple structures in the vicinity.

10.6.3 Structural monitoring

Appropriate geotechnical instrumentation should be installed and monitored throughout the design service life of the island to measure specific aspects of foundation and fill behaviour. These measurements should include, but not be limited to, the following:

- settlement, tilt, and horizontal deformation;
- pore pressure response; and
- temperatures in the fill and foundation materials.

The slope protection system shall be inspected at least once per year, and after each event or season that has the potential to inflict significant new damage to the structure. In the case of slope protection systems that employ armour units, items for consideration in the inspection should include slope deformation, armour unit damage and armour unit displacement. In the case of slope protection systems that employ sacrificial beach islands, the dimensions and properties of the remaining sacrificial material shall be assessed.

10.6.4 Maintenance

Following the annual or special inspection of the slope protection system, an evaluation shall consider whether the protection system is still capable of protecting the structure during the design events.

If collected monitoring data or an assessment indicates that the actual island performance is not in accordance with design criteria or specified response limits, the design shall be reassessed for ongoing adequacy in the light of such data or assessment. In cases where it is determined that the current state of the structure should be enhanced to ensure future operational reliability, appropriate remedial actions shall be implemented to achieve the design reliability targets.

10.7 Decommissioning and reclamation

The structure shall be planned, designed, constructed and maintained in such a manner as to minimize the risk to human life, the risk to vessel navigation and the risk of adverse environmental impacts during and after decommissioning and/or reclamation. To this end, when planning decommissioning and/or reclamation policy, the following provisions should be addressed.

a) Materials: Materials used to construct the structure and to protect its slope should either be amenable to substantially complete removal at the time of decommissioning or reclamation, or pose no significant threat to human life, safe navigation, or the natural environment if allowed to remain at the project site after decommissioning or reclamation.

b) Buried items: The location of each item that is buried in the structure fill and that can pose a significant threat to human life, safe navigation or the natural environment if allowed to remain at the field after decommissioning or reclamation should be determined with sufficient accuracy to facilitate removal of that item at the time of decommissioning or reclamation. This provision applies equally to items buried during construction of the structure or subsequently during its design service life.

c) Record-keeping: Written records documenting the as-built configuration of the structure as well as all changes thereto should be maintained throughout the design service life. These records should include the locations of all items buried in the structure fill.

d) Safety: The safety of personnel and equipment during decommissioning or reclamation operations, when protection against metocean and ice actions has been partially or totally removed, should be considered in formulating the plan for decommissioning or reclamation. The operations should be carried out in accordance with all of the safety provisions outlined in the plan.

e) Environmental protection: Decommissioning or reclamation operations should be carried out in accordance with the environmental protection measures outlined in Clause 5.

11 Fixed steel structures

11.1 General

Offshore fixed steel structures in arctic and cold regions shall meet the requirements of ISO 19902 supplemented by the requirements of this International Standard. Such structures include tubular steel frame structures, monopiles, braced monopiles, stiffened-plate gravity base structures, steel-concrete (composite) gravity base structures and combinations of the above. The design of non-tubular structural components that behave as beams, columns or beam-columns shall be in accordance with ISO 19901-3.

11.2 General design requirements

11.2.1 Plastic design

When inelastic response is invoked in order to resist specified accidental actions, extreme earthquakes, extreme ice actions or other abnormal environmental actions, arctic grade steels shall be used to achieve the ductility and toughness required for proper performance. In cases where only a portion of the structure is loaded, redistribution of action effects may be assumed to take place as long as sufficient material ductility is present.

11.2.2 Resistance factors

The partial resistance factors for use with offshore fixed steel structures in arctic and cold regions shall be specified in accordance with ISO 19902.

11.2.3 Fracture control

Fracture control shall be considered in all material selection and structural design activities. Appropriate toughness shall be established in accordance with ISO 19902 and the additional requirement of 11.9.

11.2.4 Temperature effects

The effects of restrained thermal expansion due to differential temperatures in the structure shall be considered.

11.2.5 Damage due to freezing water

Structural and mechanical systems shall be protected from damage due to freezing water by insulation, heating, drainage, provision of crushable materials or other suitable means. Any active system to prevent damage due to freezing water shall be configured to achieve an acceptable level of structure or system reliability. The acceptable level of structure or system reliability should be determined according to the principles set out in Clause 7.

11.3 Structural modelling and analysis

11.3.1 General

At each stage of analysis, the idealization of the structure and the level of sophistication of the analytical model shall be compatible with the anticipated behaviour of the structure and the accuracy of the required results; see ISO 19902.

11.3.2 Interactions

When required, ice-fluid-soil-structure interaction, as well as the dynamic properties of the foundation soil, shall be modelled.

11.3.3 Dynamic analysis

The dynamic effects of actions due to ice, waves, wind, currents, earthquakes, impacts and functional loads shall be taken into consideration. Dynamic effects are important when the resonant frequencies of a structure or one or more of its components lie in the range for which the energy content of the actions and action effects causes dynamic amplification. Particular attention should be given to the potential for ice-induced vibrations of steel structures when vertical or near-vertical components are exposed to ice actions.

Dynamic analysis can include the effects of damping, such as internal structural damping of the materials and energy dissipation at the joints.

The water-ice-structure interaction shall be taken into account by considering the added mass of water and ice, the effects of waves radiating energy to infinity (hydrodynamic damping) and the drag effect and energy dissipation of the ice. If necessary, frequency-dependent impedance functions shall be used to represent boundary conditions for complex fluid-solid-structure interactions, including those involving ice.

11.4 Strength of tubular members and joints

Structural members and joints between members that are located in an area where they can be subjected to ice actions shall be designed to resist local ice actions combined with relevant global actions.

Due consideration shall be given to the potential for damage to tubular members and joints caused by ice actions. Damage tolerance requirements shall be in accordance with ISO 19902.

11.5 Strength of stiffened-plate panels

Plate panels shall be designed to resist the actions to which they can be subjected, including in-plane bending, tension, compression, shear and actions normal to the plane of the panel. Special attention shall be given to local ice actions.

The design of stiffened-plate panel configurations should be in accordance with an appropriate standard, see A.11.5. Membrane action for stiffened plates is permitted under local ice actions (see 8.2.5) for the ELIE, as long as the plate is not ruptured and as long as it continues to fulfil its function. Membrane action is permitted provided the plate and stiffener are proportioned to allow for plastic deformation. For the ELIE local ice action design case, the plate and stiffener arrangement should be checked using non-linear finite element analysis. The results of the non-linear finite element analysis should demonstrate an adequate factor of safety against rupture, rupture strain, remaining strain and record permanent set of both plate and stiffener.

Where in-plane compression due to global structural action effects acts in combination with out-of-plane local ice actions and/or where the consequences of plate rupture are high, the use of membrane action is not permitted. The stiffened-plate panel design shall meet the requirements of the relevant standard, see A.11.5, with respect to elastic deflection criteria.

11.6 Strength of steel-concrete composite walls

11.6.1 General

The provisions of 11.6 apply to composite ice resisting walls consisting of external steel plates and concrete infill, with interconnection provided by shear connectors, stiffeners, transverse web members, longitudinal web members, or combinations thereof. These walls can also include standard concrete reinforcement, e.g. external plate, concrete infill, web plate, stiffener, shear connector, etc. Although composite design can apply to concrete-filled tubular members and tubular joints or nodes, design requirements for such members are not included in this International Standard.

The requirements of ISO 19903 shall govern the placement of concrete, the determination of concrete material properties, and any other areas applicable to concrete that are not covered by, or are in conflict with, this International Standard.

Composite walls shall be designed to resist bending and shear due to actions normal to the plane of the wall (transverse actions), and to resist in-plane tension, compression and shear due to actions parallel to the plane of the wall (vertical or horizontal).

The steel components of the composite wall shall be designed to resist the effects of all actions, including those resulting from concrete casting, that are applied to the wall prior to the attainment of concrete strength sufficient such that composite action is achieved.

Consideration shall be given to the effects of restrained deformations due to temperature changes and to the effects of thermal gradients through the thickness of the wall. Where concrete can be demonstrated to fill all voids within the stiffened panels, it may be considered that the panel stiffeners and girders are laterally restrained with respect to local buckling.

Each component of a composite wall (external plate, concrete infill, web plate, stiffener, shear connector, reinforcement, etc.) shall have a design resistance greater than the design action effect, or combination of such effects, to which it is subjected. Provision shall be made to ensure that premature buckling of the external steel plates does not occur.

Lower bound plasticity methods, upper bound plasticity methods and empirically derived equations may be used to determine characteristic resistances, provided that the applicability of the methods has been verified experimentally.

11.6.2 Analysis methods

Either an elastic analysis or a plastic analysis may be used to determine the force distribution within a member due to local actions. An analytic method shall be used that is appropriate for the type of composite wall system being designed. Additional guidance on analysis methods is provided in A.12.3.

A plastic analysis may be used, provided that the applicability of the method is verified and sufficient ductility of the member is ensured. A plastic analysis can be used for

- flexural members;
- members that allow interface slip (i.e. strain compatibility is not enforced between the external steel plates and the concrete infill);
- regions adjacent to supports or concentrated actions, or where there are abrupt changes in cross-section;
- other situations where arching action is assumed.

11.6.3 Material properties

The material properties for concrete and deformed reinforcing steel shall be determined in accordance with the requirements of ISO 19903. The material properties for structural steel shall be determined in accordance with the requirements of this International Standard and ISO 19902.

11.6.4 Design for out-of-plane actions

11.6.4.1 Flexure

The maximum usable unfactored strain at the extreme concrete compression fibre shall be assumed to be 0,003, unless special provisions are made to provide confinement to the concrete. In this case, the designer shall document the increase in usable strain.

When it is assessed that plane sections remain plane, it may be assumed that the relationship between the compressive stress and strain of the concrete is parabolic, trapezoidal or any other shape that results in substantial agreement with comprehensive tests.

When it is assessed that plane sections remain plane, the stress in the external steel plates and in any internal steel components that provide flexural resistance (webs, stiffeners, reinforcing, etc.) shall be calculated as $1/\gamma_s$ times the value of stress determined from strain compatibility based on a stress-strain curve representative of the steel, where γ_s is the steel resistance factor.

When a plastic analysis has been used to determine the distribution of forces in a member, the maximum compressive stress achievable in a concrete diagonal compression strut shall be assumed to be equal to $\eta f_c/\gamma_c$, where f_c is the concrete compressive strength, γ_c is the concrete resistance factor and where the concrete efficiency factor, η, has been experimentally determined.

When a plastic analysis has been used to determine the distribution of forces in a member, the stresses in the external steel plates and in any internal steel components that provide flexural resistance (webs, stiffeners, reinforcing, etc.) shall not exceed the stress at which yielding is assumed to occur (i.e. f_y/γ_s, where f_y is the characteristic yield strength).

The tensile strength of concrete shall be ignored in the calculation of the design flexural resistance.

Transfer of action effects from the external steel plates to the concrete infill shall be achieved using shear connectors, transverse webs or transverse stiffeners. Transfer of load via interfacial friction shall be disregarded unless shear friction reinforcement (headed studs or other mechanical connectors) is provided.

11.6.4.2 Shear

The shear resistance of a composite wall shall be provided by the concrete infill alone or by the concrete infill in combination with one or more of the following:

- longitudinal web plates that carry shear directly to the supports;
- transverse web plates that act as shear reinforcement;
- overlapping headed steel studs that act as shear reinforcement;
- standard reinforcing bars that act as shear reinforcement;
- through-thickness rods that act as shear reinforcement;
- discontinuous longitudinal webs that act as shear reinforcement.

The shear resistance of a wall subject to concentrated transverse action effects shall be the lesser of the resistance determined assuming

a) beam action, with a critical section extending in a plane across the entire width; or

b) punching action, with the critical section extending around the perimeter of the loaded area.

11.6.5 Design for in-plane actions

The design value of axial and in-plane shear resistance shall be determined using a rational method that has been experimentally verified. Consideration shall be given to the transfer of action effects between the concrete core and the external steel plates and to preventing buckling of the external plates in compression.

11.7 Seismic design

11.7.1 Steel framed structures

A fixed steel offshore structure for arctic and cold regions can take the form of a braced caisson, free-standing caisson, jacket, monotower, steel gravity structure or jack-up as defined in ISO 19902.

Guidance on procedures and criteria for seismic design is provided in ISO 19901-2.

Seismic design of braced caisson, free-standing caisson and jacket structures shall be in accordance with ISO 19902, taking into account any guidance given therein in respect of seismic reserve capacity and recommendations for ductile design.

Seismic design of all other steel structures shall also be in accordance with ISO 19902, except that the seismic reserve capacity factor shall be developed for the structure on a case-by-case basis. Alternatively, the structure shall be shown to achieve ALE and ELE performance requirements using explicit structural analysis.

11.7.2 Steel stiffened-plate structures

Steel stiffened-plate structures are typically of GBS design. The general principles for seismic design presented above shall be implemented, specifically the requirement for elastic performance under the ELE and for non-collapse condition under the ALE.

The key consideration for seismic design is the ductile performance of the steel stiffened-plate structures under the ALE. Ductile performance shall be demonstrated by explicit structural analysis combined with proper detailing of connections to ensure ductility. Alternatively, the steel-stiffened, plated structures may be designed to perform elastically for the ALE, including the design of the connections, and this eliminates the requirement to demonstrate ductile performance.

11.8 Fatigue

Cyclic stresses caused by ice action events shall be included in the fatigue assessment.

Responses of the structure to cyclic ice actions that have the potential to cause the fatigue failure of structural members and welded connections shall be considered.

The resistance to low cycle, high amplitude cyclic stresses shall be assessed using methods that are valid in this region of behaviour.

11.9 Materials, testing and NDT

11.9.1 General

The design class (DC) approach as described in ISO 19902 shall be used for material selection, and particularly to determine toughness requirements. For structures in arctic and cold regions, the LAST value used for material selection and testing should be defined in accordance with this International Standard if not specified explicitly in the regulatory requirements for the region.

Steels shall conform to a recognized standard or specification.

11.9.2 Design class

The design class for steel shall be selected in accordance with ISO 19902. The design class for components of monopiles, braced monopiles and stiffened-plate structures shall be developed in accordance with the principles defined in ISO 19902.

11.9.3 Toughness class

The appropriate toughness class shall be selected based on the considerations given in ISO 19902.

11.9.4 Toughness requirements

The minimum toughness requirements shall be in accordance with ISO 19902.

11.9.5 NDT requirements

The minimum non-destructive testing (NDT) requirements shall be in accordance with ISO 19902.

11.10 Corrosion and abrasion protection

11.10.1 Cathodic protection

For a structure exposed to sea ice interactions, sacrificial anode systems should be designed and placed to prevent ice damage and ensure functionality. The design of cathodic protection systems shall be based on established methods.

11.10.2 Ice abrasion

If the structure can be severely abraded by ice, the design shall assume uncontrolled corrosion losses. For structures where ice abrasion occurs, additional wall thickness shall be provided, or another suitable system or combination of systems shall be used to protect the structural members.

11.10.3 Knife-line corrosion

The weld metal, heat affected zone (HAZ) and parent plate chemistry shall be selected such that metallurgical and electrical potential differences between adjacent metals are minimized in order to avoid selective weld region attack.

11.11 Welding

Welding consumables shall be selected with due consideration given to minimizing preferential corrosion of welded connections.

12 Fixed concrete structures

12.1 General requirements

12.1.1 General

Fixed concrete offshore structures for use in arctic and cold regions shall be designed in accordance with ISO 19903 and the further requirements of this International Standard.

Ice or iceberg resistant concrete structures can be subject to large current and wave actions in addition to large ice actions.

12.1.2 Structural requirements

The potential for abrasion due to moving ice and spalling/cracking due to ice impact shall be considered, and measures shall be taken to keep these deterioration mechanisms to an acceptable level over the design service life of the structure. This can be achieved either by proper concrete design and detailing or, if warranted, by protective steel cover sheets (armour) in the area of concern. In particularly severe environments, a combination of the two can be selected.

The quality of the concrete and the overall design of the structure shall be selected to minimize any potential early degradation of the concrete due to the combined effects of abrasion induced by moving ice, freeze-thaw attacks and corrosion of reinforcement. If this cannot be done, suitable measures should be in place to minimize degradation or its effect (e.g. increase concrete cover, provide steel armour).

Design should favour smooth external surfaces in areas subjected to moving ice, and local design should aim to avoid the crushing and destruction of protruding details.

Post-tensioning anchorages and other critical details should, as far as possible, be located away from areas prone to direct ice actions.

12.1.3 Material requirements

Concrete materials shall have adequate resistance to freeze-thaw cycles, where applicable. In this selection process, resistance to accelerating effects of freeze-thaw cycles and corrosion should be considered.

Reinforcement steel with adequate toughness and ductility properties for the temperature conditions shall be chosen.

12.2 Actions and action effects

Application of the combinations of the actions and the partial factors for relevant limit states shall be in accordance with Clause 7.

The dynamic response of the structure and its foundation to ice impacts shall be determined, and its effect on the structure as a whole and on individual members shall be accounted for in the design.

12.3 Structural analysis

12.3.1 Dynamic analysis

Requirements for ice-induced vibrations and other dynamic actions are found in 11.3.3.

12.3.2 Loss of intended internal pressure

When the design of any portion of the structure takes into account an intended pressure differential, the temporary loss of that differential during the operating phase shall be considered. Until the intended pressure differential is restored, special consideration should be given to the crack width limitations under such circumstances.

12.3.3 Physical representation

12.3.3.1 Soil-structure interaction

Static and dynamic analyses of the complete structure shall be performed for ice actions. A simplified global model may be used to assess the fundamental dynamic responses. Appropriate dynamic soil parameters shall be considered in accordance with Clause 9. Dynamic effects may be simulated as static equivalent actions (accelerations times mass, for instance) in the global static FE analysis, in combination with the companion static actions. Further guidance is provided in ISO 19903.

Structural and foundation damping shall reflect the state-of-the-art and recognized principles. Different (smaller) damping factors shall be used for fatigue analyses. The internal damping of the soil shall reflect strain levels and soil profiles in accordance with the provisions of Clause 9.

In particular circumstances, different types of ice actions can call for different foundation modelling: for instance, cyclic and impact actions can involve different parts of the soil stress-strain relationship.

12.3.3.2 Other support conditions

Action-resisting embedments shall be properly anchored into the concrete.

Tensile stresses in all directions relative to a tensile action shall be considered.

12.3.3.3 Thermal effects

Particular consideration shall be given to the assessment of the thermally induced action effects within the structural components containing hot stored oil for concrete structures.

12.3.4 Types of analysis

12.3.4.1 Linear elastic static analysis

Linear analytical and numerical theories give generally acceptable structural response and action effect distribution for both SLS and ULS under relevant ice actions. Action effects due to structural imperfections shall be taken into account by applying relevant geometrical tolerances.

For the assessment of the transverse shear capacity of a concrete section, the enhanced shear strength near supports is acceptable for ice actions, but it shall be disregarded for that part of the shear actions due to hydrostatic pressures; see ISO 19903 for additional provisions for handling water pressure in pores and cracks.

12.3.4.2 Non-linear analysis

Material and geometrical non-linear effects may be considered where appropriate, in particular for ALS. Where it is planned to depart from the non-linear behaviour of materials described in the referenced national standard for concrete design, material performance shall be supported by physical test results or bibliographical research on materials with relevant properties.

It can be sufficient to assess the non-linear behaviour of structural components subjected to ice actions on the basis of linear structural analyses without resorting to a full non-linear elastic analysis. In the “reduced stiffness approach”, action effects induced within the structural components may be redistributed by modifying the membrane and bending stiffnesses for tensile components to account for cracking. The final equilibrium condition after redistribution should be verified by comparing the internal stress and strain conditions for the components in tension to those of adjacent components. Stress redistribution can be determined from a fine-mesh FE analysis.

Local fine-mesh non-linear FE analysis can be used to better identify those areas where local stresses can exceed allowable elastic limits. Boundary conditions derived from the global linear FE analysis should be applied to the non-linear model at a location sufficiently distant from the area of elasto-plastic behaviour. Compatibility of forces and deformations at the interface of different FE models shall be verified for the type of action under consideration.

12.3.5 Analysis requirements

12.3.5.1 Analysis of construction stages

Built-in stresses due to the sequence of construction, the pre-stressing sequence and the temperature history shall be taken into consideration in the analysis of construction stages.

12.3.5.2 In-service serviceability analysis

The SLS aspects of importance relate to crack width determination and potential corrosion and containment issues.

Depending on regional ice conditions, ice related actions may be included in the combinations of actions for the SLS analysis if they are frequent or occur with a short return period.

Limitation of displacements and motions shall also be considered with respect to serviceability.

12.3.5.3 Fatigue analysis

Fatigue analysis shall be performed in accordance with ISO 19903 for cyclic ice actions in addition to wind, wave and current actions.

Fatigue properties of reinforcement steel, embedded steel, welds, etc., and concrete shall be satisfactory under the low temperatures prevailing in arctic and cold regions.

12.3.5.4 Accidental and abnormal analyses

Sequential failure modes can potentially develop for ALIE.

When an action exceeds its limit state, the design should result in local failure of external structural components first. Oil containment should be addressed specifically as part of the analysis. Section failure on the outside face of an oil compartment leading to loss of containment is not acceptable. The section of probable failure should achieve a curvature ductility factor (ratio of curvature at failure to curvature at first yield) of 6 or more.

12.3.6 Seismic

The requirements of ISO 19901-2 shall be satisfied for concrete structures in arctic and cold regions. Seismic design of concrete structures requires elastic performance for the ELE and a no-collapse condition for ALE. A key consideration is the ductile capacity of large columns often used in concrete GBS structures as failure of a column can lead to a global collapse mode. Ductile performance of concrete structures can be obtained provided that ductile design and detailing are implemented.

Alternatively, concrete structures may be designed to perform elastically even in ALE, which meets the dual requirements of the ELE and ALE. In such cases, the design should still incorporate a ductile mode (and not a brittle mode) of failure.

For composite steel and concrete structures, the approach described in this clause shall also be used.

12.4 Concrete works

12.4.1 Design

12.4.1.1 Design principles for shell members

Arctic offshore structures are frequently subjected to concentrated actions on shells. Shells shall be designed to prevent buckling, taking into account the likely geometrical imperfections that decrease the buckling resistance and enhance induced shell moments.

12.4.1.2 Design principles for fatigue

The design shall recognize the contribution of time-varying ice crushing actions to fatigue utilization; see 8.2.6.

12.4.1.3 Design principles for durability

Freeze-thaw cycles and ice abrasion are two major mechanisms that can jeopardize the durability of concrete in arctic or cold regions. These mechanisms are addressed in 12.4.1.4.

12.4.1.4 Freeze-thaw cycles

12.4.1.4.1 General

The part of a structure subject to the largest number of freeze-thaw cycles is that closest to the water surface. If the quality of the concrete is poor, damp concrete deteriorates when subjected to recurrent freeze-thaw cycles. Repeated freezing and thawing produces continuously growing internal pressure, which eventually breaks the concrete.

Durable concrete for offshore structures in arctic and cold regions shall meet the following requirements:

- low permeability;
- low water-cement ratio;

- air entrainment and very high quality of the aggregate.

Low permeability prevents the absorption of water into the concrete. Air entrainment improves the resistance of the concrete to freezing and thawing because the protective pores reduce the pressure of freezing water in the cement stone; see A.12.4.1.4.1.

12.4.1.4.2 Abrasion

When moving ice acts against a structure, it can cause abrasion of the concrete. The design of the structure shall make due allowance for such abrasion. The concrete mix should be designed to minimize the degradation due to abrasion.

All corners and edges of concrete structural components shall have a chamfer of at least 25 mm.

For concrete exposed to abrasion and scouring actions, the minimum specified 28 day strength for test cylinders shall be a minimum of 60 MPa and the aggregates should be abrasion resistant.

NOTE ISO 19903 specifies a minimum strength of 40 MPa for offshore concrete structures exposed to seawater. In those parts of the structure where severe abrasion due to ice, pebbles, sand or silts is anticipated, the specified concrete compressive strength on cylinders at 28 days should be at least 60 MPa.

12.4.1.4.3 Concrete cover

The effect of wear and ice abrasion shall be taken into account when selecting appropriate concrete cover to reinforcement.

The effect of wear and abrasion due to repetitive ice action shall be accounted for in the definition of the concrete cover.

12.4.1.5 Design principles for buckling

Compression members shall be designed for buckling, if necessary. Adequate constraint for the compression reinforcement should be provided by through-thickness reinforcement to ensure no pull out or push out effects. Specific consideration should be given to curved components under hydrostatic or ice pressure.

For structures or portions of structures where buckling can be significant, the influence of displacements and geometric imperfections shall be taken into account when sectional forces are determined. The stiffness used in the analysis should reflect the distributions of stiffness anticipated under the action combinations corresponding to the limit state under consideration.

12.4.1.6 Design principles for imposed deformations

Deformations associated with thermal effects, differential thermal settlements and the action of ice formation within cellular compartments of the structure shall be considered.

12.4.1.7 Design for fire resistance

The potential for reduced fire resistance where cover has been increased to provide abrasion resistance should be recognized and addressed. Additional reinforcement can be required for this combination.

12.4.1.8 Partial factors for materials

The material factors shall be such that a safety level consistent with that required by Clause 7 is achieved.

12.4.1.9 System ductility

The entire structure shall have system ductility sufficient to survive accidental actions and abnormal environmental events.

Under specified abnormal environmental or accidental actions, the sectional forces throughout the structure shall continue to satisfy the static equilibrium requirements imposed by the permanent actions.

Under the influence of specified abnormal environmental or accidental actions, one or more structural components or sections can exceed their ULS. This is acceptable provided that the remaining structural system can continue to resist the actions that are expected before repairs are completed (i.e. the damaged condition). Damaged conditions can be encountered by the structure after an abnormal or accidental event, the damage being identified, for instance, as a local loss of structural strength because of puncture or yielding of material. If this approach is adopted, the integrity of the oil storage system shall be maintained.

Components that can be overloaded during an abnormal environmental or accidental event shall be designed to ensure that they possess adequate energy-absorbing capacity. Sufficient energy-absorbing capacity can be achieved when the resistance of a component at six times its yield deflection still exceeds 50 % of its characteristic resistance.

In evaluating system ductility, the concrete cover shall be assumed to spall in regions where the design resistance has been exceeded during the abnormal or accidental event.

When system ductility is being evaluated, the action-carrying ability of the pre-stressing bars shall not be relied on when local bending of the bars can occur or where pre-stressing is supported by fewer than four independent units.

For abnormal-level ice actions, the failure of a structural component shall not lead to progressive failure in the adjoining components, unless it is agreed that any damage can be readily repaired. If the decision is made to leave the structure in place during decommissioning, different progressive collapse criteria can be appropriate.

The ALS evaluation shall consider combinations involving permanent and variable actions, but no other environmental action or deformation action except for pre-stress and thermal effects.

In damaged conditions, a ULS evaluation shall be performed under permanent and variable actions, but without deformation actions (pre-stress and thermal effects excepted) in combination with extreme-level environmental actions. The ULS evaluation should reflect the anticipated repair time; see ISO 19902.

Ductility may be accounted for by dividing the elastic action effect response by the estimated ductility factor for the structure or component, which should reflect the non-linear behaviour and energy-absorption characteristics of the structure or component. The choice of ductility factor should be based on

- the energy-absorbing capability of the structure, whether general or local;
- the detailing of structural components, i.e. their inherent ductility;
- the hierarchy of failure modes for which the structure has been designed.

Where a detailed non-linear analysis of the structure is used to demonstrate survivability for abnormal-level ice actions, a time-history method should be used to verify the damaged condition.

12.4.1.10 Minimum reinforcement

The minimum reinforcement required in various components shall be specified.

In sections subjected to a combination of high compressive stresses and large shear forces, the main reinforcement shall be confined with through-wall stirrups in an amount not less than 0,4 % of the concrete area. This requirement applies when the combined axial force and bending moment exceed the strength of the concrete section without consideration of the strength distribution for the compressive reinforcement. It also applies when the shear force exceeds the strength of the unreinforced concrete section without contribution from the axial force.

In walls subject to direct ice actions, specific minimum reinforcement criteria should be specified to provide sufficient ductility and energy absorption.

Minimum reinforcement shall account for low temperatures and should minimize the possibility of water freezing in cracks.

12.4.2 Materials

12.4.2.1 Material requirements — Concrete constituents

12.4.2.1.1 Normal-weight aggregates

Aggregate shall be free from snow and ice at the time of mixing.

12.4.2.1.2 Lightweight aggregates

The use of lightweight aggregate concrete in areas subjected to ice abrasion shall be carefully considered and demonstrated by appropriate tests, because this material is generally less resistant to ice abrasion than normal weight concrete. The moisture content in lightweight aggregate at the time of placing should be kept low enough to ensure adequate freeze-thaw resistance. A 24 h absorption limit of 12 % by volume shall be imposed.

12.4.2.1.3 Admixtures

Where water is able to penetrate the concrete matrix, air-entraining admixtures shall be added to the concrete components that are subjected to freeze-thaw cycles. In permanently dry areas, adequate frost resistance can be achieved through adoption of a low water-cement ratio.

12.4.2.1.4 Repair materials

The choice of repair material shall take due account of its ability to bond with the concrete substrate so that it is not preferentially lost if adfrozen water is pulled free from the concrete. Repair materials shall have mechanical and physical properties (i.e. strength, thermal expansion, etc.) that are compatible with the concrete substrate. The repair compound should demonstrate an ice abrasion resistance comparable with the adjacent concrete.

Vapour permeable bonding compounds such as latex should be considered for repairs in the splash zone and above.

If coatings are applied to the concrete, these should preferably be vapour-permeable to avoid potential delamination.

12.4.2.2 Material requirements — Concrete, grout and mortar

12.4.2.2.1 Concrete

The concrete composition shall be tested to demonstrate adequate freeze-thaw resistance for arctic and cold regions.

For structural reinforced concrete exposed to chlorides under freezing and thawing conditions (marine structures in tidal zone), the following apply.

— The 28 day compressive strength shall be equal to or greater than 45 MPa.

- The water/cement ratio shall not exceed 0,40.
- The air content shall be in the range
    1) 6 % to 9 % for aggregates < 10 mm,
    2) 5 % to 8 % for aggregates 14 mm to 20 mm,
    3) 4 % to 7 % for aggregates 28 mm to 40 mm.

When freezing of the hardened concrete can occur during the operational phase of the structure's design service life, air-entraining admixtures shall be used.

Before concreting operations begin, tests shall be performed to determine the nature of the air-void system in concrete produced with the proposed materials, mixing systems and placing systems. The air-void parameter requirements are as follows.

a) The specific surface shall be greater than 25 mm^2/mm^3.

b) The maximum average spacing factor shall be 0,23 mm.

c) No single spacing factor shall be greater than 0,26 mm.

The concrete shall be tested to determine the air-void parameters in accordance with an applicable standard. The amount of air in plastic concrete mixes necessary for conforming to these air-void parameters shall be used to establish the required air content for subsequent job site testing.

Increased air-void parameter limits may be used for concrete containing super-plasticizers and supplementary cementitious materials, provided that appropriate data from freezing and thawing tests for the materials in question are available.

During construction, the air-void parameters of the hardened concrete shall be checked at approved intervals, and the level of air content in plastic concrete shall be controlled so that the air-void parameters comply with the limits a) through c) specified above.

The primary criterion for selecting the required air content should be from a determination of hardened concrete air-void parameters.

Ducts, climbing-rod holes and other small openings in the concrete shall be filled with Portland cement grout unless alternative means of excluding water that can freeze have been provided.

Reference should be made to 12.4.1.4.2 for concrete specifications in areas exposed to ice abrasion.

12.4.2.2.2 Grout and mortar

The grout should have a low permeability, be resistant to freezing and thawing and have a compressive strength similar to the surrounding concrete. Expansive admixtures should be chosen to avoid the accumulation of gaseous voids, which can become water-filled.

12.4.2.3 Material requirements — Reinforcement steel

Reinforcement shall be specified to ensure that adequate ductility exists for the expected construction and operational temperatures.

In parts of the structure with potential for corrosion of the reinforcement, the required properties of the reinforcement shall be maintained through the concrete quality, cover and corrosion-resistant reinforcement materials.

12.4.3 Execution

12.4.3.1 Falsework and formwork

Formwork systems shall be constructed from materials that have satisfactory ductility at the temperatures experienced at the construction location.

Care shall be taken to ensure that all temporary recesses and block-outs in formwork are filled with cementitious grout. Structural foam or grease may be used if the void can be tolerated in the permanent condition.

12.4.3.2 Pre- and post-tensioning

Consideration should be given to having recessed anchorages suitably sealed by concrete when these are present in a region where ice abrasion or adfreezing followed by ice removal can occur.

If it is necessary to carry out post-tensioning during periods with temperatures below +5 °C, the strand shall be tested to failure at the temperatures that are expected as well as at +5 °C to demonstrate that the ductility of the strand is satisfactory.

12.4.3.3 Protective measures

Water or steam shall not be used to clean ducts. Oil-free compressed air may be used.

To prevent the splitting of the concrete due to ice expansion in tendons having a significant vertical rise, provision shall be made to ensure that bleed water is not trapped at the top of the duct.

12.4.3.4 Concreting

Openings that can lead to a chimney effect in cold weather should be avoided, given that these can lead to shrinkage cracking.

12.4.3.5 Embedded components

An appropriate design guide should be used for embedded components; see A.12.4.3.5.

12.4.3.6 Hydrotesting

Structures constructed in a dry dock, and for which the opportunity of testing all the vulnerable parts at a deep water completion site is not achievable, shall be hydrotested in the dry dock to the maximum extent possible with appropriate means for demonstrating that adequate leak resistance has been achieved. The beneficial effects of autogenous healing may be invoked to minimize the extent of the repairs required. Autogenous healing can be effective in sealing small through-thickness cracks that have arisen through early-age thermal effects or restraint introduced during construction. Hydrotesting should be of sufficient duration for a completion of the autogenous healing process.

12.4.3.7 Hot and cold weather works

12.4.3.7.1 Concreting in cold weather

Provisions shall be made during the curing process to ensure that the required concrete strength is reached in ambient temperatures.

12.4.3.7.2 Grouting of pre-stressing duct during cold weather

During cold weather periods, all ducts shall be kept clear of water to prevent the formation of frost or ice in the ducts. Neither water nor steam shall be used to clean ducts, but oil-free compressed air may be used. At the start of each grouting operation, some grout shall be allowed to pass through the ducts and be wasted to ensure removal of any moisture trapped within the duct.

No grouting of prestressing tendons shall take place during cold weather periods unless the temperature of the ducts is above 2 °C. The temperature of the grout shall not be allowed to fall below 2 °C for at least 48 h after grouting.

12.4.3.7.3 Placing and bending reinforcement during cold weather

Field bending of reinforcement (bending on site or in the completed works) is typically not permitted. For particular and limited instances where it is not possible to do otherwise, the following shall apply.

- Reinforcing steel shall not be field bent or welded unless the temperature is above –10 °C.

- If there is a heated bar-bending facility on site, then bar bending can proceed in cold weather.

No bar partially embedded in concrete shall be field bent except as shown on drawings.

12.5 Mechanical systems

12.5.1 Introduction

For mechanical systems in platforms operating in arctic and cold regions, the following provisions apply.

a) Materials chosen shall be suitable for the conditions under which they are intended to perform, such as low temperatures and subject to the magnitude of action effects (such as internal overpressure) and repetitive action effects (fatigue).

b) The systems should be designed such that water inside or outside the systems cannot freeze.

c) The external parts of the mechanical outfitting including appurtenances should be located or designed such that they are protected from ice actions, or such that their function is not hampered by the presence of ice.

12.5.2 Permanent mechanical systems

12.5.2.1 Crude oil storage system

For wet storage systems, measures shall be taken to avoid the freezing of the water underneath the oil and in the connecting piping systems. Heating, insulation and circulation of the water are possible protective measures.

The requirement for measures to avoid possible clogging of the system due to presence of ice frazil in cold water should be assessed.

12.5.2.2 Other storage systems

The considerations for other storage systems, including permanent ballast water systems, seawater systems, drains, sumps and bilges should be the same as in 12.5.2.1 for crude oil storage systems.

The inlets and outlets of seawater systems should be located in areas where they cannot be damaged by ice.

12.5.2.3 Risers and J-tubes

In addition to the provisions of ISO 19903, risers and J-tubes shall be routed to avoid damage by ice.

12.5.3 Mechanical systems — Temporary ballasting/deballasting water systems

The considerations for temporary ballasting/deballasting systems should be the same as in 12.5.2.1 for crude oil storage systems.

12.5.4 Attachments and penetrations

Attachments to the external surface of the concrete structure should preferably be located away from areas subjected to ice actions. If deemed feasible, the attachments or special protective structures should be designed for ice actions.

Materials and welding procedures adapted to the actual temperatures during welding and during the design service life on site shall be used.

12.5.5 Mechanical systems — Design of piping supports

For arctic offshore structures with the potential for impact by large ice features, high intensity local ice loading can cause large deformations in the structure. Piping and piping supports shall take such effects into account.

12.6 Marine operations and construction afloat

Marine operations and construction while afloat shall be conducted in accordance with ISO 19901-6.

Ice actions shall be included in the design situations for operations during temporary phases.

12.7 Corrosion control

The detailing of corrosion prevention measures should recognize the presence of mobile ice. The cathodic protection design shall take into account that it is generally not feasible to locate anodes in zones subject to ice action. Further, where steel plates are used to prevent ice abrasion of the concrete, allowance should be made for sufficient current drain from the plate when sizing cathodic protection. The extent of coating loss through abrasion should also be considered.

12.8 Inspection and condition monitoring

Special attention shall be paid to deterioration due to abrasion, scour and spalling/cracking due to ice impact and to freeze-thaw attacks.

Special attention should be paid to possible degradation of concrete protected by external steel panels and not easily accessible for visual inspection.

Inspection and condition monitoring should be conducted on an annual basis, or as required to monitor ice effects on the concrete.

13 Floating structures

13.1 General

Floating systems operating in arctic and cold regions shall comply with the provisions of ISO 19904-1, while their mooring systems shall comply with the provisions of ISO 19901-7. This International Standard provides additional requirements and guidance for floating systems in arctic and cold regions. Particular emphasis is placed on ice actions and hull design, cold weather materials and design of marine systems, and disconnection.

Requirements and guidance are provided for the design and operation of floating offshore structures to support the following functions:

- production;
- storage and offloading;
- drilling, production, storage and offloading

The provisions of Clause 13 may be applied to other floating structures located temporarily or permanently at the location and used as part of oil and gas operations in arctic and cold regions.

Floating structures considered within the context of this International Standard include

a) ship-shaped hull (e.g. FPSO, FSO) or barge units;

b) column-stabilized (e.g. semi-submersible), spar and buoy type units.

The provisions of this clause are not exclusive to steel structures, and may be applied to concrete structures and various composite structures.

The provisions of Clause 13 may be applied to other floating structures located temporarily or permanently at the location and used as part of oil and gas operations in arctic and cold regions.

The floating structure includes the hull, marine systems, offloading systems, mooring or stationkeeping system to hold the structure on location and risers connecting the unit to the well head. Floating structures may also be used to support other types of subsea operations.

13.2 General design methodology

13.2.1 Design philosophy

The design philosophy and operational approaches for floating structures include the following:

a) potential to suspend operations and move off location, to avoid any interactions with extreme or abnormal ice features;

b) ice management support techniques to actively modify ambient ice conditions and thereby mitigate potential adverse ice actions.

The design and operational components of a floating installation and its subsea components shall be treated jointly as a system, including ice management support where provided. For overall reliability assessment see Clauses 17 and 18.

13.2.2 Design and operational approaches

Floating structures that are deployed in ice covered waters are often supported by ice management vessels, with the intended role of modifying the local ice environment, reducing ice load levels on the structure and enhancing ice clearance around it.

The type of ice management system deployed can have a significant influence on the design approach taken for a floating structure. This influence depends upon the expected ability to consistently detect potentially adverse ice conditions and successfully manage them before they interact with the structure (e.g. by towing icebergs or fragmenting thick sea ice features).

The ability for a floating structure to move off location, the time that is required to do so, and acceptable levels of operational downtime shall be considered to ensure that the structure can move off site without incident if there is a failure of the ice management system.

The following design and operating approaches may be used for floating petroleum installations in ice-prone waters:

a) passive: no move-off capability, no ice management capability;

b) semi-active: move-off capability, no ice management capability;

c) active: move-off capability, ice management capability.

For active and semi-active operating approaches, design values of ice actions on a floating installation can be considerably less than for a fixed installation. Any mitigation measures (i.e. ice management and move-off strategies) that are intended to ensure appropriate levels of safety should be properly identified, considered and quantified, along with expected levels of reliability.

Operational strategy may be used to influence the consequence category or life-safety category of a floating structure. Life-safety category and consequence category are discussed in Clause 7.

13.2.3 Design considerations

The designer shall take into account all relevant issues and associated parameters for each scenario considered, including, but not limited to,

- the type of structure, e.g. permanent, temporary;
- the operating period, e.g. seasonal, all year;
- design conditions, e.g. metocean and ice conditions;
- the ice features, e.g. first-year ice (ridges, rubble fields, landfast ice, pack ice), glacial (small ice masses, icebergs), multi-year (floes, ridges);
- the ice situations, e.g. high ice drift speeds, changing drift directions, ice pressure events, poor visibility;
- the ice management, e.g. none, low capability, comprehensive capability;
- the brash ice and its influence on ice management effectiveness;
- the stationkeeping method, e.g. moored, dynamically positioned;
- the operations, e.g. operating, standby, disconnecting, reconnecting;
- the human factors, e.g. cold stress, isolation;

- the system components, e.g. risers, subsea, offloading tanker;
- the storage capacity, i.e. with or without;
- the on-site maintenance, e.g. hull, stationkeeping system including anchors, ballast system.

13.3 Environment

In addition to the environmental information requirements outlined in Clause 6, the following relevant factors shall be considered for the design of floating structures, particularly when ice management systems are involved. Relevant factors include, but are not limited to,

a) the combined influence of ice, wave, wind and current action, and the effect of their respective orientations on the applied actions (e.g. on an FPSO that is designed to vane into oncoming pack ice);

b) the joint effects of ice, waves and structure motions on ice action scenarios, and the areas of the structure where ice impacts can occur;

c) the effects of factors such as low air and water temperatures and icing;

d) the beneficial effects of ice management on modifying the ambient ice environment and potentially eliminating most of the hazardous ice features within it;

e) the potentially adverse effects of secondary factors such as poor visibility, precipitation and darkness on the reliability of ice detection and ice management systems;

f) the complicating effects of factors such as waves on sea ice and iceberg management methods, and the presence of sea ice on iceberg towing operations;

g) the increased importance of factors such as ice pressure events and combined ice drift velocity and thickness information, particularly for sea ice management considerations;

h) the degree of variability of many of the physical environmental parameters;

i) the potential lack of long-term physical environmental data, from which proper designs and operational procedures and plans are developed;

j) the identification of the full range of ice interaction scenarios that can give rise to adverse ice effects on a floating installation, (e.g. excessive load levels on a mooring system, hull damage from undetected small ice masses, thruster damage in ice pressure, mooring line exposure to deep draught ice keels).

13.4 Actions

13.4.1 Applicability

These provisions shall apply to actions on the hull and its components, including turret, buoy, risers, mooring lines and tension legs that materially influence the behaviour of the structure interacting with ice. The system reliability shall also include attached loading tankers and attending vessels, where appropriate.

13.4.2 Ice scenarios

In addition to the provisions of Clause 8, pressure events due to convergence of surrounding ice or presence of a coastline shall be considered for floating structures.

13.4.3 Interaction factors

In addition to the factors described in 8.2.4, the following should be considered:

- physical ice management;
- operational criteria, including ice detection, forecasting, threat analysis and decision-making as primary criteria (other operational factors, such as avoidance, measurement of actions, weathervaning, shutdown, flushing of risers and flowlines, disconnection, and seasonal operations).

These can act in combination with the ice scenarios and features or influence the nature of the interaction.

Appropriately scaled physical models can be used to determine the response (e.g. offsets, weathervaning, mooring line forces) of the floating structure and moorings to ice and current actions. Model tests can also be used to investigate ice accumulations on the mooring system and turret for monohull or buoy shapes, and ice accumulations to the legs of semi-submersibles.

13.4.4 Determination of ice actions

Ice actions shall be considered in combination with motions of the floating installation due to actions from ice, wind, wave or current processes. The flexibility of the stationkeeping system shall be considered when determining ice actions.

The magnitude of ice actions may be altered through ice management measures, ice avoidance procedures, ice clearing and friction reduction systems (e.g. bubblers or thrusters), seasonal operation, disconnection or displacement of the installation. Changes to the ice detection system as a result of the disconnected state shall be considered in the assessment of ice actions.

Relevant, full-scale ice action data for floating structures should be used for the determination of design actions. Experience with icebreaking vessels and scaled ice basin experiments may also be used. Particular attention should be given to managed ice conditions. Where appropriate, the approaches outlined in A.8.2 may also be applied.

Active intervention through physical management procedures (e.g. towing, icebreaking, ice clearing, etc.) shall be considered within the framework of an ice management plan; see Clause 17.

Where the global action on the hull is limited by the capacity of the stationkeeping system, the unfactored failure resistance of the stationkeeping system shall be used for the calculation of actions on the hull; see ISO 19904-1.

13.4.5 Other ice action considerations

Where relevant, the following factors shall be considered when calculating the magnitude and frequency of ice actions:

- ride-down or ride-up of the ice from the initial point of contact, rubble building and any resulting changes in the interaction scenario, including ice intrusions into a turret;
- rotations or changes in orientation of the floating installation as a consequence of changes to ice actions, metocean conditions and ballast;
- floaters designed to weathervane to reduce ice and wave loads, which should have the capability to do this for the local sea ice conditions;
- presence of ice lodged within the installation (such as in the legs of a semi-submersible);
- ice adfrozen to the structure or components thereof;

- ice action on mooring lines, risers, propulsion systems, positioning systems, steering systems and other appendages essential to the integrity and operation of the floater;
- friction between the ice and the hull, including the effect of friction reduction methods (over the design service life of the structure);
- condition of the surface coating used for calculating ice actions and allowing for the anticipated conditions over the design service life of the structure;
- buffering from surrounding sea ice (including ice floes, ice rubble, brash ice);
- ice actions on the hull resulting from managed ice;
- sheltering in the lee of a structure when offloading, taking into account the potential for ice pressure events and rapid changes in ice drift direction;
- actions from the offloading tanker, which shall be included when calculating the actions on the structure and stationkeeping system.

13.4.6 Action variations

The time-varying nature of the magnitude and direction of the ice action (including potential changes in failure modes and ice clearance behaviour) shall be considered where it materially influences the structural response (including stationkeeping system) to the ice action.

Both global effects (e.g. hull hydrodynamics and hydrostatics, stationkeeping system stiffness, foundation resistance) and local effects (e.g. hull response) shall be considered when calculating response to ice actions.

The effect of ice management on the behaviour of the system shall be taken into account.

The effect of slow drift oscillations due to combined ice and metocean actions shall be recognized.

13.5 Hull integrity

13.5.1 Structural design philosophy

The designer may utilize the appropriate formulations in guidelines for ice-strengthened vessels of a recognized classification society (RCS). IMO guidelines and national requirements shall be incorporated in the design. In addition, the requirements of 13.5 shall be met.

Extreme-level, abnormal-level and other ice actions can apply to areas of the external hull and inner hull excluded from RCS guidelines and requirements. In such cases, the ice-strengthened area shall be extended as required to ensure that strength and robustness of the affected areas of the external hull and inner hull meet the requirements of this International Standard.

13.5.2 Hull ductility

The ductility of the hull structure shall account for the design values of low air and water temperatures, as outlined in 6.3.1 and 6.4.4.4. Structural steel class and grades for weather exposed plating and for inboard framing members attached to this plating shall meet

a) the requirements of 11.9 based on the definition of LAST in this International Standard; or

b) the vessel class requirements based on ambient low temperatures at the site.

13.5.3 Structural analysis and design

The global and local structural models of the floating structure as discussed in ISO 19904-1 shall incorporate the ice actions given in 13.4.

The following provisions apply for the ice/structure interaction analysis and for the design.

a) Global ice actions shall be specified in accordance with 8.2.4. The global ice action shall be applied to determine whether the structure meets the ULS and ALS criteria for the floating structure as a whole and for the area in the vicinity of the impact point.

b) The area of application for local ice pressures shall be selected to provide the design condition for shell plates, stiffeners, tubulars and other supporting members. Guidance on local ice pressures is provided in 8.2.5.

c) Ice loads on appendages shall be calculated, and the limit states should be determined for the appendage, the local structure and the floating structure as a whole.

13.5.4 Structural considerations

The design shall ensure that there is no progressive collapse nor shall the inner hull be ruptured by AL ice actions. The interior framing of the structure (e.g. the longitudinal bulkhead and scantlings) shall be designed to prevent progressive failure in a damaged state. This should include the inner boundaries when in the damaged condition, for instance the upper strakes of longitudinal bulkheads.

The hull shall be designed to resist emergency disconnect and re-connect loads.

FLS from cyclic ice actions shall satisfy the provisions of ISO 19904-1.

Equipment and structures essential for safe operation of the floater shall be designed for accelerations arising from impacts of EL and AL actions.

13.5.5 Condition monitoring

With reference to the provisions of 8.2.4 and 13.4, appropriate ice and physical environmental conditions shall be monitored and documented on a regular basis.

Continuous monitoring of global hull girder bending moments and shear forces shall be undertaken in accordance with ISO 19904-1.

The monitoring system shall be incorporated into the ice management and alert monitoring systems in accordance with Clause 17.

13.6 Hull stability

13.6.1 Subdivision

Longitudinal subdivision shall be in accordance with ISO 19904-1.

For floaters on which hydrocarbons or contaminated water are stored, double hulls shall be provided for the appropriate compartments. All tanks used for fuel oil or for the storage of hydrocarbons or contaminated water shall be protected by double hulls.

Fluids potentially harmful to the environment should not be carried next to the external hull; see also 5.6.

13.6.2 Intact stability

Stability shall be maintained in combination with the various operational loading and ballast conditions under

- extreme-level marine and atmospheric icing events, distributed in the most unfavourable manner;
- extreme-level ice ride-down or ride-up events;
- extreme-level ice jamming or lodging events in the structure.

13.6.3 Damaged stability

Damaged stability shall include flooding of adjacent compartments. Guidance with respect to the dimensions of ice damage penetration is provided in A.13.6.3.

Damaged stability calculations shall include the effect of ice accumulation, whether from icing or other ice encroachment.

13.7 Stationkeeping

13.7.1 General

The design of the positioning system for the floating structure shall be in accordance with ISO 19901-7 and ISO 19904-1, where appropriate. The specification of actions on all stationkeeping systems, whether mobile or permanent, should satisfy the requirements of Clause 7. The values of EL and AL actions may be calculated through a risk assessment, taking into account the possible consequences of a failure of the stationkeeping system, the proximity to other installations, the nature of the operations (permanent or seasonal), the capability for disconnection (normal and emergency) and associated implications thereof, in accordance with ISO 19901-7.

13.7.2 Design of the stationkeeping system

The stationkeeping system shall maintain the installation in place under specified combinations of ice, wave, wind and current actions, and changes to ice actions as a result of ice management. The relevant action combinations shall be established based on available ice and metocean statistics.

Mooring lines should be routed so as to avoid direct exposure to ice actions in the splash zone and below, depending on the design ice interaction scenarios.

Ice features caught by the mooring lines can result in additional ice actions on the mooring system. Anchor fairleads shall be positioned to minimize such effects or localized ice management may be adopted. Additional actions on the mooring system arising from these scenarios shall be included in the system design.

Propulsion and dynamic positioning systems shall be designed to withstand ice actions for ULS (intact and redundancy check system conditions) and for the relevant FLS. For ALS, the design shall be such that the complete failure of the system is avoided.

13.7.3 Disconnection and reconnection

13.7.3.1 System description

The installation may be designed with a system for disconnection and/or reconnection of mooring lines as well as lines necessary for hydrocarbon drilling, production and export.

13.7.3.2 System requirements

If the installation is equipped with an arrangement for disconnection, then this system shall be designed consistent with the provisions of this International Standard for an acceptable level of risk to personnel, pollution and major structural damage.

13.7.3.3 Mechanical requirements

Specific requirements additional to those of ISO 19904-1 shall include the following, if relevant:

a) protection from ice for the safe operation of all systems and equipment;

b) safe design and operation of a disconnectable turret under various ice situations;

c) turret dropping to a safe distance below the structure and ice feature;

d) local heaters;

e) hydraulic and/or pneumatic systems for operation in arctic and cold regions;

f) units subjected to direct ice action that are designed for the expected ice situations;

g) materials to satisfy the low temperature requirements of this International Standard;

h) accessibility and proper operation of all equipment under the expected situations.

13.7.3.4 Design modes for disconnection

Potential disconnection modes include

- planned disconnection, which allows ample time for depressurizing and flushing of flowlines and for start-up of production after the floater has been reconnected; and

- emergency disconnection, which allows sufficient time only to shut down wells.

13.7.3.5 Reconnection

Reconnection shall be carried out in an orderly sequence in the appropriate design situations.

13.7.3.6 Design

The design of the disconnection/reconnection system should be as simple as possible to allow for reliable operations. The system shall provide the reliability assumed when calculating the design actions. The system shall be designed for disconnection and reconnection under the combinations of ice and environmental actions relevant for the design situations.

Suitable and proper backup systems and controls shall be provided.

The system for disconnection may be designed for both (semi) automatic and manual operation.

The part disconnected from the floating structure shall be designed to allow for inspection in the reconnection sequence.

Emergency and planned disconnection criteria shall be defined according to site-specific ice events and the design actions associated with the installation and its positioning system.

The time needed to perform a successful emergency or planned disconnection shall be consistent with that assessed to give an acceptable level of safety within the context of the safety study carried out for the event. The alert and ice management procedures shall take full account of the applicable operations and associated time requirements for a controlled disconnect.

13.7.3.7 Move off

The disconnected floating structure shall be capable of moving away (self-propelled, towed) from the mooring system and any other connected lines safely and in the context of the design situations. If disconnection requires that the vessel be towed, the ability to establish at towline should be demonstrated.

13.7.3.8 Monitoring requirements

Appropriate ice and environmental conditions shall be monitored and documented on a continuous basis, in accordance with the provisions of 8.2.4 and 13.4. These functions shall be maintained in the disconnected state to ensure the safety of risers and subsea equipment and to allow for safe reconnection. Monitoring of offsets, mooring line tensions, thruster loads, accelerations and stability shall be considered to ensure that the installation is operated within its design envelope.

The load monitoring system shall be incorporated into the ice management and alert monitoring systems in accordance with Clause 17.

Local winch and chain stopper control shall be specified and can involve remote control and monitoring of winches, chain stoppers and mooring lines.

13.7.4 Planned and emergency disconnect

In cases of worsening ice and environmental conditions, alert and ice management procedures can trigger production shutdown. Under planned conditions, this includes a complete flushing of all necessary systems. If ice conditions continue to worsen, the mooring system and product lines shall be released in a controlled manner.

If the design and operating scenarios involve cases of rapidly worsening or emergency conditions, the mooring system and product lines shall be designed for quick disconnection.

13.7.5 Stationkeeping system failures

The possibility of a failure of the mooring line or dynamic positioning system shall be considered in ice design scenarios.

Further guidance is provided in ISO 19901-7 and ISO 19904-1.

In cases of stationkeeping system failure, ice management may be considered in the design scenarios to ensure that progressive failure does not occur. Operational ice management capability shall reflect the assumptions inherent in the design.

13.8 Mechanical systems

13.8.1 General considerations

13.8.1.1 Applicability

Mechanical systems of floating production systems can be broken down into the following main components:

a) hull systems (bilge and ballast systems);

b) mooring or stationkeeping systems;

c) accommodation and associated utility systems;

d) production and utility systems (produced water system, offloading, material handling, safety systems including fire-fighting).

ISO 19904-1 provides general requirements for mechanical systems on floating structures. Special concerns and provisions applicable for operation of systems and equipment onboard floating structures in arctic and cold regions are addressed in 13.8.

Only those mechanical systems associated with a) and b) that normally have a strong interface with the structural design and operation of a floating structure are addressed in 13.8. Other mechanical systems on a floating structure are considered in Clause 15.

13.8.1.2 General considerations for all systems in arctic and cold regions

Mechanical arrangements, systems, and equipment essential for the safety of the operation of the unit or for prevention of pollution shall take into account the expected low air temperatures for operation in arctic and cold regions. Heating and insulation systems shall be provided as required.

Essential systems and equipment, when stored or located in an exposed position, shall be rated to perform design functions at the minimum EL or AL air temperature. Guidance on annual minimum temperatures is provided in regional annexes for various regions; see Annex B.

Systems and equipment should be designed so that personnel exposure to cold temperatures during normal operations including routine maintenance is minimized.

Upon failure of the primary heating system, essential systems and equipment exposed to outside ambient air temperatures should be

— provided with an independent source of heat; and/or

— fabricated from materials that are not susceptible to brittle fracture under the anticipated actions and temperatures.

Heating and insulation shall be provided in spaces where low temperatures can affect the safe working of personnel or affect the proper functioning of equipment.

For operation of systems and equipment in arctic and cold regions, consideration shall be given to the following, if relevant:

a) requirements for piping systems, pipe fittings and valves containing fluids that can freeze at low temperatures;

b) use of anti-freeze agents;

c) provision of heat in addition to the insulation of external pipes and pipe penetrations;

d) circulation of fluid in closed systems (or emptying the system) as an option to prevent freezing in the event of loss of heat;

e) requirements for additional protection in areas where the pipe insulation is exposed to wear/damage due to ice formation and/or removal of ice;

f) capacity and regularity with regard to drying of air;

g) altered effect of heating/cooling systems due to use of glycol or other anti-freeze agents;

h) requirements for electrical cabling;

i) provision for drainage of fire water, thereby avoiding direct risk to personnel and potential hull instability.

13.8.1.3 Icing and snow

Under given climatic conditions, icing and snow can build up in exposed places on structures and equipment, e.g. on crane booms, derricks, pipe racks. Procedures shall be in place for the removal and proper disposal of ice and snow. Consideration shall be given to covering critical marine equipment when not in use.

Measures initiated to remove ice shall not increase the risk of accidents by falling ice or increased health hazards due to use of chemicals.

13.8.2 Hull systems

13.8.2.1 Sea inlets and cooling water systems

Sea suctions shall be designed such that they can be cleared of slush ice accumulation.

The cooling water system shall be designed to ensure an appropriate supply of cooling water when operating in ice. The sea cooling water inlet and discharge for main and auxiliary engines shall be so arranged that blockage of strums and strainers is prevented.

NOTE A strum is a perforated metal box fitted around a bilge suction pipe opening to prevent debris from choking the pipe and bilge pump.

Where ice conditions warrant, the following shall be required:

a) sufficient redundancy to ensure operation of the cooling system in all expected ice conditions;

b) one or more sea inlets situated near the centre line of the ship and well aft if possible, the inlet grids of which shall be designed to resist ice actions;

c) one or more sea inlets sufficiently low to avoid ice accumulation due to pump suction;

d) increased sea chest (opening in the hull to accommodate marine system inlets and outlets) volume, including the requirements of auxiliary engines;

e) pipe for discharge cooling water connected to the sea chest, allowing full capacity discharge;

f) at least one fire pump connected to the sea chest or to another sea chest with de-icing arrangements;

g) area of the strum holes designed to prevent clogging with ice;

h) heating coils installed in the upper part of the chests.

Ballast water may be considered for cooling purposes in special circumstances only.

13.8.2.2 Ballast system

Ballast systems shall be designed to operate under the design environmental conditions.

Due to potential for freezing, tanks located fully or partly above the ballast waterline (BWL), the line of minimum draught, fore and aft, shall be given special consideration.

13.8.2.3 Marine systems instrumentation

All marine systems instrumentation, including the following, shall be designed for the cold environment:

- oil-gas instrumentation;
- hydraulic instrumentation;

- air instrumentation;
- process control;
- safety control.

13.8.2.4 Lighting

Lighting systems used to support floating structure operations shall be designed for ambient low light conditions. Where applicable, searchlights for operation in cold environments should be considered.

13.8.2.5 HVAC and air systems

The following shall be considered in the design and proper operation of the HVAC systems in cold environments:

- ventilation air intake;
- control of humidity;
- demister equipment;
- dampers;
- automatic damper shutting in the event of fan failure, loss of pressure and fire and gas detection;
- icing of ventilation equipment.

13.8.2.6 Starting arrangements

Starting arrangements shall be commensurate with the operating environment.

13.8.2.7 Propulsion, thrusters and steering for self-propelled floaters

The propulsion machinery, gear boxes, shafting, propellers, thrusters, steering gear and pintles shall be designed for transiting and stationkeeping in the operating environment. Consideration shall be made in the design for slowing and jamming of the propeller by ice.

Marine propulsion systems for moored disconnectable facilities (FPSO, FSU) should be adequate for the operating environment, considering design service life and required maintenance.

13.8.3 Offloading systems

Hardware associated with offloading shall be designed to reflect the cold weather environment, cold weather operations, icing, the ice environment, ice actions on the hose, as well as ice actions on the floating production system and the offloading vessel or fixed offloading system.

Provision shall be made for planned and emergency disconnects where operating limits are exceeded, and should be governed by an ice alert procedure.

13.9 Operations

13.9.1 General

Operations associated with the safe functioning of the floater as a vessel, including the propulsion and steering systems, hull systems (bilge and ballast systems), and mooring or stationkeeping systems, are addressed in 13.9.

13.9.2 Operations and emergency procedures manuals

A floater shall be equipped with dedicated operations manuals dealing with the following aspects of operation in arctic and cold regions:

- mobilization to the site;
- installation on site;
- disconnection and reconnection;
- demobilization from site;
- materials and fluids used for operation at low temperatures;
- equipment requiring heating and/or insulation for proper operation;
- inspection and maintenance of equipment;
- emergency procedures;
- requirement for standby and ice management vessels;
- ice incursion onto the deck, under the hull or within the hull of the floater system;
- environmental aspects affecting all operations (i.e. fog, icing, low temperatures, low visibility);
- supply and logistics to and from the floating structure.

13.9.3 Deck surfaces

Measures to prevent spillage from the main deck surfaces shall include the following minimum requirements:

- installation of save-alls on the exposed deck and around all drip areas and containment areas;
- provision of safe means of transport on deck;
- installation of drains and scuppers to prevent the formation of ice on deck.

Proper risk analyses shall be carried out to ensure that systems function in combination.

13.9.4 Damage control

Procedures and plans shall be in place to monitor and record the proper functioning of the operations of the floater. These damage control procedures and plans shall include

- safeguard functioning of main and fallback systems;
- functioning of mechanical and structural systems;
- frequent tours by experienced crew members;
- proper record keeping.

13.9.5 Equipment and doors

Mechanical systems on exposed decks or in cold spaces shall be checked for proper functioning on a regular basis. This can include measurement of temperatures and turning the equipment.

Watertight doors shall be checked to ensure safe operations. In critical operational circumstances, such as during ice alerts, local repair and maintenance activities shall be suspended and watertight doors shall be shut.

The operating procedures of equipment shall be adjusted for arctic and cold regions, and the criticality of such equipment or systems shall be taken into consideration.

13.9.6 Inspection and maintenance

Operation in a cold climate requires dedicated inspection and maintenance schedules, plans and procedures. The severity and criticality of equipment failure shall be taken into consideration in the assessment of priorities.

An operational manual shall be prepared for the proper inspection and maintenance of equipment.

Inspection sequences and procedures shall reflect the distinction between immediately accessible systems and those systems that are not immediately accessible for inspection and maintenance.

13.9.7 Planning and operations

Operational plans shall reflect the remote and challenging work environments, with a focus on the safety of all personnel, the environment and the equipment. Normal and critical operational procedures shall be distinguished.

Personnel shall be safely transferred. The planning and execution of all logistics shall be dedicated to the intended operation. Selection of transfer equipment, clothing and other gear shall be commensurate with the environment, the equipment and transfer systems available (i.e. vessels, helicopters, accommodation ladders).

13.9.8 Requirement for an ice management plan

An ice management plan shall be prepared in accordance with Clause 17.

14 Subsea production systems

14.1 General

14.1.1 System components

Ice actions are considered for components of subsea production systems, which can include but are not limited to

- risers disconnected from a floating platform;
- subsea components of loading and unloading systems;
- flowlines;
- umbilicals;
- templates;
- manifolds;

- subsea wellheads and xmas trees;
- jumpers;
- subsea storage tanks;
- subsea processing and compression equipment;
- structures designed to protect the above installations from ice and fishing gear.

14.1.2 Exposure level for system components

An exposure level may be assigned to the entire subsea system or to components thereof. The exposure level for various components of the installation may vary depending on the nature of the material stored or transported and on their role in ensuring the reliability of the entire installation. The presence of hydrocarbons shall be considered in the assignment of consequence categories for the components of a subsea production system. Exposure levels are defined in 7.1.4.

14.1.3 General provisions for ice actions

A subsea production system may be divided into components for the assessment of ice actions; see 14.1.1.

Ice actions shall be considered in the context of other (non-ice) actions.

14.1.4 Repair

Delays in repair of or access to subsea installations in ice environments should be mitigated through operational procedures, redundancy or other design features.

14.2 Ice and seabed considerations

14.2.1 Interactions above the sea floor

The following physical environmental parameters shall be included in the assessment of ice actions:

- ice keel draught;
- ice keel shape;
- keel frequency;
- ice drift speed and direction;
- mechanical properties of ice keels;
- hydrostatic and hydrodynamic characteristics of ice features that can have an effect during keel interaction with a subsea installation.

The provisions of 8.2 shall also apply for subsea structures.

14.2.2 Interaction with gouging ice features

For interactions with subsea installations or components below the sea floor, the following parameters should be included in the assessment of ice actions:

- location, frequency and orientation of ice gouge events, distinguishing between events in which the keel drags along the seabed (evidenced by furrows) and those in which the keel drops onto the seabed (evidenced by pits);
- ice gouge geometry, including length, width and depth, and corresponding variations along and across the impressions in the seabed;
- ice gouge effects, including pressures exerted on the seabed soils and consequent soil displacements;
- mechanical properties of the soil and the ice keel.

14.2.3 Strudel scouring

The following parameters should be included in the assessment of actions due to strudel scours:

- potential sources of freshwater runoff onto the sea ice;
- location and frequency of strudel scour events;
- velocity and extent of jet at seabed;
- plan dimensions and depth of strudel scours on the seabed;
- variability in dimensions as a function of soil parameters and water depth;
- mechanical properties of the soil.

14.2.4 Permafrost

The following parameters should be included in the assessment of actions due to permafrost:

- distribution of permafrost and associated distribution of soils;
- depth of permafrost;
- thermal properties of the permafrost, including present temperature and salinity profiles and their state relative to thermal equilibrium, and potential for salt migration;
- mechanical properties of the soil and permafrost, including ice content;
- potential changes in the properties and distribution of permafrost, including those resulting from operations.

Special consideration should be given to trenching or digging in seabed soils containing permafrost, whether for installation or placement of production system components, flowlines and umbilicals, glory hole construction or anchoring system installation.

14.2.5 Geohazards

Enhanced effects of geohazards (e.g. shallow gas, hydrates) as a result of the cold environment shall be considered. The frequency of boulders can be greater in arctic and cold regions.

14.3 Actions on subsea production systems

14.3.1 General action requirements

The following shall be taken into account:

- frequency of ice actions;
- magnitude of direct (through contact) and indirect (through soil) ice actions;
- action effects and the changes produced in the state of the installation and surrounding soil that can influence subsequent ice actions; and
- influence of wind, wave, current and seismic processes on ice actions, as well as action combinations with these processes.

14.3.2 Ice protection structures

The provisions of 14.3.2 apply to structures designed to protect a subsea installation from ice action and also to any structure designed specifically to displace or otherwise fail under ice actions (i.e. sacrificial structures), thereby protecting the installation.

Direct ice actions and indirect ice actions through soil or rockfill (granular material used to stabilize or protect a subsea installation) displacements shall be considered in the design of ice protection structures.

Changes in the nature, frequency and magnitude of the ice actions, and in the action effects as a consequence of the protection structure, shall be considered.

Through appropriate design, maintenance or repair, a sacrificial structure shall perform its intended function for the design service life according to the requirements of Clause 7.

14.3.3 Glory holes

The provisions of 14.3.3 apply to the burial of subsea installations in open holes or depressions below the sea floor for reducing the risk from ice keels. Glory holes may be cased or otherwise reinforced.

Ice actions and soil properties should be used to determine the shape and depth of the glory hole.

The path of the ice feature can be altered by the presence of the glory hole, the ice feature can drop into the glory hole or the feature can be trapped in the glory hole. Corresponding actions and action effects shall be considered.

The motions of the ice keel upon entering the glory hole shall be taken into account when assessing the frequency and magnitude of ice actions. Consideration shall be given to gouging ice features and those that drop directly into the glory hole.

Clearance above and around the subsea installations in a glory hole shall be provided to reduce the frequency of ice actions to a level consistent with the requirements of Clause 7.

Due account shall be made for damage to the subsea installation from debris entering the glory hole.

The glory hole shall be designed, maintained and dredged to perform its function for the design service life of the system.

14.3.4 Risers and loading/unloading systems

Disconnected risers include all subsurface components, including buoys that are released and remain attached following disconnection.

The frequency of ice interactions shall be determined based on anticipated environmental conditions, operational schedules and procedures, ice detection capabilities, ice management protocols, disconnection systems and disconnection procedures.

Hydrodynamic effects shall be considered in combination with ice actions.

Anchoring and positioning systems (e.g. mid-water buoyancy chambers and associated foundations) shall be considered in the assessment of response to ice actions.

Buoys used for positioning and stabilization shall be designed to resist ice actions, where relevant, according to the provisions of this International Standard.

The flexibility of the system may be used in the assessment of response to ice actions.

Where appropriate, ice actions shall be considered for features that can remain trapped following initial contact.

When in a disconnected state, risers and anchoring systems shall be designed and operated to avoid entanglement with subsea facilities.

14.3.5 Flowlines and umbilicals

Flowlines and umbilicals laid on the seabed, partially or fully buried are considered in 14.3.5.

Direct ice actions or ice actions through the soil shall be considered. Appropriate soil, ice gouge and ice parameters shall be considered, depending on the action. For example, the average depth across the width of an ice gouge can be appropriate for the consideration of actions through soil displacement, while maximum gouge depth can be applicable for direct contact.

Changes to ice keel morphology and mechanical properties as a consequence of interaction with the soil should be considered.

The relative orientation of the flowline/umbilical and ice gouges shall be considered where this materially influences the action.

Extension, ovalization and bending behaviour (and combinations of these) under ice action shall be considered where appropriate. Due account shall be taken of welds and of the state of the line resulting from the laying procedure. Ice actions shall be considered in combination with action effects resulting from operational procedures and other environmental actions.

Due account shall be made of permafrost, and changes such as upheaval buckling to the flowline/umbilical and soil as a consequence of operational procedures.

Ice actions and action effects shall take due account of the geometry and state of backfill or infill material as a consequence of sedimentation, littoral transport, strudel scours or operational procedures. Changes over the design service life of the system shall be given due consideration (e.g. cover requirements for erosion over a buried line).

The influence of weight coatings, gravel coverings, mats and other anchoring structures on ice actions shall be considered.

Ice actions shall be considered in the design of connections. As with other actions, connections are generally designed to release prior to failure of the line or damage to the component.

14.3.6 Resistance to ice actions

Due account shall be made for the interaction between the soil and the structure when assessing the consequences of ice actions.

Structural components below the sea floor and connected to the wellhead may be considered in so far as they can affect the response of the components exposed to ice actions.

14.4 Seismic design

Subsea structures used to protect wellheads, templates and other equipment located on the sea floor from ice shall be designed for seismic action. Such structures should follow the guidance contained in ISO 19901-2, and ISO 19902 for steel structures and ISO 19903 for concrete structures.

Glory holes and berms used to protect subsea equipment from ice can be subject to slope failure triggered by an earthquake. Slopes shall be engineered to prevent such a failure for seismic conditions.

14.5 Risk reduction

Risk reduction measures can include

- disconnection of all or certain components of the installation;
- design of a preferential failure mechanism;
- removal of all or certain components of the installation;
- installation and operation of hydrocarbon leak detection systems capable of detecting small leaks beneath the winter sea ice;
- active operations to remove hydrocarbons from all or part of the installation (e.g. flushing of flowlines);
- use of subsurface or subsea safety valves;
- use of temporary or permanent barriers to alter the ice regime or to prevent ice features from reaching the installation; see 16.3;
- ice management procedures that alter the ice regime or that prevent ice features from reaching the installation; see Clause 17.

These measures may be taken to reduce the frequency, magnitude or consequence of the action (or change the consequence category) for the installation or a component of the installation. In such cases, the reliability of the risk reduction measures shall be demonstrated through calculations, documented experience and implementation protocols. Implementation protocols shall reflect all phases of the production operation and relevant ice scenarios. They shall include step-by-step procedures and identify the responsibilities of personnel, where appropriate.

Where active measures are used to reduce the frequency or consequence of ice actions, consideration shall be given to the uncertainties involved in the successful execution of such measures.

15 Topsides

15.1 Overall considerations

15.1.1 Design considerations for topsides facilities

15.1.1.1 General

Clause 15 supplements the requirements of ISO 19901-3.

Winterizing of equipment, instrumentation and piping is critical for topsides facilities design and operations in arctic and cold regions. Winterizing is also required to protect personnel working in arctic and cold climates.

Winterizing can be achieved by a variety of techniques, including

- elimination of pockets or dead-ended pipes or legs in piping and design of piping to be self-draining;
- maintaining a flow in lines (such as fire water mains and cooling water branch lines) that are sometimes filled with static liquid;
- insulation;
- protective heating, generally combined with insulation; heating may be internal (e.g. when heating components are within a tank or vessel) or external (e.g. when heat tracing tapes are installed on instrumentation and piping);
- use of an enclosure, generally accompanied by heating from an internal heating element or by a heating/ventilation system;
- use of chemical or mechanical seals on instrumentation;
- use of windwalls to reduce rate of heat loss;
- addition of chemicals (methanol, for example) to reduce the freezing point of material.

Piping for offshore platforms often involves numerous deck penetrations that can present unique accessibility challenges. The design of heat-tracing systems shall consider the installation, operations and maintenance challenges in these areas, especially the areas below decks. When a piping system passes into indoor areas, the extent of heat tracing should be evaluated to ensure that icing in the system is avoided.

Winterization characteristics that should also be considered include the build-up of atmospheric or spray ice, as well as protection for personnel and equipment from ice falling from higher equipment, flare towers and communication towers.

Sufficient capacity shall be considered in the steam, electric or hot oil tracing system for losses, system deterioration (internal or marine fouling) and expansion for additional equipment.

Special attention shall be given to the following areas to determine whether protective heating is required during start-up, operation and shutdown periods. These areas, and similar areas not listed here, shall be accounted for in systems that generally do not require protective heating:

a) equipment and piping in water service when intermittent operation or minimum flow does not maintain the temperature above freezing;

b) water seals;

c) relief valves and their discharge lines;

d) instrument leads and taps;

e) field instruments;

f) auto-refrigeration at control valves and letdown stations;

g) piping and equipment that can contain significant amounts of moisture during start-up or upsets;

h) undrained low points in equipment and piping and dead-ended pipes or legs;

i) drains on flowlines, pumps, tanks, hydraulic power systems and other equipment;

j) lube and seal oil systems;

k) closed-system cooling water tanks for compressors in wet gas service;

l) fuel oil and diesel fuel tanks and lines;

m) diesel-driven equipment, particularly fire pumps and emergency generators;

n) drains and traps at low points in compressed air lines;

o) fuel gas knockout pot drains;

p) instrument gas;

q) turbine inlet air systems;

r) air or water exchangers in condensing service;

s) natural gas cooler tubes, if hydrate formation is possible;

t) gas used for cold start;

u) suction piping to compressors in saturated gas service;

v) fire foam lines;

w) pigging operations;

x) equipment for EER; see Clause 18.

15.1.1.2 Ambient temperature

Low ambient air temperature can have a significant impact on the selection of materials for construction. Certain metals that can become brittle at low temperatures shall be avoided in the construction of piping and equipment. Reference should be made to ISO 19901-3 in this respect.

Certain polymers become brittle and crack easily at low temperatures. Thus these polymers should be avoided in areas like cable insulation. Structural materials should be selected based on the requirements of 11.9 and the lowest ambient service temperature (LAST).

15.1.1.3 Sea and glacial ice — Impact on topsides structures

Topsides facilities, decks and working surfaces shall be designed for ice actions based on the annual probabilities of exceedance for EL and AL specified in 7.2.2.3 and 7.2.2.4. In the absence of data to quantify the potential for ice events, ice actions shall be assessed as if there were a reasonable probability of interaction. All realistic interaction scenarios with potentially adverse consequences should be considered in this respect. Reference should also be made to 8.3.1.4 for wave-induced ice motion and Clause 18 for EER equipment.

In addition, the following issues shall be considered in the design of the topsides production system, support structures, piping, equipment and fixtures:

- ice actions on the sub-structure inducing abnormal vibrations similar to vibrations experienced during seismic events;
- normal, continuous actions on the sub-structure associated with short-period ice-induced vibrations;
- resonance between the natural (ice-induced) vibration/frequency of the structure and the vibration/frequency of rotating production equipment (i.e. compressors, pumps, gas turbine power generators).

Fatigue shall be given particular attention at cold temperatures.

15.1.1.4 Ice accumulation

Ice on topsides can occur in the form of atmospheric icing or marine icing caused by sea spray. Ice accumulation can also result from hail and snow, which can fall on the production deck. Consequently, due consideration shall be given to the environmental actions (i.e. weight) on the design of structures. The weight of snow or ice load shall also be considered in the design of equipment, including insulation covering hot process equipment and piping. Certain insulations (e.g. foam based) can easily be crushed and become ineffective if sufficient weight is applied to them.

15.1.2 Operational considerations

The effects of icing and snow build-up should be minimized through physical, chemical or thermal management methods. Any use of chemical de-icing shall be in accordance with the local regulatory framework. Egress and operations routes should be kept clear of ice and snow. Meteorological forecasting can help predict the formation of new icing and snow, which can be used to mitigate the impact on the production system operations. Special attention shall be given to the operations of topsides equipment on floating vessels where sea spray icing can occur.

15.1.3 Sparing philosophy

15.1.3.1 Bulk spares

Due to the remote nature of most offshore facilities in arctic and cold regions, consideration shall be given to ensuring that sufficient bulk spares are provided for systems critical to health, safety and the environment. Serviceability-level ice events (SLIE) shall be considered with respect to the probability of a failure of a critical system that makes the structure inaccessible by a work-boat, helicopter, etc., whereby the critical system can become inoperable for a duration that can have an adverse impact on the health or safety of the offshore personnel.

15.1.3.2 Equipment spare

At least two independent communication system technologies shall be provided on the facility to ensure redundant communication to shore-based facilities under adverse environmental events in arctic and cold regions. Communication technology may include

- fibre-optic cable;
- microwave;
- UHF;

- VHF;
- VSAT.

Due to the extreme temperatures in arctic and cold regions, sufficient redundancy shall be provided in the HVAC (heating) system for the living quarters to ensure that in the event of a system failure, sufficient heat is available until EER plans are implemented.

Redundancy shall be provided for emergency power generation for all structures in cold regions.

15.2 Design and operational requirements

15.2.1 General

15.2.1.1 Deck elevation

For determination of deck elevation, due consideration shall be given to ice run-up, ice ride-up, ice rubble build-up or ice lifted onto the deck, impact of ice features such as icebergs with deck facilities and sea spray causing icing on the deck; see 5.3.2 and 15.1.1.3. These considerations are in addition to meteorological and oceanographic actions on the deck.

15.2.1.2 Extent of enclosures

Consideration shall be given to enclosure and heating for process and drilling facilities. Process facilities may be fully enclosed or partially enclosed with vessels and some of the equipment located external to the modules. Rotating equipment should normally be located in a heated enclosure.

Where vessels are located outside, vessel instrumentation including level bridles and transmitters should be located inside the module, in heated enclosures or insulated and heat traced.

Drilling facilities should be fully enclosed except for the derrick or mast for which, where appropriate, it can be necessary to enclose only the drill floor, the racking board and the crown level. Bulk mud and cement tanks as well as pipe laydown areas may also be located external to the modules. A heated pipe barn fully enclosed to the v-door should be available. As a minimum, the pipe barn should be sized to store the largest casing string and spare drilling tubulars.

Consideration should be given to the ventilation of enclosed areas. Of particular concern is ventilation in the case of a possible release of gas or harmful chemicals in enclosed areas; see 15.2.9. An assessment of the ventilation requirements for enclosed areas shall be prepared as part of the design.

15.2.1.3 Intervention

An intervention programme shall be put into place to protect equipment and piping in the event of a heating system malfunction or platform shutdown. This should include drain-down or blow-down of vessels, tanks, equipment and piping as required for the prevention of damage from ice formation and actions caused by the expansion of freezing fluids.

Backup or emergency power systems can be required to maintain critical equipment during intervention, e.g. air compressors and drain handling equipment. Heat tracing, powered from the emergency or backup power supply, can be required for certain equipment or piping that is impractical to drain. Other methods, such as circulation of fluid in piping or agitation of fluid in tanks, can also be used to prevent ice formation.

15.2.1.4 Heating requirements

Normally, enclosed areas associated with unmanned processes and drilling should be heated to 5 °C as a minimum.

Redundant heating equipment and systems should be considered to minimize or potentially eliminate the requirement for operator intervention or insulating and heat tracing, as described in 15.2.1.3 and 15.2.8.2.

Production structure design should consider continued fluid circulation on loss of heating systems during sub-zero conditions. This also applies to gas inerting, where purging air cannot be heated to a temperature above 0 °C. In each of these conditions, heat conservation and winterization design is critical to maintain appropriate temperatures in vessels, piping, and instrumentation.

When the air temperature is below 0 °C, it is not necessary that redundant heating equipment and systems be provided if drilling operations are suspended on loss of the primary heating systems.

15.2.2 HVAC and utilities

Air intakes and outlets shall be fitted with weather cowls to prevent build-up of snow or ice.

Provision shall be made in the design to allow for shut-in of the HVAC system when fire or gas is detected on the platform.

A steam system should be provided for the thawing and cleaning of process and drilling piping and equipment.

The HVAC system should provide control of humidity, particularly in manned spaces.

15.2.3 Architectural

External bulkheads and decks shall be insulated to eliminate condensation or icing. This is particularly important for deck areas where a slippery surface can be a hazard to personnel.

Temporary or permanent wind shielding should be provided for exposed equipment requiring periodic maintenance. Laydown areas, external temporary refuge areas and evacuation vehicle/boat loading stations should also be equipped with adequate wind shielding.

Measures shall be considered to reduce the likelihood of ice or snow build-up on walkways and stair treads, for example, by the use of grating.

15.2.4 Electrical

Cabling used in festoons or drag chains shall be rated for offshore use in marine cold weather climates.

Motors located outdoors or subject to large and rapid variations in temperature shall be supplied with anti-condensation heaters that are energized when the motor is off. Power panels, control panels and junction boxes located outdoors shall be supplied with thermostatically controlled, anti-condensation heaters.

Motors installed outdoors in cold environments shall be supplied to specifications for arctic and cold regions. They shall be constructed with cold temperature steel casings and bearings shall have low temperature lubrication.

Batteries should be kept fully charged and stowed in a heated space to minimize the probability of freezing in cold weather.

15.2.5 Isolators

The material used for an electrical isolator shall not become brittle at the minimum extreme-level (EL) ambient temperature. Electrical isolators are used to separate dissimilar metals.

15.2.6 Instrumentation and controls

Instruments should be installed in heated buildings or enclosures. Where this is not practical, insulation and heat tracing should be used and an adequate means provided for instrument maintenance.

If steam tracing is specified, pre-traced tubing bundles with stainless steel process and tracing tubes shall be used. Heavy trace tubing bundles shall be used in applications where the process fluid becomes too viscous for proper instrument operation at normal ambient temperature. Heavy trace tubing bundles are fabricated to ensure a close contact between the process tube and tracer. Where heavy trace tubing is not required (freeze protection and general warming), light trace tubing bundles generally can provide sufficient warming. Light trace bundles contain an insulated tracer that protects the process tube(s) from “hot spots” and overheating.

Process connections and associated instrument piping shall be traced and insulated in the same manner (light trace and heavy trace) as the process tubing. Care shall be taken to ensure that process taps for flowmeters are traced for even heating and securely insulated.

Electric or glycol heat tracing should be used where liquids can boil if steam tracing is used.

Bulb-type and other fill-type instruments shall be specified with a fill that does not require winterization.

Adequate heat tracing should be provided for each instrument with due consideration to redundancy and the importance of the instrument.

The process characteristics of all instruments that are traced shall be determined prior to the specification of any winterization method or system. Precautions shall be taken not to overheat, to the point of vaporization, instrumentation and instrument tubing that contain bubble-point fluids. Overheating can cause equipment to function improperly.

For instrument impulse lines, consideration shall be given to how the line will be insulated and traced, particularly for lines run in a tray.

Enclosure boxes for transmitters shall be designed for the cold environment. The electric heat tracing shall not be terminated prior to the point where the impulse line enters the box. The heaters inside the boxes are designed to keep only the transmitter warm, so there is a vulnerable section of the impulse line right at the entrance to the enclosure. Electric heat tracing shall be on the impulse line into the enclosure and shall also be tied to the transmitter sensor.

The facilities design shall include mechanisms to ensure that the motorized power sources for instrumentation, such as instrument air or gas, are adequately dried to maintain a water or hydrocarbon dew point at least 10 °C below the design minimum ambient EL temperature (at system operating pressure).

15.2.7 Mechanical equipment

15.2.7.1 Vessels

Vessels generally require protective heating only of the liquid space.

- Vessels in acid or other severely corrosive service shall be heated only on the external surface.
- Precautions shall be taken in determining maximum allowable temperature for vessels in acid service because this temperature varies with material used and acid concentrations.
- Vessel external instrument “bridles” shall also be considered for protective heating.

In vessels containing water as a separated fluid, heating normally shall be limited to the water draw-off boot.

a) Heat is required over the entire bottom of vessels when there is the possibility of a refrigeration effect from the expansion of light hydrocarbon liquids.

b) The presence of a flare knockout drum is an example of when the refrigeration effect shall be considered.

15.2.7.2 Fuel

The pour-point of a fuel should be at least 10 °C below the lowest EL ambient temperature (LAST). The fluid viscosity shall be considered in the design of the fuel transfer system.

15.2.7.3 Gas dehydration

Gas shall be dehydrated to at least 10 °C below the lowest EL ambient temperature to ensure that hydrates do not form in the system during normal operation.

15.2.7.4 Fuel gas system

Fuel gas systems shall be heat traced from the local knockout drums to the outlet of burner manifolds and supplies to engines and turbines to prevent the condensation of propylene or propane and heavier components. When it is intended to burn propane or heavier hydrocarbons in concentration above 50 %, vaporizers shall be provided in the knockout drum (in addition to the heat tracing).

15.2.7.5 Insulation

The selection of insulation material should be based on the desired insulation temperature range requirement and the suitability of the material at the given applications. Insulation materials should be rated at least 10 °C below the lowest EL ambient temperature. Suitable vapour barrier materials shall also be specified for outdoor application.

Insulation jacket type and materials shall withstand the EL and AL actions from snow, atmospheric ice and spray ice build-up.

15.2.7.6 Vibrations

Anti-vibration mounts should be considered for sensitive rotating equipment, such as gas turbines and equipment, which induces vibration such as reciprocating compressors. The design of the mounts should take into account the weight of snow and icing. Vibrations possibly caused by sea ice interacting with the structure should also be taken into account.

15.2.7.7 Vessel testing and inspection

All pressure-containing vessels and their supports shall be suitable for the minimum EL ambient temperature. Impact testing of the vessels and their supports may be required.

Vessel inspection requirements shall be considered where vessels are insulated. Removable insulating blankets may be used.

15.2.7.8 Pumps

For pumps that are located outside or operated when the heating system is not available, pump materials including seals and casings shall be rated for the minimum EL temperature.

15.2.7.9 Engine heaters

Standby or emergency engines shall be maintained in heated enclosures or shall be equipped with engine heaters to enable low temperature start-up.

15.2.7.10 Drilling equipment

Drill floor and derrick/mast equipment shall be rated for the minimum EL temperature. Kelly hoses, if not heat traced, shall be provided with a means to blow down when mud is not circulating through.

Where drilling risers and wellheads are exposed to low ambient temperatures, a means to prevent the fluid in the riser from freezing shall be installed. Similarly, the injection annulus for a cuttings injection well shall require freeze protection.

15.2.7.11 Hydraulic oils, lubricants, and coolants

Hydraulic oils, lubricants and coolants that are rated for the minimum EL operating temperature shall be used.

15.2.7.12 Seals and gaskets

Seals and gaskets exposed to operation in low ambient temperatures shall be suitable for the service specified.

15.2.8 Piping

15.2.8.1 Pipe testing and inspection

Piping shall be designed to withstand simultaneous low temperatures and maximum operating pressures; see A.15.2.8.1.

Piping inspection requirements shall be considered where piping is insulated. Removable insulating blankets may be used.

15.2.8.2 Heat tracing and insulation of piping

15.2.8.2.1 General

Heat tracing and insulation of piping shall be installed when any of the following conditions apply.

- Pour or freezing point is above the lowest EL ambient temperature.
- Ice formation or hydrating within the piping occurs due to pressure reduction of moisture-bearing gases.
- Corrosive compounds form if condensation occurs.
- Condensation occurs in fuel gas lines.
- Flow rates are reduced to an unacceptable level due to increased viscosity of fluid.
- Relief piping can become plugged due to freezing or congealing of viscous liquids.
- Liquids in tank or vessel drain lines are subject to freezing.

Freeze protection should also be considered for piping in low areas of the modules where cold air can accumulate.

Heat tracing may be electric, steam, glycol or hot oil. Electric is preferred where precise temperature control is required or where glycol or steam is not practical.

Redundant or “double tracing” should be considered for critical lines such as relief and flare lines.

15.2.8.2.2 Steam tracing

Steam tracing shall be limited to applications that permit relatively wide temperature variations. It may be used in hazardous areas where defects are usually easily located and repaired.

Steam tracing installations shall be laid out in an orderly manner with provision for thermal expansion and easy access to all flanges, unions, valves, traps, strainers and instruments. Valves and flanges, unions or tubing fittings shall be provided at traps so that they can be tested and readily removed.

Steam tracer supply and condensate return piping shall be valved.

Whenever practical, valves should be located so that they are accessible at grade or from permanent working platforms. When this is not practical, valves should be located so that they can be accessed with a ladder.

15.2.8.2.3 Electric tracing

Electric tracing provides more accurate temperature control. Since electric tracing is sized based on heat losses, the quality and condition of the piping insulation are a critical aspect that should be considered. Excessive heat loss at missing or poorly insulated areas can make an electric traced system ineffective. Certain types cannot be used in all classified (designated hazardous) areas and defects are usually more difficult to locate.

Classified areas that contain electric heat tracing systems shall be indicated on a plot drawing that designates the boundary of each classification.

Selection and installation of electrical tracing in hazardous areas should be in accordance with international or applicable national electric codes.

15.2.8.2.4 Hot oil/glycol system

Hot oil/glycol systems provide accurate temperature control where high temperatures are required.

15.2.8.3 Circulation of fluids

Piping systems such as utility water, cooling water, and fire water may be protected from freezing by circulation in lieu of heat tracing. Bleed lines may also be used to maintain sufficient flow to prevent freezing.

Cooling water, utility water and fire water lines should be insulated for condensation control.

15.2.8.4 System draining and blow down

Piping drains should be installed in all piping low points where required for system draining. Pipe work pockets in lines should be eliminated where possible.

Where winterization by draining, pumping out or heat tracing and insulating is not feasible, connections shall be provided for blow down of the system with compressed air or gas.

15.2.8.5 Deck drains

External deck drain boxes and associated piping should be heat traced and insulated to prevent frost build-up inside the drain.

15.2.9 Safety

15.2.9.1 General

Due consideration should be given to the effects that enclosures can have on safety issues, such as increased frequency of gas accumulation, increased explosion pressure and additional requirements for area classification and preventive measures.

15.2.9.2 Blast protection

Blast pressures used for accident scenarios should reflect the confined conditions resulting from the presence of sealed compartments.

15.2.9.3 Fire protection

The choice of fire suppression or extinguishing systems should reflect potential hazard to personnel in enclosed spaces.

15.2.9.4 Human factors/ergonomics

Material handling systems consisting of cranes, fixed davits and mono-rails should be considered.

Due to the potential of snow and/or ice settling on the production decks, cart-based material handling systems should be avoided. Due to the extreme temperatures, solutions requiring assembly should also be avoided (i.e. A-frames).

15.2.9.5 Safety showers and eyewash stations

Safety showers and eyewash stations intended for operations at temperatures below 0 °C shall be located in a heated enclosure and water lines to the showers/stations shall be trace heated with thermostatically controlled, low voltage electric heating systems.

15.2.9.6 Changing rooms and storage

Topsides facilities for arctic and cold regions should provide changing rooms and personal storage facilities for additional cold weather items and PPE that can be required.

15.2.9.7 Safety equipment

Monitors, hose reels and deluge and sprinkler skids shall be fitted with heat tracing or cabinet heaters as required.

15.2.10 Relief and flare system

Consideration should be given to adding pressure safety valve (PSV) outlet piping with weep holes, allowing water to drain and thereby prevent freezing. Weep holes should be large enough to ensure that rain water collecting in the tail pipe can drain out. The weep hole should be in the base of the elbow at the PSV outlet. A weatherproof cover should be installed over the weep hole.

PSV sizing should be adequate for cold EL ambient conditions.

Heat tracing or insulation should be considered to prevent freezing of balance bellows PSVs.

Rupture disk material should be selected to account for ambient temperatures, including daily variations.

The flare header knock-out drum shall be insulated and heat traced. Consideration should be given to installing heating in the flare header knock-out drums/water seal drums.

Provision shall be made for draining liquids from low points in piping and equipment. To reduce hydrate formation, low points on a flare header or relief system where liquid can accumulate should be drained.

Consideration shall be given to insulating and heat tracing the flare system piping downstream of the flare header knock-out drum in order to prevent potential ice build-up in the flare tower piping.

15.2.11 Storage

To minimize failures due to freezing within the channel of a closed ball valve, consideration shall be given to the use of pre-drilled ball valves for the storage tank drain and load valves application.

The storage tank relief system should be designed to avoid potential freezing of water accumulation. Relief valves for atmospheric storage tank overpressure and vacuum protection shall be designed to avoid any water accumulation that can lead to the seat sticking from freezing.

15.2.12 Actions on structure

For multi-leg substructures with the deck rigidly connected to the substructure, differential and multi-directional ice actions on the substructure legs shall be considered for the deck design. Typically, the exposed legs experience larger actions than the downstream legs.

Snow and ice accumulations can be significant in arctic and cold regions and shall be considered for the global deck design.

Differential temperatures between parts of a single structure (e.g. substructure to deck) can induce differential thermal contraction/expansion. If structures are constrained with respect to each other, then significant internal forces can be generated. These shall be addressed in the deck and topsides design.

To derive thermally induced topsides expansion/contraction values, EL temperatures shall be used to obtain design temperature changes relative to installation temperatures.

Where topsides facilities are founded on man-made islands or on any permafrost foundation, differential settlement should be considered in the design of structures. Provision should be made for shimming of support points to accommodate long-term settlement.

15.2.13 Provisions supply and mechanical handling

Because the structure can be inaccessible from a specific direction for an extended duration, due consideration shall be given to seasonal ice drift directions in locating the laydown area(s) and the cranes.

The operator should consider providing independent cranes and laydown areas in at least two different areas to maximize availability of supply in most ice and metocean conditions.

An approach to mechanical handling should be developed to account for the cold conditions, defining the equipment and routes that can be used for all maintainable equipment.

15.2.14 Working environment

To counter extreme environmental temperatures, a workable environment should be created in all normally or routinely occupied areas for topsides operations personnel. To achieve this, frequently visited process areas should, for example, be temperature sealed.

The use of enclosures to protect personnel from low ambient air temperatures should be considered for structures in all regions covered by this International Standard. Enclosures can be temporary or permanent based upon the minimum air temperature expected and the duration of air temperatures that can cause discomfort for working in an open environment. Guidance on wind chill can be found in A.6.3.3.

Other means of weather protection should also be evaluated for temporary and emergency work.

Topsides facilities for arctic and cold regions should provide changing rooms and personal storage facilities for additional cold weather items and PPE that can be required.

15.3 Seismic design

15.3.1 General

Seismic design shall be considered, where relevant, for topsides placed on bottom founded structures in arctic and cold regions. The provisions of 15.3 shall be applied to all topsides structures and systems, including the primary structural framing, deck appurtenances, fixtures and fittings in living quarters, fixed equipment for drilling, production and support, distributed systems, such as piping, HVAC, electrical, and instrumentation and controls, equipment/systems supports and attachments, and topsides systems such as EER and emergency power. Seismic design shall be based on ISO 19901-2.

15.3.2 Seismic design of the topsides structure

Structural performance for primary topsides structural steel shall be the same as for the substructure. Little or no damage shall occur for the ELE, while no collapse shall occur for the ALE. In addition, no excessive displacements that can affect the functionality of critical systems or affect EER activities shall occur. Coupled analysis shall be used for dynamically sensitive topsides or structures containing passive protection systems.

Structural framing shall be configured to the extent possible with a regular pattern and complete lateral load systems. Structural columns shall be designed with strength exceeding that of the beams. Caution should be used when trying to achieve this goal by using materials with different yield strength such that the actual expected or nominal yield stress, not the minimum yield stress, is considered.

Where process considerations require irregular framing systems, the framing shall be designed and analysed to demonstrate ductile performance in all directions.

Structural connections shall be designed in accordance with the seismic provisions of ISO 19902. The connections shall be designed for actions based on the capacity of the members framing into the connection, unless the calculated actions are less than 50 % of the member capacity, in which case the joint may be designed for the maximum calculated actions.

15.3.3 Seismic design of topsides equipment and supports

The anchorage, supports, structural systems and attachments for all equipment shall be designed and constructed to prevent structural and mechanical damage such that the following shall not occur:

- movement of the equipment or components in a manner that can affect personnel safety or emergency egress (e.g. falling, sliding, and toppling hazards);
- movement of equipment in a manner that can affect function of adjacent designated critical systems equipment (e.g. via impact);
- loss of containment of materials that can have significant fire or HSE consequences.

Supports for piping and other similar systems shall be designed such that damage does not occur during an ELE and collapse does not occur during an ALE. However, damage to individual supports during the ALE is acceptable.

In-structure accelerations or spectra (vertical and horizontal) shall be used to determine seismic actions of the equipment or supports at their relative location on the topsides, based upon the structural analysis of the topsides structure described in 15.3.2. Time history analysis should be considered for dynamically sensitive equipment, such as communications towers or drilling masts.

For distributed systems, such as different modules, that cross between structural systems, actions due to potential out-of-phase differential displacements shall be considered. This includes actions on the distributed system itself, as well as actions on the support system. They also apply to components required to contain hydrocarbons or maintain functionality of critical systems.

Piping containing hydrocarbons or hazardous materials shall maintain pressure integrity following the ALE. Piping spanning between flexible components, modules, skids, etc., shall have adequate flexibility to withstand movement of “anchor points”. Cable trays, conduit and other similar systems shall be required to maintain their general position following an earthquake.

15.3.4 Seismic design of component interfaces

The interface of the offshore structure with other components such as bridges or systems such as subsea pipelines shall take into account the relative motions between these systems that can occur during an earthquake.

15.3.5 Passive protection systems for seismic design

Guidance on the design and testing of seismic passive protection systems is provided in 15.3.5. The provisions shall be applied to all such systems, whether they are used to protect an entire platform or parts thereof. The guidance is aimed mainly at seismic isolation and energy damping systems.

Appropriate analysis procedures should be used for the design of the passive protection systems and for the design of a protected structure for the ELE. Such procedures include single mode or equivalent static analysis and response spectrum analysis.

Detailed non-linear time history analysis shall be used to verify the ALE performance of all structures with passive protection systems. The non-linear model shall account for the non-linearity of all passive protection devices as well as the non-linear behaviour of the protected structure, where such behaviour is expected.

The passive protection system shall be designed with consideration given to other conditions including low ambient EL temperatures, wind, sea ice, wave, ice accretion, aging effects, creep, fatigue, operating temperature, and exposure to moisture or damaging contaminate substances.

Means of access for inspection and replacement of all components of the passive protection system shall be provided. An inspection plan and schedule shall be developed to establish a periodic monitoring, inspection and maintenance programme for passive protection systems.

A fabrication quality control and testing programme for passive protection systems shall be established.

Prototype tests shall be performed on each type and size used in the design. Representative sizes of each type of device may be used for prototype testing, provided that the similarity of the device to previously tested devices can be substantiated. Test specimens shall not be used for construction.

Passive devices shall be replaced following any seismic event that exceeds the ELE, unless structural analysis or testing can demonstrate otherwise.

16 Other ice engineering topics

16.1 Ice roads and supplies over ice

16.1.1 General

Ice roads provide temporary and seasonal access routes to locations otherwise inaccessible by road, and produce minimal long-term disturbance to the environment.

Floating ice roads and bridges provide temporary water crossings constructed from natural ice, which can be thickened artificially, if required, to allow safe passage of loads. Grounded ice roads are supported continuously along the ground or seabed. The design and operational requirements for floating and grounded roads are different.

Expert guidance should be sought in determining the proper design ice thickness, construction technique and operating procedures.

16.1.2 Floating ice design criteria

Ice roads shall be designed and operated to minimize risk to life, damage to the transfer system and risk to the environment.

The following criteria shall be met for the static bearing capacity of an ice cover.

- The ice shall not fail in flexure.
- The freeboard shall remain positive.

NOTE Loss of freeboard causes flooding of the ice cover, submergence of the load and rapid deterioration of the ice bearing capacity.

The safety of an ice road with respect to bearing capacity failure shall be assessed in one of two ways:

a) the provisions of Clauses 7 and 8 may be applied, or

b) the prescriptive methods and parameters outlined in A.16.1 may be applied.

Calculation methods shall be based on sound physical principles and previous experience shall be taken into account.

If required, the ice can be thickened artificially to allow safe passage of loads.

16.1.3 Ice flexural strength for design

The bearing capacity of the ice is determined by its flexural strength. The flexural strength should be either estimated by *in situ* beam testing or derived from measurements of the physical properties of the ice. See Clauses 7 and 8 for guidance on characteristic values.

16.1.4 Dynamic behaviour and dynamic amplification factor

Moving actions such as those arising from moving vehicles create a pressure wave in the water under the ice that can amplify the deflection and stress in the ice. The speed of the actions moving on the ice shall be limited to avoid dynamic effects where overstressing, excessive dynamic deformation or fracture of the ice is or can likely be experienced. This is particularly important if the weights are close to the maximum static weights allowed for the particular ice thickness.

16.1.5 Safe use of ice roads and standard procedures

The thickness of the ice road (or bridge) shall be measured at regular intervals along and across the road. The interval shall be adequate to determine the average minimum ice thickness with sufficient confidence for a determination of the bearing capacity and to ensure that thin or weak spots are located. Measurement intervals of 25 m to 50 m are typically employed.

For longer roads, it can be necessary to subdivide the road into lengths or sections known as reaches and then to determine the average thickness for each reach. The interval between measurements shall be decreased where anomalies are indicated or suspected.

The thickness should be determined by drilling holes using augers or thermal means and measured using a tape or a calibrated stick or rod. Visual estimation of the ice thickness is not acceptable. Continuous thickness profiles may also be obtained using electronic methods but, if so, periodic calibration of the device shall be performed by measurements of thickness from regularly spaced holes.

A floating ice sheet has a characteristic wave propagation velocity for flexure that depends on the ice thickness and the water depth. If the velocity of the moving load approaches this characteristic velocity, the deflections under the load will exceed those normally anticipated for static loads. To mitigate this situation, vehicles should drive below a critical maximum speed and there should be a minimum separation distance between trucks and other large vehicles for safe use of ice roads. Elastic waves in the ice can be reflected from shorelines and potentially interfere with new waves generated by vehicles. Shore approaches that are normal to the shoreline should be avoided and the incorporation of a bend in the road near the shore is recommended.

The mass of equipment and vehicles placed on the floating ice road shall be determined accurately from existing records and reliable knowledge, or shall be obtained by weighing using available highway load scales or equivalent means. This weighing requirement also applies to any equipment or vehicles used in the thickening process of the ice.

The ice road shall be inspected for wet cracks running the entire depth of the ice. Bearing capacity shall be verified and appropriate mitigative action shall be undertaken where necessary to ensure safe travel.

If pumps are used, they should be capable of operating at the extreme-level minimum temperature for the site.

Complete coverage of the road surface during the flooding process is important and thus adequate equipment, personnel and support are required. Flooding shall be conducted only when the ambient temperature is sufficiently below freezing to allow the flood water to freeze. Intervals between applied floods shall be sufficient to allow previous floods to completely freeze before the next is applied. The thickness of each flood layer should normally be between 35 mm and 50 mm. Free flooding, whereby the water is allowed to flow freely from the pump without restraint, should be used to avoid undue stress concentrations. Dyking with snow should be used only where necessary to contain the water. Loads from other sources such as spoil piles stored on the ice or snow banks should also be taken into account.

16.1.6 Grounded ice roads

Grounded ice roads are usually suitable for construction in very shallow water or on tundra or swamp. Grounded ice roads can also be used to cross streams or channels. Typically, the ice is thickened and pushed down by its own weight onto the underlying soil. Roads can also be constructed onshore to protect the native soil, vegetation or tundra from damage by wheeled and tracked traffic.

Soil provides a stiffer support or sub-grade than water for the thickened ice. The ice shall be constructed with sufficient thickness to spread the wheel loads and avoid overstressing of the tundra sub-grade. In the case of offshore grounded ice roads, the value of the sub-grade stiffness and strength shall be high enough to ensure that the ice is not overstressed.

16.1.7 Helicopter landings on ice

Helicopters are sometimes required to land on sea ice, for example to rescue or to provide access for personnel. In such cases, the criteria recommended for ice roads in 16.1.2 can be applied. Where operating procedures such as leaving rotors on are used to reduce the risk of breakthrough, the criteria recommended for ice roads in 16.1.2 may be reduced.

16.2 Artificial ice islands

Artificial ice islands have been used for exploration drilling and relief well purposes in arctic and cold regions. There are three basic types of ice islands:

a) grounded ice islands created from flooding, spray ice and chipped ice;

b) floating or grounded ice islands, created by flooding to thicken the ice until sufficient area with sufficient bearing capacity is created;

c) rubble manipulation, with or without flooding and spraying.

Design and maintenance criteria for artificial ice islands are provided in A.16.2.

16.3 Protection barriers

16.3.1 General

If the design ice actions on structures are contingent on ice defence and ice control methods, this shall be specified in the design and operational documentation. The operator shall ensure that these methods are properly maintained during the design service life of the structure as appropriate to the life-safety and consequence categories.

16.3.2 Ice protection structure

16.3.2.1 Grounded ice as a protection barrier

If grounded ice rubble forms around a structure, the ice actions on the structure can be reduced because changes in the ice failure modes experienced at the rubble boundaries can result in lower effective ice failure pressures and consequently lower global ice actions. In addition, the grounded ice rubble can absorb part of, or all of, the ice action. Consolidation of ice rubble over time in the vicinity of a structure should be considered in the transmission of actions to the structure.

The action of ice on grounded ice rubble shall be determined using the principles for ice actions described in Clause 8.

The sliding resistance of the ice rubble depends on its dimensions, its mass and the characteristics of the interface between the ice blocks and the sea floor. Interface strength can be reasonably well defined if the rubble is grounded on a sand berm. If the ice rubble pile is grounded on the natural sea floor, the interface strength can be uncertain and requires investigation and assessment of both geotechnical and ice mechanics aspects.

The sliding resistance of grounded ice rubble shall be determined using the principles of foundation sliding resistance described in Clause 9. Further provisions with respect to failure mechanisms are given in 10.3.3.5.

Additional guidance on grounded ice as a barrier and how it can be supplemented with spray ice is given in A.16.3.

16.3.2.2 Rubble generation

Natural rubble generation can be supplemented using rubble generators, typically consisting of structures deployed on the sea floor to stimulate the rubble formation and provide protection from drifting ice impact.

Stability of rubble generators and rubble generation effectiveness should be maintained for the expected range in water level.

The potential for interaction between rubble generators and the structure, as well as other components of the production system, shall be considered.

Ice rubble generators may be considered in the assessment of ice actions if their effectiveness can be demonstrated in the context of Clauses 7 and 8.

The designer should consider ice conditions that can affect the efficiency of rubble to reduce the ice pressure or global action. For example, the accumulation of ice rubble on the face of wide structures can significantly affect the ice failure mode and the resulting ice actions.

16.3.2.3 Ice barriers

Ice rubble may be used as an ice barrier and may be supplemented with spray ice. If the seabed consists of a frictional material (e.g. sand), the ice barrier can be built with a smaller cross-section and a high freeboard to minimize the lateral ice actions. If the seabed consists of a cohesive material, large spray ice/rubble barriers with a low freeboard can ensure adequate sliding resistance.

If a spray island/barrier is built on a smooth, level ice sheet, consideration should be given to the ice sheet impeding the drainage and consolidation of a cohesive soil.

Lateral ice actions on the spray ice/rubble barrier tend to cause failure in one of four ways:

a) sliding along a weak plane through the ice barrier;

b) sliding along the bottom at the ice-soil interface;

c) sliding along a weak plane through the soil;

d) passive edge failure.

Grounded ice islands or ice protection barriers shall be designed to resist lateral ice actions in so far as they are used for developing the design ice actions on the structure. Further provisions with respect to failure mechanisms are specified in 10.3.3.5.

16.3.2.4 Ice actions and ice/barrier interaction

When grounded ice rubble is used to limit the ice actions applied to a structure, site-specific soil parameters, representative ice rubble properties and ice rubble geometries consistent with the structure and local ice conditions shall be used. The possibility that grounded ice rubble can be crushed or otherwise displaced after formation should be considered. Prudent design should, therefore, assess the potential for loss of the protection from a grounded ice rubble field after formation and the ice loads that can result both during and following displacement.

Knowledge of ice rubble properties is important for characterizing the transmission of ice actions to the structure. In areas of low sail height and minimal snow cover, heat loss through rubble can be large and the refrozen layer can attain thicknesses that are double the normal ice growth for the region. The characterization of the refrozen layer is important with respect to the potential action transmission.

The strength and elastic modulus of the refrozen ice layer should be estimated from *in situ* measurements. Large-scale *in situ* tests are the best indices of strength. Measuring salinity and temperature is not a reliable means of determining the strength of the refrozen ice layer.

The properties of grounded ice keels affect how ice actions are transmitted to the sea floor or an underwater berm if one is constructed. Generally, ice rubble keels have sufficient strength and stiffness to transfer most of the ice actions to the sea floor or berm.

Model testing may be undertaken in appropriate circumstances as an alternative to verify or to supplement calculations of ice actions. Due account should be taken of the capability of the model basin to simulate ice rubble processes.

16.3.3 Methods for mitigating the effects of ice

16.3.3.1 Ice control and defence

Passive ice control and defence methods may be used for decreasing the magnitude of ice actions.

If passive ice control and defence methods are employed, they shall

- be effective for their intended purpose;
- be implemented at all times when the structure is exposed to the ice environment;
- not adversely affect the integrity of the structure in any other way.

A wide range of passive ice control or defence options may be considered including

a) cutting a trench or moat in the ice around an island or structure;

b) placing barriers in front of the structure to initiate the formation of a grounded rubble pile;

c) utilizing satellite structures to relieve the ice load on the production structure;

d) using spray ice to form a protective ring or mounds;

e) placing piles in front of the structure;

f) designing the structure's perimeter to minimize local loads.

16.3.3.2 Mitigation of ice encroachment

Ice control and defence methods may be used to protect the structure and its facilities against ice encroachment. Mechanisms addressed should include ice pile-up and override.

Ice encroachment can generally be considered as a local action and the provisions of 8.2.5 shall apply where appropriate. The ELIE and ALIE criteria of Clause 7 apply to local actions associated with ice encroachment. Based on the provisions of 7.1.4, reduced exposure levels may be applied to local facilities that can potentially be impacted by encroaching ice.

16.4 Measurements of ice pressure and actions

16.4.1 General

Measurements of ice pressure and actions are recommended for

- assuring the safety or reliability of an existing structure, in relation to pre-set alert levels;
- improving design criteria for future structures, since empirical treatment of full-scale data is often the best approach for determining design ice loads.

If an ice pressure measurement system is used for either purpose, the recorded data should be specific and appropriate for the intended purpose.

The monitoring of ice actions and effects is also considered in Clauses 10 and 13.

16.4.2 Measurement techniques

Ice pressure measurements are categorized as either

a) measurements of the pressure or strain in the ice; or

b) measurements of structural and foundation response.

Examples are provided in A.16.4.

16.4.3 Limitations and requirements for different techniques

The following shall be considered in the interpretation of ice measurements:

- correct set-up of the sensors;
- frequency and stiffness response of the sensors;

- compatibility between the measurement system and ice-structure interaction processes;
- edge effects on the load measurement devices;
- reading and data handling errors;
- proper calibration, and changes over time and as a result of environmental conditions.

With multiple measuring devices in use, the results should be cross-checked for consistency among the different devices.

16.4.4 Documentation of environmental conditions

Physical environmental conditions, such as wind speed, ice movement speed and direction, water level variations and ice feature dimensions, should be measured in conjunction with ice actions and pressures.

16.4.5 Observations of the ice-structure interaction process

For ice-structure interaction events, an understanding of “what happened” is fundamental for the correct interpretation of measured ice pressure data. Data on the ice feature and the ice failure mode that occurred should be documented with as much detail as possible. The use of video recording devices to provide this documentation should be considered.

16.4.6 Ice load databases and synopses

Existing ice load databases and synopses should be referenced for calculation of ice actions or for placing site-specific measurements in the proper context.

16.5 Ice tank modelling

16.5.1 General

Model tests with offshore structures in ice basins can be used in conjunction with other methods of ice/structure interaction analysis for obtaining ice related design values.

Ice model tests are normally performed to measure global ice actions on the structure, to verify theoretical estimates or to investigate basic interaction mechanisms of ice and the structure. Ice model tests can also provide information about ice rubble formation, ice pile-up near the structure, ice jamming and ice clearing around the structure.

An assessment should be made as to whether the problem can be investigated reliably using the proposed ice tank modelling techniques.

Calibration of model results to field data and observations provide added confidence when model results are extended beyond field information. Confirmation that the ice failure processes are modelled correctly should also be performed in any model test programme.

16.5.2 Scaling

In ice model tests, the geometrical and mechanical properties of the ice should be scaled in accordance with an appropriate similarity theory as accurately as possible. Attention should be paid to minimize and assess errors due to scale effects. The particular mechanical properties of the ice that are most important for the expected ice failure mechanisms and the test objectives should be modelled as accurately as possible. The effect of imperfections in the ice modelling material should be assessed.

The modelling scale should consider

- the model ice type and its properties;
- the dimensions of ice test tank;
- the dimensions of the model;
- the processes being studied.

16.5.3 Test methods

The following issues should be considered and modelled correctly when contributing to ice actions or other test objectives:

- ice boundary conditions;
- ice geometry and range of ice types, such as level ice, ice rubble and consolidated portions of ridges or rubble fields;
- hydrodynamic effects;
- effect of whether the structure is moved through the ice or ice is moved past the structure.

Key ice parameters and conditions should be documented before, during and after a test.

16.5.4 Model ice properties

Geometrical and mechanical properties of the model ice (such as ice strength and thickness) should be scaled according to ice properties anticipated at the production site. The adjustment of test data to full scale should take deviations from similarity theory into account if the correction method is properly substantiated.

16.6 Offloading in ice

16.6.1 General

The use of export tankers has been an economic and reliable mode of transporting liquid hydrocarbons (including LNG). In arctic and cold regions, special consideration should be given to the offloading operation, which involves the transport of the hydrocarbons via the loading unit to the tanker.

16.6.2 System reliability

The reliability associated with offloading concepts used in ice shall meet the criteria specified in Clause 7.

The integrity of all components of the offloading system shall be ensured under all expected ice actions, direct or indirect. Global and local actions, including dynamics, shall be considered; see Clause 8.

Passive or active means can be considered to reduce global or local ice design actions, provided that it can be shown that, in combination with the structural resistance of the various components of the offloading system, the intended level of safety is achieved; see 8.2.7.

Ice management procedures developed in accordance with Clause 17 shall be in place and shall meet the operational time requirements for unloading operations. Tanker approach, connection, loading, disconnection and tanker departure operations should be considered in the assessment of ice management requirements.

16.6.3 Requirements for the offloading terminal

The structural integrity of the terminal should be ensured under all expected conditions, whether operational or otherwise, according to the provisions of Clauses 7 and 8.

If the terminal is free to drift, the risk of collision with other structures in the area should be evaluated in the context of Clause 7.

Particular attention should be given to the design of the interface between the tanker and the terminal. Direct and indirect actions associated with cold temperatures, ice impact, pressure from ice, vessel motion, terminal motion and ice build-up on the face of the terminal shall be considered. The interface between the tanker and terminal should be designed to minimize the risk for hydrocarbon release in the case of rupture.

16.6.4 Requirements for the tanker

Tankers that are loaded under sea ice conditions should be

- classed for polar operations by a recognized classification society;
- crewed with a complement experienced in operations in ice;
- provided with double hull protection of all cargo and fuel tanks.

The manoeuvrability of the tanker should be consistent with the ice and environmental conditions and operational scenarios used for the calculation of ice actions.

Operational limit conditions for the loading operations should be defined based on the terminal configuration, the ice management strategy and the tanker performance.

The risk of tanker collision with other structures during the loading process shall be compatible with the provisions of Clause 7.

17 Ice management

17.1 General

Ice management involves various operational procedures that can be used to reduce global and local design ice actions. Ice management is most commonly used to support floating systems in both sea ice and glacial ice environments and can significantly influence the design philosophy that is adopted for them. It can also be used to mitigate the risk of deep draught ice features interacting with sea floor facilities. In certain cases, ice management can be used as a means of modifying ice actions on fixed structures, although this approach is not common. It is also a relevant consideration in terms of supporting other in-ice activities, such as EER systems and tanker offloading operations.

An ice management system can include ice detection, tracking, forecasting, threat evaluation, icebreaking, ice clearing, iceberg towing and ice alert procedures. Ice alert procedures can be used to initiate appropriate operational reactions to any ice hazards or adverse ice situations in a timely manner, in order to mitigate threats. Appropriate operational reactions can include shut-in of production, disconnection of the structure, moving it off location or the evacuation of personnel, depending on the nature of the offshore system that is being supported.

17.2 Ice management system

17.2.1 Overall reliability and design service life

Any ice management approach that is intended to support the operation of an offshore system (floating, fixed, subsea or otherwise) shall be configured to achieve an acceptable level of overall system reliability, in combination with structural resistance. The acceptable level of system reliability should be determined according to the principles set out in Clause 7 over the design service life of the system(s) the ice management system is supporting.

17.2.2 Ice management to reduce ice actions

According to 8.2.7, an ice management system may be used to reduce both the frequency and severity of ice actions on offshore systems operating in ice environments, by altering ice interaction scenarios within the framework of a systematic ice management plan.

During the basic design work for any offshore system that is reliant on ice management, calculations shall be carried out to quantitatively demonstrate that the intended level of success can be achieved. The approach used should be founded on documented experience wherever possible and shall reflect the related uncertainties.

17.2.3 Characterization of ice management performance

Where ice management is used for reducing the applied ice actions on an offshore installation, the following provisions apply.

a) The expected performance of ice detection, tracking and forecasting capabilities and the associated uncertainties shall be documented, and should reflect the actual performance of the types of systems or devices that can be used in the context of expected metocean conditions, visibility and offshore operations.

b) The expected performance of physical ice management approaches that are planned and the associated uncertainties shall be documented, and should reflect actual performance of the types of vessels and systems planned for use in the context of expected metocean conditions, visibility and offshore operations.

c) The overall performance of ice detection and management systems shall be characterized in terms of their ability to reduce or alter the frequency and nature of adverse ice events, and should reflect the influence of the other ice and physical environmental factors that can be associated with these events. Parameters influencing this performance can include

   - ice feature dimensions and drift speed,
   - ice feature mechanical properties,
   - ice pressure occurrences, pack ice presence around icebergs,
   - metocean conditions (e.g. poor visibility, sea state).

Ice management performance may also be considered (and measured) in terms of its ability to extend operations, reduce downtime levels, allow disconnection, facilitate structure move off, and enable safe and efficient reconnection.

17.2.4 Ice management system reliability

Design and operational considerations shall be used to assess the overall reliability of an ice management system. The reliability of an ice management system shall be maintained for all of the anticipated physical environmental and operating conditions over the duration of the project.

17.3 Ice management system capabilities

17.3.1 Requirements

An ice management system should provide specific capabilities for

a) ice detection, including tracking and forecasting;

b) threat evaluation, including procedures to identify potentially hazardous ice features or ice situations;

c) physical ice management, including methods to physically manage these hazardous ice features or ice situations (e.g. icebreaking, ice clearing, iceberg towing), on an as-required basis;

d) ice alert procedure designed to initiate appropriate operational reactions to ice hazards or adverse ice situations in a timely manner, when physical ice management is not successful;

e) provision for disconnection and move off, where appropriate.

All of the system components associated with ice management should be demonstrated to operate in the context of offshore operations and expected environmental conditions (e.g. all weather, day/night, storm waves, etc.).

All responsible personnel involved in ice management activities should be trained with respect to the metocean and ice environment, the performance capabilities and limitations of the installation (or system) being supported, the production operations of the installation, the performance capabilities and limitations of the ice management support vessel(s), and the interrelationships within the overall ice management system.

17.3.2 Ice detection

Ice detection should be capable of identifying and tracking all of the potentially hazardous ice features or ice situations. The suite of platforms, devices and data integration systems used for ice detection should

a) provide adequate and demonstrable ice detection capability for the expected ranges of environmental conditions and visibility;

b) provide sufficient information to characterize the potential threat of ice features or situations, which can involve factors such as metocean forcing, morphological information, ice type and kinematics;

c) provide sufficient information to allow for the ongoing tracking of potentially hazardous ice features;

d) provide long-range detection and tracking capability to ensure adequate detection success and, where applicable, forecasting accuracy;

e) take into consideration the risks of the potential ice hazards, their probabilities of becoming a threat, and the appropriate operation specific reaction times.

The overall performance requirements of the integrated ice detection system should be evaluated and ensured, with due consideration given to any limitations in the performance of its individual components.

17.3.3 Threat evaluation

Potentially adverse ice scenarios that can lead to the exceedance of design or operating parameters (such as offsets, mooring line tensions or ice resistance capabilities) shall be pre-defined. The field methods used for threat evaluation should

a) consider the information provided by the ice detection system;

b) forecast movements and changes to any ice threats and their expected time of arrival;

c) characterize ice events in terms of potential consequences to the installation for the various operations and phases of the development;

d) identify circumstances when active intervention in the form of physical ice management activities is required;

e) identify the thresholds where installation-specific operational response actions (e.g. production shut-down, disconnect, personnel evacuation) are triggered and the advance warning time required for the response actions to be carried out.

17.3.4 Physical ice management

The resources that are associated with physical ice management should be available on a timely basis, consistent with ice detection capabilities, threat evaluation systems and operational requirements. Resources should include qualified personnel and appropriate vessels. Any systems that are used for physical ice management should

a) be available on a fit-for-service basis, when required;

b) be designed to operate under the anticipated range of physical environmental conditions;

c) provide a demonstrated level of effectiveness;

d) operate at an efficiency level that is consistent with the reliability requirements of the overall ice management system.

17.4 Ice management planning and operations

17.4.1 Scope of ice management plan

Ice management shall be implemented through an ice management plan, which includes an ice alert procedures manual. The plan should

a) be available on all offshore installations, ice management vessels and at locations where personnel are involved in the management of the offshore operation;

b) define the scope and expected range of ice management operations;

c) outline relevant specifications for equipment used in ice management operations and provide guidelines for the use of such equipment;

d) define the various operations expected on the installation when ice is present;

e) define ice events requiring action in the context of ice management operations and, when required, appropriate precautionary response operations on the installation;

f) define protocols and responsibilities for action when such events occur.

17.4.2 Ice events, threat evaluation and decision-making

The ice management plan should contain clear documentation of the ice alert procedures that define ice event (hazard) thresholds, the activation of ice management systems, subsequent decision-making requirements and their timing, and the consequent operational reactions.

Ice alerts requiring active responses should be defined in the context of the ice events and the operations of the installation. Specific provision shall be made for specifying the effectiveness of systems and equipment, time allowances and thresholds precipitating action associated with the systems identified in 17.3.1.

The ice management plan should ensure the proper definition of levels of responsibilities, accountabilities and actions for all parties, as well as the issuance of clearly identifiable alert levels.

Monitoring for the ice management and ice alert systems should be continuous during the ice season.

17.4.3 Support vessel requirements

All vessels used for ice management operations should

a) be registered with an RCS for operations in the ice regimes that can be present at the installation site, and in all waters transited during the course of ice management operations, re-supply and refuelling;

b) be suitable for undertaking the required ice management operations on a timely basis (which often involves aggressive icebreaking duties that translate into vessel capability requirements exceeding those normally needed for transiting of the ice regime);

c) be staffed with personnel trained in the performance of various ice management duties and the ice management plan;

d) be equipped according to the ice management plan.

17.4.4 Continued implementation of ice management plan

Ice management operations should be conducted in accordance with the ice management plan throughout the design service life of the installation.

17.4.5 Maintenance of ice management plan

The ice management plan shall be updated periodically over the operating life of the installation

- to reflect improved knowledge of the characteristics of the ice environment;
- to incorporate acquired knowledge of operations in the ice environment;
- to reflect changes in the operation of the installation;
- to reflect changes in the available ice management resources and capabilities;
- to ensure that the effectiveness of the ice management system is consistent with the design and operational requirements of the structure.

18 Escape, evacuation and rescue

18.1 General

The escape, evacuation and rescue (EER) provisions of this International Standard are intended to promote the successful escape from the incident, subsequent evacuation from the installation (emergency or precautionary evacuation), and the ultimate rescue of installation personnel. The EER provisions should be used as part of a continuous improvement process for managing risks and the safety of personnel working offshore in arctic and cold regions.

The EER provisions are performance-based provisions, in which verifiable attributes or benchmarks that provide qualitative levels or quantitative measures of performance shall be achieved. The key characteristic of a performance-based standard is that it is focused on what shall be achieved rather than on how it should be done. One of the performance targets shall be that use of the EER system incurs no casualties in the process. The performance target is developed in the context of a design health, safety and environment (HSE) case.

The provisions of Clause 18 should be used by stakeholders including designers and owners.

18.2 EER philosophy

18.2.1 General

EER components shall be developed taking into account environment (see Clause 6), reliability (see Clause 7) and continuous assessment (see 18.6).

18.2.2 EER governing principles

The provisions for EER shall be designed, assessed and ultimately implemented accounting for hardware design, personnel competence and EER procedures and controls. The emergency response plan developed from these components accounts for all specified credible hazard scenarios.

The EER system shall be continuously monitored, maintained and improved or corrected against the determined performance standard.

18.3 EER strategy

An EER strategy shall be developed within the context of 18.2.2 to integrate the structure design as it is developed and the operational characteristics for the anticipated range of physical environmental and accident scenarios.

18.4 Environment

18.4.1 General

Relevant physical environmental conditions shall be considered through the stages of design, implementation and continuous assessment of the EER system, including hazard and risk analysis; see 18.5.

18.4.2 Environmental conditions

The EER system shall be designed to achieve a consistent level of safety and effective operation throughout the complete range of physical environmental (i.e. climatic, ocean and ice) conditions expected for a given location over the design service life of the installation. Conditions shall include, but not be limited to, the following environmental factors and any associated issues affecting the performance and reliability of the EER system:

- air temperatures, including wind chill;
- natural light anticipated;
- wind;
- sea spray and atmospheric icing;
- visibility;
- cold open water;
- ice-wave combinations;
- sea state;
- local residual, wind-driven and tidal currents;
- ice and snow conditions.

NOTE Unless the water column is completely frozen or ice covered, sea state is the key environmental condition that influences the behaviour of surface marine EER systems.

The offshore installation shall incorporate provisions for appropriate forecasting and monitoring of the physical environmental conditions affecting the reliability and performance of the EER system.

The offshore facility operator shall have competency for evaluating the risk associated with the physical environmental conditions on the EER system.

18.5 Hazard and risk analysis

18.5.1 General

Formal hazard identification (HAZID) and risk analyses shall be performed and documented (typically in a design HSE case) for the EER system. These analyses shall be performed for the phases of the offshore operation during which time personnel can be exposed to hazards.

Risk tolerability criteria shall be set for all operationally involved personnel, who also govern the EER system under emergency response. These criteria shall be maintained throughout the design service life of the facility.

The owner shall ensure that installation design service life EER system performance standards are established at the earliest stages of design, coordinated with other inter-related emergency response performance standards and appropriately implemented.

Documented compliance with EER performance standards shall be available to support ALARP demonstration as part of the installation HSE case and prior to commencing operations.

The duty holder shall ensure that

a) the equipment provided for the purpose of protecting personnel during the EER process satisfies the performance standards and is maintained in a state of readiness;

b) the implemented EER measures, associated design and procedure decision processes are documented for the examination (by a competent and independent organization) of the system, comprising

   - escape (from workplace to muster station);
   - evacuation [from muster station/temporary refuge (TR) to beyond hazard zone];
   - rescue (and recovery to a place of safety).

18.5.2 Hazard identification

Formal hazard identification study techniques shall be applied to each component of the EER system and to the system as a whole.

EER HAZID studies shall

a) identify and record major accident hazards and their consequences in so far as they can influence the selection of EER system design, components, support services and procedures;

b) determine environmental factors that can influence the selection of EER system design, component specifications and support services or affect related procedures;

c) establish the safety-critical systems and their elements on which the EER system performance standards shall be based;

d) establish risk levels (acceptable, ALARP or unacceptable) for application during ranking of various system design options to achieve or improve the targets;

e) provide primary input to risk and failure mode and effect analyses, which when undertaken shall demonstrate that risks to personnel during the EER process are ALARP.

18.5.3 Risk analysis

EER analyses shall be undertaken to support ALARP demonstrations that are required for installation HSE case(s). These analyses contribute to the ALARP demonstration that considers a range of fundamentally different options and documents the process by which the low risk option has been selected. ALARP strikes a balance between risk reduction and the cost of the resultant benefit.

Each component of the EER system shall be analysed, taking into consideration relevant hazards, failure mechanisms, controls and safeguards provided to satisfy the performance standards.

18.6 Continuous assessment

The EER system and its various components shall be assessed continuously throughout the design service life of offshore installations.

To ensure that the EER system integrity is maintained, risk analysis shall be updated for changes impacting the HSE case, or the assumed or actual external EER resources and their capabilities.

18.7 EER system design

The EER system shall ensure that, in the event of a potential or actual emergency, installation personnel are protected and can be moved to a place of safety.

The EER system design shall be fully integrated within the overall emergency response system, complying with the governing principles described in 18.2.2.

The selected components and procedures of the EER system for any offshore installation in ice covered waters shall be determined by a formal assessment that documents a fully auditable decision trail.

The specific EER system on a given installation shall be installed, tested and operated based on the established performance standards.

The EER system design shall take into consideration the requirement for regular inspection, maintenance and testing, including functionality readiness assessments.

Power supplies shall be available to allow all safety-critical equipment to perform their emergency functions for the required duration.

The design of rescue systems shall be compatible with the design of the evacuation system, in the context of the physical environment of the arctic or cold region.

Lifesaving appliances exposed to freezing environments shall be protected and regularly inspected.

18.8 Emergency response organization

The installation emergency response organization shall be documented and summarized (e.g. in a station bill), and posted at strategic locations throughout the installation.

18.9 Competency assurance

The operator shall ensure that all personnel on board the installation are adequately familiar with the operator's safety management system, including the emergency EER response plans and hardware systems, and that they are adequately trained and competent in accordance with their safety related responsibilities and duties.

Personnel shall be given appropriate installation-specific EER education, training and/or drills and their competency maintained and regularly tested. Training shall take into account the ice and open water operating environments.

The installation design shall provide for testing the EER system through a systematic programme of emergency scenario drills with specific pre-planned learning objectives in a realistic manner.

The EER system shall not pose hazards to the safety of personnel undertaking drills.

18.10 Communications and alarms

The communication system shall operate under all emergency scenarios, taking into account geography, distance and environment (within the operational network offshore, onshore, standby vessel support, on the platform).

Public address announcements, visual and audible communications, including external communications, shall be operable from the TR and wherever identified as necessary.

The condition of the installation, the process controls and detection status shall also be provided in the TR.

Muster stations shall be capable of communicating with the on-scene commander following the general or abandonment alarm.

Emergency information and signs shall account for language/culture differences and be strategically located throughout the EER system.

Relevant parts of the EER system (e.g. escape routes, evacuation boarding areas) as determined by the EER analysis shall be illuminated for the required duration to perform the functions required by EER.

18.11 Personal protective equipment

The need for, and numbers, types and storage locations of, personal protective devices shall be determined in the EER analysis.

Personal protective equipment (PPE), as determined by the EER analysis, shall be provided for personnel in sufficient numbers. Deployment locations shall include the living quarters and other strategic areas.

Evacuee PPE shall include devices to facilitate evacuee movement from the sea to ice floes, if required by EER analysis.

If evacuation onto solid ice is part of the EER strategy, the evacuees shall have adequate clothing, footwear and traction devices to provide protection and mobility until rescued.

Externally stored PPE shall account for extreme cold temperatures and snow and ice accumulations. The requirement for heating storage areas shall be assessed.

18.12 Man overboard recovery

The installation shall have a means to recover a man overboard including injured personnel under anticipated incident and physical environmental conditions.

18.13 Escape design

18.13.1 General escape design

Escape system design shall consider communications and alarms, escape routes, temporary refuge, muster station and PPE locations and their integrated function in the escape process.

18.13.2 Escape routes

Escape route(s) shall be designed to ensure that all personnel can safely move from any part of the installation to the TR or muster station under credible incident, physical environmental and operational conditions.

Escape routes, stairways and ladders shall be sized to take into account bulky cold weather PPE and the maximum flow of personnel in emergencies.

Appropriate emergency escape lighting shall be provided to illuminate routes leading to the TR, taking into account icing and/or snow accumulations and the direction of escape.

Exit doors, stairways and ladders shall be appropriately designed and maintained accessible, taking into account icing and/or snow accumulations and the direction of escape.

18.13.3 Temporary refuge

A temporary refuge (TR) shall be provided except where the EER analysis or risk assessments demonstrate that one (or more) is not required.

The TR shall protect personnel from any incident and physical environmental effects for a time sufficient to allow control of the emergency or until a decision is made to abandon the installation.

A TR impairment analysis shall be performed as part of the EER analysis, taking into account the aspects of impairment including ice and other physical environmental conditions that can delay evacuation.

It is not necessary that a TR be usable under all incident scenarios, provided contingency plans are in place to ensure the safety of personnel.

18.13.4 Muster station

As determined by the EER analysis, there shall be strategically located muster stations sized to accommodate all personnel on board, taking into account the environmental conditions.

18.14 Evacuation design

18.14.1 Evacuation — General

Personnel moving from the TR or muster station to the primary embarkation areas shall be protected from the installation hazards and environment.

There shall be as many independent evacuation systems and configurations as needed in accordance with the EER analysis.

The methods of evacuation (whether installation or non-installation based) shall be assessed in the EER analysis according to the number, location, orientation and means used.

The design and selection of evacuation method(s) shall include a risk assessment of the lowest probability of incurring casualties, taking into account the range of credible physical environmental conditions during emergency, precautionary and scenario drill evacuations.

Evacuation methods (e.g. boarding, securing, deployment, clearing the hazard zone, etc.) shall be designed to perform reliably for the credible environmental, operational and accident condition combinations as determined by the EER analysis.

The evacuation system shall be designed such that it is visible and identifiable and provides location information to search and recovery platforms under design installation hazard and environmental conditions.

Precautionary and emergency evacuation methods shall be designed and operated in accordance with the risk criteria established in 18.5, and should also satisfy conventional certification, national authority and international standards and codes.

18.14.2 Evacuation method design

Each independent method (type) of evacuation shall accommodate the full complement of personnel on-board (POB) the installation, including visitors, under any emergency scenario requiring evacuation.

The design integrity of each independent method of evacuation shall be assessed in terms of impact with other evacuation methods, the installation, environmental conditions including the ice cover, and rescue craft.

Evacuation methods shall be designed and located to minimize the effect of the surrounding ice cover in their deployment and movement beyond the incident hazard zone.

Occupant space and restraint design shall consider bulky cold-region PPE, the distribution of individuals and their mass as well as acceleration.

The design of the boarding area layout for the evacuation methods, and the launching equipment and method, shall consider the safety of personnel during emergency use as well as during drills and maintenance.

If determined by EER analysis, the evacuation method shall be capable of being operated by personnel donning respiration protection for launches in toxic atmospheres (e.g. smoke, H_2S) in cases where pressurized access routes have not been provided.

Evacuation methods shall be designed to protect personnel from the effects of the incident and arctic or cold region environment until recovered to a rescue platform.

The evacuation system shall have a provision on board for retrieval of personnel, including injured personnel from the sea or ice.

18.15 Rescue design

The design integrity of the rescue system shall ensure that evacuees are recovered in the prevailing physical environmental conditions.

Rescue systems shall be designed to ensure that evacuees can be rescued in the event that they do not clear the hazard zone.

A means shall be available to recover evacuees from the sea, the ice, or from evacuation systems, onto a rescue platform.

Rescue platforms shall have equipment and capabilities suitable for locating and recovering evacuees.

Annex A
(informative)

Additional information and guidance

NOTE The clauses and subclauses in this annex provide additional information and guidance on the clauses in the body of this International Standard. The same numbering system and heading titles have been used for ease in identifying the subclause in the body of this International Standard to which it relates.

A.1 Scope

No additional guidance is offered.

A.2 Normative references

No additional guidance is offered.

A.3 Terms and definitions

No additional guidance is offered.

A.4 Symbols and abbreviated terms

No additional guidance is offered on the symbols listed in 4.1. The following additional symbols are used in this annex. These symbols are also defined locally where they are used so that the meaning of symbols with more than one definition is unambiguous.

A	actual contact area between ice and structure
A_{N}	nominal contact area between ice and structure
$\overline{A}$	average floe area
A_{L}	local contact area
A_0	area corresponding to background pressure
a	site-specific constant that depends on local winds, currents and snow cover
a	coefficient relating to local ice shape
a	loaded height for local ice actions
a_{d}	frame spacing for local ice actions
B	beam width
b	empirical heat conduction coefficient
b	coefficient relating to local ice shape

b	effective beam length
b_k	base width of keel
C_A	local ice shape coefficient for ice feature
Ca	Cauchy number
C_FDD	accumulated freezing degree days
C_h	ice strength parameter for floe impact
C_i	ice strength coefficient
C_ir	coefficient for ice road operation
C_N	fraction of sea surface area covered by ice floes
C_P	coefficient in ice pressure relationship
C_R	ice strength coefficient
C_R0	strength parameter for reference area
C_w	local ice shape coefficient for planar ice feature
c	ice rubble effective cohesion
c	bottom cohesion
$c_\mathrm{ice,aw}$	above-water cohesion for spray ice
c_soil	soil cohesion
D	width of ice feature
$\overline{D}$	average width of ice features in region
D_A	local ice shape coefficient for ice feature
D_c	core diameter
D_ice	total damage to structure due to ice
D_i^k	damage to structure due to ice scenario k
D_P	coefficient in ice pressure relationship
D_w	local ice shape coefficient for planar ice feature
$D_{1,2}$	coefficients relating to local shape for planar ice feature
d	water depth
d	width of ice feature
E	modulus of elasticity of ice (Young's modulus)
E_f	elastic modulus in bending

E_K	reduced kinetic energy of ice feature after rotation on impact
E_0	initial kinetic energy of ice feature
E_0	modulus of elasticity (Young's modulus) for freshwater ice
E_1	elliptical integral of first kind
E_2	elliptical integral of second kind
e	encounter or event
e	porosity of ice rubble
$f_X(x)$	probability density function, p.d.f., for random parameter, X, specified at value, x
F	ice action
F	ice bearing action
F	load applied to cantilever free end
F_b	failure load
F_B	limit ridge building action
F_c	action component due to consolidated part of ridge
F_E	action at end of impact
F_G	global ice action normal to surface
F_H	horizontal component of ice action
F_ii	pack ice action imposed on ice island
F_k	keel action component
F_L	local ice action
F_max	maximum value of ice action
F_min	minimum value of ice action
F_N	normal load on contact surface
F_R	ice ridge action
Fr	Froude number
F_S	global ice action incorporating sheltering for multi-leg structure
F_T	tangential (friction) load during steady motion
F_V	vertical component of ice action
$F_X(x)$	cumulative distribution function, c.d.f., for random parameter, X, specified at value, x
F_1	ice action on one leg of a multi-leg structure

F_0	peak value of ice action
$F_1, F_2, ..., F_m$	individual cumulative distributions
ΔF	difference between maximum and minimum values of ice action
f	geometrical parameter for conical structures
f	frequency
f_n	natural frequency of eigenmode
G	parameter in icebreaking component for actions on conical structures
g	acceleration due to gravity
g_r	geometrical parameter for conical structures
H_B	horizontal action on structure due to ice breaking
H_k	keel depth
H_L	load required to lift ice rubble on top of advancing ice sheet prior to breaking it
H_P	load component required to push ice sheet through ice rubble
H_R	horizontal action on cone due to ride-up
H_R	load to push ice blocks up slope through ice rubble
H_s	sail height
H_T	load to turn ice block at top of slope
h	ice thickness
h_c	consolidated layer thickness
h_E	characteristic ice thickness for ELIE
h_fb	island freeboard
h_k	distance between base of consolidated layer and base of keel
h_r	ice ride-up thickness
h_r	rubble height
h_v	geometrical parameter for conical structures
h_1	reference unit ice thickness
h_0	initial or known ice thickness
K_Ic	fracture toughness
k	foundation modulus or sub-grade reaction
k_j	ice jamming coefficient

k_n	non-simultaneous failure coefficient
k_s	interference and sheltering coefficient
L	clear distance between legs of multi-leg structure
L	length
L	length of beam
L_c	characteristic length of ice sheet
l_b	breaking length of ice sheet
l_c	total length of circumferential crack
M	mass
M_n	modal mass
m	empirical coefficient in global ice strength relationship
m	empirical coefficient that depends on snow depth
m	number of scenarios
N	component of action normal to structure surface
N_c	bearing capacity constant
n	number of events
n	empirical coefficient in global ice strength relationship
n	number of legs for multi-leg structure
n	number of panels
n	number of parameters
n	number of ice layers
n_r	number of realizations
P	probability or annual probability
P	applied load or action
P	load per unit width on conical structure
P	ice sheet resistance
P_0	initially applied load
p	ice pressure
p_D	ridge building action, per unit width
p_F	full thickness pressure

p_G	ice pressure averaged over nominal contact area associated with global action
p_L	local ice pressure
p_T	thermal ice action, per unit width
p_u	ultimate ice strength in borehole test
p_0	average global pressure
p_0^p	background pressure to be applied around local pressure patch
Q	variable action
q	bearing capacity per unit area
$q(...)$	specified function
q	range of actions as a proportion of maximum action
R	coefficient for ridge building action
R_ii	ice island resistance to ice actions
r_c	radius of loaded area
r_T	rate of temperature increase
r_y	radius of gyration of ice feature about horizontal axis
r_z	radius of gyration of ice feature about vertical axis
S	ice salinity
s_min	lower bound factor on compressive strength
s_max	upper bound factor on compressive strength
s_u	characteristic undrained shear strength
T	ice temperature
T	period of ice action
T_a	mean daily air temperature
T_b	freezing temperature of water
T_i	ice temperature
t	time
u	integration parameter
u	structure displacement
V	volume
V	ice speed

V_B	vertical action on conical structure due to ice breaking
V_j	individual actions in a year
V_R	vertical action on cone due to ride-up
v	ice speed
v	vehicle travel speed
$\overline{v}$	average drift velocity (speed) over region
v_b	brine volume fraction
v_c	maximum vehicle velocity for dynamic magnification
v_T	total void volume fraction, brine and air
v_t	highest ice velocity at which lock-in condition can occur
W	rubble weight parameter for conical structure
W_ii	on-bottom weight of an ice island
w	width of structure
w_L	loaded width for local ice actions
w_T	top diameter of a conical structure
x	parameter in equations for ice actions on conical structures
x	distance from centre of load
$X_{1,\mathrm{E}}$	ELIE parameter value
$X_{1,\mathrm{A}}$	ALIE parameter value
X_j	parameter value
$X_{j,\mathrm{N}}$	nominal parameter value
Y	coefficient in equations for ice actions on conical structures
$y_{\mathrm{r}1,\mathrm{E/A}}, y_{\mathrm{r}2,\mathrm{E/A}}, \dots, y_{\mathrm{r}m,\mathrm{E/A}}$	ELIE/ALIE level representative actions
$Y_1, Y_2, ..., Y_m$	actions corresponding to scenarios
Z	action
z	distance from mid-depth of ice
z	depth below ice keel
z	action
z_E	ELIE action
z_A	ALIE action

$z_{\mathrm{r,E}}$	representative action corresponding to ELIE level
$z_{\mathrm{r,A}}$	representative action corresponding to ALIE level
$z_{\mathrm{r},\alpha}$	representative action corresponding to annual exceedance level, α
α	annual exceedance level
α	slope of structure from horizontal
α	coefficient representing decrease in ice pressure with area
α_{k}	keel attack angle
Δ	deflection of a beam
δ	penetration depth of structure into ice
δ	deflection
δ_0	initial deflection
$\dot{\varepsilon}$	strain rate
ε_{y}	eccentricity in horizontal plane
ε_{z}	eccentricity in vertical plane
η	average annual encounter frequency
ϕ	ice rubble friction angle
ϕ	bottom friction angle
ϕ'	characteristic friction angle
$\phi_{\mathrm{ice,aw}}$	friction angle for spray ice above water
ϕ_{is}	friction angle at ice/soil interface
$\phi_{n\mathrm{c}}$	non-normalized modal amplitude at point of ice action
γ_{e}	effective buoyancy, expressed as a unit weight
γ_{i}	above-water spray ice unit weight
γ_{is}	below-water spray ice unit weight
γ_{L}	pressure distribution coefficient
γ_{v}	coefficient relating loading frequency and highest velocity for lock-in
γ_{w}	seawater unit weight
λ	geometric scale factor
μ	annual exposure level, expressed as number of interactions per year
μ	ice-structure kinetic friction coefficient

μ_i	ice-to-ice kinetic friction coefficient
μ_ϕ	ice rubble passive pressure coefficient
v	Poisson ratio for ice, typically 0,3
ρ_A	areal density of ice features
ρ_i	mass density of ice
ρ_w	mass density of water
σ	measured or inferred strength index
σ	normal pressure
σ_c	uniaxial compressive strength
σ_D	standard deviation of ice floe diameter
σ_edge	maximum extreme fibre flexural stress
σ_f	flexural strength of ice
σ_is	normal stress due to weight of ice
σ_max	maximum flexural stress in ice sheet
σ_t	tensile strength
σ_x	extreme fibre flexural stress at distance x from centre of action
σ_0	strength index for reference area
τ	shear strength
τ	duration of loading/unloading cycle
$\tau_\mathrm{ice,aw}$	above water shear strength of spray ice
$\tau_\mathrm{ice,bw}$	below water shear strength of spray ice
τ_is	shear strength of ice
θ	angle of rubble from horizontal
θ	damping coefficient
θ_k	keel angle from horizontal
ξ	parameter relating to horizontal and vertical components of ice action
ξ_n	total damping of eigenmode as a fraction of critical

A.5 General requirements and conditions

A.5.1 Fundamental requirements

No additional guidance is offered.

A.5.2 Design methods

No additional guidance is offered.

A.5.3 Site-specific considerations

A.5.3.1 General

No additional guidance is offered.

A.5.3.2 Long-term climate change

Strong evidence of climate change has been documented by Working Group 1 of the Intergovernmental Panel on Climate Change (IPCC). Details can be found in Reference [A.5-1].

A.5.3.3 Structural configuration

No additional guidance is offered.

A.5.3.4 Winterization

No additional guidance is offered.

A.5.4 Construction, transportation and installation

No additional guidance is offered.

A.5.5 Design considerations

No additional guidance is offered.

A.5.6 Environmental protection

Most offshore structures contain fluids in the form of fuel for machinery or electric power generation in addition to some amounts of processed hydrocarbon fluids. Furthermore, stored processed water can contain traces of hydrocarbons. Ballast water, used during transportation and installation, can contain micro-organisms that can be detrimental to the local environment.

Special attention should be given to containing fluids and materials used for commissioning to avoid potential harmful releases to the environment.

Double barriers on the underside have been used effectively for insulation of ballast water tanks placed over permafrost.

A.5.7 Vibrations and crew comfort

The parts of ISO 2631[A.5-2] through [A.5-5] deal with human exposure to whole-body vibration and shock in buildings with respect to the comfort and annoyance of the occupants. Repeated ice actions that can potentially lead to structure vibrations are addressed in A.8.2.6.

A.6 Physical environmental conditions

A.6.1 General

No additional guidance is offered on the number of years of measured data required to develop the basis for design parameters. This should be agreed upon by the owner and the appropriate regulatory agency.

A.6.2 Daylight hours

Depending upon the latitude, the number of daylight hours can vary from none in the winter period to 24 h in the summer period. Platform and re-supply operations can be affected by the lack of sunlight and sufficient lighting is a requirement for safety. Tables and figures showing daylight hours by latitude and month are available in several publications. An example is Figure 23 of Reference [A.6-1].

A.6.3 Meteorology

A.6.3.1 Air temperature

Air temperature is a critical parameter not only in the design of an offshore structure, but also in its day-to-day operation. As such, it is important to include this parameter in a real-time metocean measurement unit with display at convenient locations.

A.6.3.2 Wind

ISO 19901-1 provides information on wind actions and action effects, wind profiles and wind spectra.

A.6.3.3 Wind chill

Starting in 2001, the US and Canadian weather offices applied a new wind chill index[A.6-2]. The new approach takes into account modern heat transfer theory, and uses a human face model as a consistent standard for skin tissue resistance. Most importantly, the new wind chill equation continues to refer to input wind speed values at 10 m (standard anemometer height), but includes a height correction factor to correct this wind speed to give an estimated wind chill index at face height (1,5 m above ground).

Additional guidance can be found in Reference [A.6-3].

A.6.3.4 Precipitation and snow

ISO 19901-1 provides general information on snow accumulation on buildings and topsides.

In the absence of specific information, new snow can be assumed to have a density of 100 kg/m^3.

A.6.3.5 Ice accretion

A.6.3.5.1 General

Icing on a structure at sea requires a combination of water or moisture and surfaces above sea level at sub-freezing temperatures. There are two major types of icing: atmospheric and sea spray.

A.6.3.5.2 Atmospheric icing

Atmospheric icing is related to precipitation. Dry snow does not usually adhere to a surface and, by itself, it poses little hazard. The density of accumulated snow can be as low as 100 kg/m^3, while that of ice is around 900 kg/m^3. If sea spray or sleet dampens the snow, the wet snow freezes to the surface. The ice thus formed is porous, with low mechanical strength, and can usually be removed. In contrast, water that is super-cooled freezes solid on contact with a cold surface. Super-cooling in the atmosphere occurs when the liquid phase reaches temperatures below the freezing point. Super-cooled droplets exist in the form of frost smoke, super-cooled fog, or freezing rain and drizzle. These are the most common sources of atmospheric icing.

Opinions on the seriousness of atmospheric icing differ. Atmospheric icing can produce a uniform layer of ice on all surfaces over the height of the structure starting from a few metres above the waterline. Freezing rain can potentially cover only the upward or windward surfaces; for tubular members, it can be assumed that it covers half the circumference. By itself, atmospheric icing does not necessarily cause major structural consequences, though its operational consequences are severe. If atmospheric icing occurs at the same time as sea spray icing, it can accelerate the build-up of icing. The last phenomenon is called mixed icing.

Atmospheric icing is possible in arctic and cold region seas throughout the year. It normally occurs when air temperature is between 0 °C and –20 °C and wind speed is less than 10 m/s. As a result of atmospheric icing, the higher elevations of the structure can be covered with 10 mm to 20 mm of ice; in rare cases, up to 60 mm. For combined marine and mixed icing, ice thickness can reach 1 m in some cases.

Further guidance on atmospheric icing is provided in ISO 12494[A.6-4].

Ice accretion from freezing rain can be estimated by using theoretical models such as those described in Reference [A.6-5].

A.6.3.5.3 Marine icing

Marine icing caused by sea spray is the most frequent and most important form of icing in the sea. Another cause of marine icing is shipped water, which enters the deck of a vessel over the bow or sides. The latent heat content of this water, even if its temperature is near the freezing point, is sufficient to avoid freezing if it flows off the vessel quickly. This water, in addition, contributes to the melting and flushing away of ice that has already formed on deck. If the scuppers freeze or the railings are covered with ice, the water can be trapped and frozen. The probability of marine icing at height on a structure is dependent on extreme crest heights and sub-zero air temperatures.

Sea spray is formed in two ways. The most important with regard to icing is sea spray generated by the vessel or structure itself as it interacts with waves. The second form is created when the wind blows droplets of water off wave crests and depends on the form and steepness of the waves and wind speed. Sea spray icing begins to occur at wind speeds of 8 m/s to 10 m/s. The stronger the wind, the higher the spray is lifted. While the height of sea spray icing is usually limited to 15 m to 20 m above the sea surface, there have been reports of sea spray icing at up to 60 m above the sea surface.

Certain ranges of air temperature, water temperature and wind speed are required to cause a significant accumulation of superstructure icing. These conditions are

- an air temperature less than the freezing point of seawater (depending on the salinity of the water);
- a wind speed of 10 m/s or more;
- a seawater temperature colder than 8 °C.

A strong wind, cold air, and cold seawater all contribute to greater accumulations of ice. In arctic and cold region seas, icing can occur throughout the year. Icing is most likely at the end of autumn or in winter when air temperatures are below zero and there is no ice cover on the sea surface. Generally, from mid-winter to mid-summer, salt water icing is unlikely. From the end of summer to mid-winter, marine icing accounts for about half of all cases of icing; most of the remainder are mixed icing, simultaneous marine and atmospheric.

Icing can be classed by its intensity as slow, fast, or very fast. Broadly speaking,

a) slow icing (ice accumulation of less than 10 mm/h) occurs with air temperature between 0 °C and –3 °C and any wind speed, or with air temperature of –3 °C or lower and wind speed of less than 7 m/s;

b) fast icing (ice accumulation between 10 mm/h and 30 mm/h) occurs with air temperature between −3 °C and −8 °C and wind speed of 7 m/s to 15 m/s;

c) very fast icing (ice accumulation greater than 30 mm/h) occurs with air temperature at or below −8 °C and wind speed of more than 15 m/s.

The rate of ice thickness accumulation also depends on the structure and the height above water. The duration of the icing phenomenon exceeds 12 h in three quarters of reported cases; its maximum duration is seven days. During the period prior to freeze-up, the occurrence rate of slow icing is 20 % to 40 % in the coastal areas and 50 % to 70 % in the central parts of the arctic seas. The occurrence rate of fast icing ranges from 1 % to 5 % in the southern parts and up to 10 % in the northern parts of the arctic seas. These values increase by about 10 % in the latter part of this period. Icing can also accumulate through a series of independent icing events. Much depends on the degree of melt and loss of adhesion between events as well as possible countermeasures.

Methods for calculating marine icing are described in References [A.6-6] to [A.6-9].

A.6.3.5.4 Sources of data for atmospheric and marine icing

Information on ice accumulation can be obtained from climatic atlases, site measurements from rigs in the area, coastal stations and ships. Additional data help to define the site-specific hazard. Table A.6-1 provides an example set of data for a location off Norway.

Table A.6-1 — Icing for environmental action checks
(from Reference [A.6-10])

Height on structure above sea level m	**Action case 1**			**Action case 2**	
	Sea spray icing			**Ice caused by rain snow**	
	Thickness for 56 °N **to** 68 °N mm	**Thickness for** > 68 °N mm	**Density** kg/m³	**Thickness** mm	**Density** kg/m³
5 to 10	80	150	850	10	900
10 to 25	Linear from 80 to 0	Linear from 150 to 0	Linear from 850 to 500	10	900
> 25	0	0	500	10	900

An analysis of 3 000 vessel icing events[A.6-11] showed that 86 % of the time, ocean spray icing was the sole cause of ice accretion. Spray combined with fog, rain or drizzle accounted for 6,4 % of the occurrences; spray combined with snow accounted for only 1,1 % of the occurrences; and fog, rain or drizzle accounted for only 2,7 %.

Figure 19 of Reference [A.6-1] provides a nomogram that relates the rate of “fishing” vessel superstructure icing to the above meteorological and oceanographic parameters. As ice accretion reduces less with elevation, and the nomogram is based on vessel data, use of this nomogram for elevations associated with offshore facilities can be non-conservative because fishing vessels tend to avoid the worst environmental conditions.

A.6.3.6 Visibility

No additional guidance is offered.

A.6.3.7 Polar lows

Polar lows form when cold air flowing over warmer water creates an atmospheric instability that can grow such that small low pressure centres of up to a few hundred kilometres in diameter are generated. This phenomenon is found mainly in the European sector of the sub-arctic and arctic.

Most of the polar lows affecting Norwegian and Russian waters originate in the regions south of Svalbard and east of Jan Mayen and move eastward into the Barents Sea. Their frequency decreases from west to east in the Barents Sea. Polar lows originating in the Iceland-Greenland region mostly affect Scotland and the North Sea. Polar lows are most frequent from October through March, during which period, on average, five to ten polar lows occur.

The importance of polar lows lies in how they develop, their intensity and speed of propagation and how these effects can influence operations. They are seldom registered by the ground observation network due to their scarcity and their small size, and hence are difficult to forecast. Satellite remote sensing has, therefore, become the most important tool to detect polar lows, and the ability to forecast their occurrence has improved.

When a polar low moves, it grows in size. The problems of prediction are most difficult in the far north and improve with increasing southerly latitude. If a polar low moves towards the south, it normally maintains its intensity and can finally reach sufficient size that it can be observed and predicted. Polar lows move southward with the speed of the wind at high altitude, with some reduction caused by friction at the surface. Typical speeds of propagation range from 5 m/s to 12 m/s.

Field measurements and studies of wind and waves during polar lows for the Barents Sea region show that the strongest observed wind is 35 m/s and the highest observed significant wave height is 10,5 m. Although neither of these values is at the design level, the impact of polar lows on operations should be taken into account. In some cases, the winds and the sea state can grow equally fast because the polar low can move at a speed comparable to that of the group velocity of the dominant waves. Waves close to being fully developed can, therefore, appear approximately simultaneously with the onset of strong winds; see ISO 19901-1.

A typical duration for a polar low is 1 h to 6 h, after which the weather conditions generally improve, although the temperature is usually somewhat lower than prior to the onset of the polar low.

The frequency and occurrence of polar lows can be influenced by the present warming arctic climate. When considering these parameters, potential allowance should be made for a changing climate.

A.6.4 Oceanography

A.6.4.1 Water depth

No additional guidance is offered.

A.6.4.2 Waves

A.6.4.2.1 General

Wave generation in ice covered seas is reduced relative to that in open water since the ice cover limits the available fetch. Locations of ice edges and ice concentration should be considered when performing a wave hindcast study or wave forecasting. A practical approach to wave generation is to cut off further wave growth when the ice cover concentration exceeds a certain value, such as 50 %.

Wave propagation is reduced when waves travel into ice covered regions. In addition, waves are attenuated as they move through an ice covered region. The amount of attenuation is a factor of wavelength, ice concentration, ice floe size and distance travelled through the ice. Studies have been performed to investigate wave propagation in ice covered channels[A.6-12]. Actual measurements of wave propagation through an ice field[A.6-13] to [A.6-17] have shown that after travelling through thin and medium first-year ice for over 300 km, waves with amplitudes greater than 1 m can still be observed, although the average amplitudes are much less.

In sea ice, internal waves have caused surface waves with periods up to 30 min and a phase velocity of 2 m/s[A.6-18].

Theoretical models for wave attenuation in ice covered seas are provided in References [A.6-19] and [A.6-20]. Recent reviews[A.6-21], [A.6-22] update the information known about wave interaction in sea ice.

A.6.4.2.2 Wave-induced break up of ice

The global geophysical role of wave-ice interaction has two aspects: the physical effects of waves on the ice cover and the use of waves as a diagnostic tool in ice mechanics. The physical effects include the ability of waves to break up ice sheets into floes and to herd these floes into patterns that determine the morphology of the marginal ice zone (MIZ), the break-up of tabular icebergs, the calving of ice tongues, and the generation of ambient noise. The diagnostic role stems from the long-range propagation of wave energy in the form of flexural-gravity waves through ice sheets, and the information that the dispersion relation and attenuation rates provide about ice properties and mechanics.

As waves move into the MIZ, they cause drifting ice sheets to experience an increasing degree of flexure. Eventually the flexure causes the ice to break up into fragments, which themselves break again until a distribution of floe sizes is established with the smallest floes in the steepest wave field at the extreme ice edge. The floes thus created act as a shield for the interior pack, selectively damping out the shorter-period waves. If the ice field is an open one so that the floes do not collide, the wave attenuation process can best be described by a scattering model[A.6-14], [A.6-22], [A.6-23]. As soon as the pack tightens up, floe collisions occur and the pack begins to behave hydrodynamically either as a collection of very large floes or as a single entity. Since the floes can no longer surge in response to the waves, energy attenuation can occur more significantly in the form of viscous losses from the boundary layer under the ice.

Once the waves have crossed the MIZ and reached the interior of the pack ice or a landfast ice boundary, further propagation can be considered as a flexural-gravity wave with altered dispersion, which can then be effective in breaking up the interior ice sheets.

The most extensive measurements of wave decay across floe fields in the MIZ have been described in References [A.6-14] and [A.6-15]. The main conclusions from the observations are as follows.

a) The attenuation of waves with distance into the pack takes a negative exponential form, with an attenuation coefficient that decreases with increasing wave period over most of the spectral range. In heavy compact ice (e.g. East Greenland) the energy attenuation coefficient typically varies from $2 \times 10^{-4}\ \text{m}^{-1}$ for the longest swell to $8 \times 10^{-4}\ \text{m}^{-1}$ for 8 s to 9 s waves, corresponding to e-folding distances of 5 km to 1,2 km (distances over which attenuation is $1/e$).

b) There is some evidence of a “roll-over” at the shortest periods (less than 6 s to 8 s), where the decay rate can actually start to diminish as the wave period shortens.

c) The directional spectrum increases in spread inside the ice field until it is essentially isotropic within a few kilometres of the edge.

d) Some waves are reflected from the outer edge of the ice field by only a few percent, even when the edge is compact.

The general problem of ice break-up by waves is addressed in References [A.6-24] and [A.6-25], and the theory has also been applied to the break-up of tabular icebergs[A.6-26]. Reference [A.6-27] describes a mathematical model for the evolution of floe size distribution with time, given a specified break-up rate.

A number of mechanisms have been proposed for the way in which very large floes are broken up by waves. The simplest approach is to consider standing waves[A.6-28], [A.6-29]. A second mechanism, wind-induced tilt[A.6-30], occurs when a wind blowing over a large ice sheet causes the downwind end of the sheet to tilt downwards. Periodic cracking of the ice can relieve bending stresses due to the tilt. Break-up can also be influenced by the gradual weakening of the sea ice that occurs through the process of fatigue induced by the unremitting action of the ocean waves[A.6-31].

A phenomenon that can affect coastal facilities, man-made islands and structures with low freeboard is called an “ice storm”. The event, which occurs when high onshore winds occur with low ice concentrations offshore, causes ice pieces to be thrown onto the shore. Such events have been reported in Norton Sound, Beaufort Sea and along the Russian Northern Sea Route.

A.6.4.3 Ocean currents

Ocean current information plays an important role in the prediction of ice movement and pressure. In regions of high tidal currents with dominant directions, the period when the tide changes from one direction to another can cause significant pressure within an ice field with a concentration of 9/10 to 10/10 as it tries to respond to the direction change.

NOTE The concentration represents the number of tenths of the total area under consideration that is covered by ice; e.g. 9/10 indicates that ice covers nine tenths of the considered area; see A.6.5.2.2.2.

For lower ice concentrations, this effect is minimized. For offshore operations in the Okhotsk Sea, this resulting pressure is sufficient to cause icebreakers with propulsion in the range of 10 MW to 12 MW to become “stuck” until the ice field pressure relaxes after its direction has changed.

In regions of high current velocities, the current affects not only the speed with which ice interacts with a structure but also the encounter frequency associated with various ice features. Accurate estimates of the anticipated current speed are, therefore, important.

A.6.4.4 Other oceanographic factors

A.6.4.4.1 Marine growth

Ice interactions with structures remove marine growth. Complete cleaning to a depth equal to the tidal range plus the average ice floe thickness can be assumed with partial cleaning down to a depth equal to the tidal range plus the average ridge keel.

A.6.4.4.2 Tsunamis

In regions affected by the possibility of a tsunami, the potential for ice cover to reduce the tsunami wave height as it comes to shore can be taken into account.

A.6.4.4.3 Dissolved oxygen

No additional guidance is offered.

A.6.4.4.4 Water temperature and salinity

No additional guidance is offered.

A.6.5 Sea ice and icebergs

A.6.5.1 General

A.6.5.1.1 Nomenclature and modelling

The WMO sea ice nomenclature[A.6-32] should be used when describing sea ice and icebergs.

Statistical modelling from limited site-specific data sets is generally performed by Monte Carlo simulations where theoretical probability distributions are fitted to the data and then randomly sampled; see, for example, References [A.6-33] and [A.6-34].

A.6.5.1.2 Ice growth

Sea ice is a complex material that is composed of solid ice, brine, air and, depending upon the temperature, solid salts. Ice growth mechanisms can produce several different grain structures, depending on the prevailing conditions. The most common grain structures include granular, frazil, columnar and discontinuous columnar. The details of the ice microstructure significantly influence the mechanical and physical properties of the ice. When the ice grows, it traps some of the salt that is present in the seawater. By the end of the ice season, first-year sea ice has a salinity in the range of 4 ‰ to 6 ‰. Ice found in brackish waters, such as the Caspian and Baltic Seas, has a salinity closer to zero. Multi-year ice also has a salinity near zero. The brine, air and solid salts are usually trapped at sub-grain boundaries between a mostly pure ice lattice. Because there are a number of salts within the ice, the phase relationship with temperature is multifarious; see, for example, Reference [A.6-35].

With the sea surface layer cooling to the freezing temperature, ice crystals form as a thin elastic layer. The thickness of this layer increases due to the difference between the heat fluxes to the atmosphere from ice and to ice from the sea. The upward heat flux through ice is proportional to ice heat conductivity and the temperature gradient, and the crystallization heat is proportional to the mass of ice formed. The heat balance equation characterizing the ratio between these fluxes at the ice-water boundary is presented in References [A.6-36] and [A.6-37]. Equation (A.6-1)[A.6-38] is an example of an empirical equation that takes into account the influence of the air temperature and the snow depth on the ice thickness growth:

$$h = -m + \left[\left(m + h_0 \right)^2 - 405 \sum T_\mathrm{a} \right]^{1/2} \qquad \text{(A.6-1)}$$

where

T_a is the mean daily air temperature at the meteorological shelter height, expressed in degrees Celsius;

m is an empirical coefficient that depends on the snow depth;

h_0 is ice thickness at the start of the period, expressed in metres;

h is ice thickness at the end of the period, expressed in metres.

The sum is taken over the number of days in the period.

Accumulated freezing degree days (C_FDD) for a winter is a means of characterizing the general severity of ice conditions. Degree-days for a given day represent the number of °C that the mean temperature is below a given base temperature, in this case the freezing point of water. The number of freezing degree days is summed to get the accumulated freezing degree days for a winter using Equation (A.6-2):

$$C_\mathrm{FDD} = \left| \sum \left(T_\mathrm{a} - T_\mathrm{b} \right) \right| \qquad \text{(A.6-2)}$$

where

T_a is the mean daily temperature, expressed in degrees Celsius;

T_b is the freezing point of water, equal to –1,8 °C for seawater of salinity 32 ‰, higher for seawater of lower salinity, expressed in degrees Celsius.

The summation is made over the number of days in the winter.

Only the days with an average temperature below the freezing temperature of seawater are used. Most national meteorological services can provide average and 20 year, 50 year or 100 year maxima for accumulated freezing degree days.

The maximum thickness of undisturbed level ice grown in a winter season can be inferred from Equation (A.6-3):

$$h = a\,C_{\mathrm{FDD}}{}^{b} \tag{A.6-3}$$

where

a is a site-specific constant that depends on local winds, currents and snow cover (see Reference [A.6-6] for typical Alaska values; values for other regions can be found in the literature from that region);

b is an exponent that can be estimated from data or assumed to be 0,5 for linear heat conduction according to the Stefan equation.

The maximum thermally grown level sea ice thicknesses are in the range of 2 m for the arctic region. The heat flux from the water has a significant influence on the ice thickness growth. When the heat flux through the water is equal to the flux through the ice, the ice growth stops. Increasing the convection layer thickness entrains underlying water that is typically warmer, thereby decreasing the ice growth rate. Increasing the salinity of the sub-ice water layer decreases the freezing temperature and, consequently, the growth rate. Spatial differences in the water density stratification and the resultant differences in the heat fluxes during the period of ice growth contribute to spatial non-uniformity of ice thickness[A.6-39].

A.6.5.1.3 Sea ice salinity

For level first-year sea ice, the salinity, S, is usually expressed as the fraction by mass of the salts contained in a unit mass. It is usually quoted as a ratio of grams per kilogram of seawater, that is, in parts per thousand by mass (‰ or ppt). In sea ice, there is usually some salinity variation with depth in the ice sheet. This depth dependence of the salinity changes throughout the winter as the salt within the ice migrates downward through the ice. While there can be marked salinity variations even within a small sample, the average salinity, expressed as parts per thousand by mass, of a cold, growing ice sheet is related to the ice thickness[A.6-40], [A.6-41] as given by Equation (A.6-4):

$$S = \begin{cases} 13{,}4 - 17{,}4h & \text{for } h \leqslant 0{,}34\ \text{m} \\ 8{,}0 - 1{,}62h & \text{for } h > 0{,}34\ \text{m} \end{cases} \tag{A.6-4}$$

where

h is the ice thickness, expressed in metres.

An alternative relationship can be found in Reference [A.6-42].

A.6.5.1.4 Brine volume and total porosity

Historically, sea ice properties have been analysed in terms of the brine volume, υ_{b}, in the ice. The brine volume represents the amount of liquid brine in the host ice matrix. The determination of the brine volume integrates the influence of both temperature and salinity. For sea ice, the brine volume can be estimated from Equation (A.6-5)[A.6-43] or from the alternative method; see, for example, Reference [A.6-44]:

$$v_{\mathrm{b}} = S\left(\frac{49{,}2}{|T_{\mathrm{i}}|} + 0{,}53\right) \tag{A.6-5}$$

where –22,9 °C $\leqslant T_{\mathrm{i}} \leqslant$ –0,5 °C.

The brine volume is usually quoted in terms of volume in parts per thousand by volume. Alternatively, it can be expressed as a volume fraction. A brine volume of 20 ‰ is equivalent to a brine volume fraction of 0,020.

Air is present in the ice and in certain instances, where brine drainage occurs, the air volume can be significant. For this reason, it is usually better to express the porosity of the ice as the total porosity, which is the sum of the relative brine volume and the relative air volume. Equations are given in Reference [A.6-44] to calculate the total porosity. To do this, an accurate value for the bulk ice density is required.

A.6.5.1.5 Ice decay and melting

Increasing air temperatures and solar radiation are the primary reasons for sea ice decay. When the ambient air temperature warms to approximately −10 °C, most of the salt within the ice has been converted from a solid to a liquid phase. For air temperatures above −10 °C, the brine pockets rapidly increase in size and interconnect to form “brine drainage channels” that promote desalination of the ice. The decrease in ice strength has been directly linked to the decay of sea ice[A.6-45].

The change in ice thickness during the warm period of the year occurs not only due to melting from the top, but also as a result of ice melting from the lower surface. This usually takes place at the edge of a floe or at a fracture where heated water forms. Empirical equations also exist for the calculation of the rate of melting from the bottom and top ice surfaces[A.6-39].

The melting of ice floes by wave action can play a major role in their decay near the ice edge and for grounded ice features in open water. Ice drift into warmer water also plays a role in the removal of ice in the summer.

A.6.5.2 Ice types

A.6.5.2.1 Stage of development

Ice types can be characterized as first-year, second-year, and multi-year sea ice, shelf ice and glacial ice. The term “multi-year ice” is sometimes used to include second-year ice.

The surface appearance of first-year sea ice changes as the ice gets thicker going from black-grey for new and young ice to white when thicker. The stages of development of first-year ice are categorized by the WMO as follows[A.6-32], [A.6-46]:

a) new (< 1 cm thick): sea ice found in small platelets or lumps, usually subdivided into frazil, grease ice, slush or shuga;

b) nilas (1 cm to 10 cm thick): a thin crust of floating ice that easily bends with the waves and swells and has a matt surface appearance;

c) young ice (10 cm to 30 cm thick), subdivided into

   — grey (10 cm to 15 cm thick), which often breaks under wave action,

   — grey-white (15 cm to 30 cm thick);

d) thin first-year ice (30 cm to 70 cm thick), is separated into

   — stage 1 (30 cm to 50 cm thick),

   — stage 2 (50 cm to 70 cm thick);

e) medium first-year ice (70 cm to 120 cm thick);

f) thick first-year ice (> 120 cm thick).

In some arctic regions, ice persists all summer and the freezing process restarts in the autumn. Ice that has survived one (summer) melt season is termed second-year ice. Generally, over the next winter, it becomes thicker than first-year ice. The WMO states that second-year ice normally does not exceed a thickness of

2,5 m. Second-year ice has a higher freeboard, i.e. stands higher out of the water, and has a smooth undulating surface. In summer and early autumn, it often has numerous bluish-green puddles of water on the surface.

Ice that has survived more than one (summer) melt season is termed multi-year ice. It has a very low salinity and is considerably stronger than first-year sea ice. Multi-year ice can be very thick and strong.

A.6.5.2.2 Concentration and form

Ice is also characterized according to its concentration. The concentration is expressed in tenths and describes the amount of the water surface covered by ice as a fraction of the entire area. The actual area in the denominator varies depending upon the viewpoint of the observer, i.e. from a ship, from an aircraft or viewing a satellite image.

Ice can also be characterized by its form and the WMO code uses ten categories to describe the horizontal dimension. The categories consist of the smallest forms (pancake, brash and ice cakes), floes (small, medium, big and vast), landfast ice, icebergs and uncertain.

Acceptable concentration definitions include the following:

a) ice free: no ice present;

b) open water: a large area of freely navigable water in which ice is present in concentrations less than 1/10;

c) drift ice/pack ice: term used in a wide sense to include any area of ice, other than landfast ice, no matter what form it takes, or how it is disposed; when concentrations are high, i.e. 7/10 or more, drift ice can be replaced by the term pack ice;

d) very open drift: ice in which the concentration is 1/10 to 3/10 and water dominates over ice;

e) open drift: ice in which the concentration is 4/10 to 6/10, with many leads and polynyas; floes are generally not in contact with one another;

f) close pack: ice in which the concentration is 7/10 to 8/10, composed of floes mostly in contact with one another;

g) very close pack: ice in which the concentration is 9/10 to less than 10/10;

h) compact ice: ice in which the concentration is 10/10 and no water is visible;

i) consolidated ice: ice in which the concentration is 10/10 and the floes are frozen together.

The following terms are used in ice messages and forecasts to describe the distribution of ice in a given area:

- ice cake: any relatively flat piece of ice less than 20 m across;
- ice openings: includes all forms of fractures and cracks;
- crack: any fracture of landfast ice, consolidated ice, or a single floe, which is followed by separation ranging from a few centimetres to several metres;
- strips: long, narrow area of drift ice, about 1 km or less in width, usually composed of small fragments detached from the main mass of ice, which run together under the influence of wind, swell or current;
- ice edge: demarcation at any given time between the open water and sea, lake or river ice whether landfast or drifting, which can be classified as either compacted or diffuse.

A.6.5.2.3 Icebergs

Glaciers and ice caps with access to open water can be found in many regions. As they are formed by snow falling and gradually being compressed into ice over many hundreds of years, they consist of freshwater ice. The extremely large (several tens of million tonnes) ice pieces that calve from a glacier are called icebergs. Smaller pieces are termed bergy bits and growlers. Iceberg sizes are classified according to waterline length as growlers (0 m to 5 m), bergy bits (5 m to 15 m), small (15 m to 60 m), medium (60 m to 120 m), large (120 m to 200 m) and very large (> 200 m) The average density of icebergs is generally in the range 850 kg/m^3 to 910 /m^3[A.6-47].

Icebergs can survive in the ocean for many years, either floating or grounded. Reference [A.6-32] provides an accepted iceberg shape terminology. Unfortunately, this shape terminology is not really useful for dealing with icebergs in offshore operations. An alternative shape terminology[A.6-23] has been modelled after Reference [A.6-48]. The distinction between tabular and non-tabular icebergs is useful from design and operational perspectives. Some wedge or dome-shaped icebergs can be more difficult to tow.

A.6.5.3 Ice morphology

A.6.5.3.1 General concepts

The density of ice is less than that of water; thus, ice is generally found floating. Some forms of non-floating ice like anchor ice, ice foot, stranded ice and grounded ice can also be found.

Anchor ice is submerged ice attached or anchored to the seabed. It is found in the shallow sub or intertidal zones when the air temperature is below the freezing point of water.

An ice foot is a narrow strip of ice that is frozen to the shore of an island or beach. In the context used here, it is formed when crushed ice remains frozen against an island or structure after an ice floe impact event has occurred.

Stranded ice is floating ice that is aground in shallow water.

Grounded ice refers to ice that is attached to or in contact with the seabed.

A.6.5.3.2 Level and pack (broken) ice

Level ice can be defined as sea ice with un-deformed upper and lower surfaces. Level ice normally has a granular top layer, a transition zone and then columnar grains through most of the remainder of the thickness of the ice sheet.

A subset of level ice (termed S2 and S3 in scientific terminology)[A.6-49] is classified according to the orientation of the c-axis (the axis of symmetry of the hexagonal lattice). The mechanical properties (flexural strength, compressive strength, Young's modulus, etc.) are influenced by the crystal structure of the ice and its c-axis orientation. If the ice cover has been rafted at an early stage of growth and then continues to grow, it is difficult to distinguish it from pure level ice without ice texture analysis. If the rafted layers are thin, < 10 cm, the rafted ice behaves for most practical purposes as pure level ice.

While the WMO does not recognize the term “broken ice”, it has gained acceptance within the industry as meaning pack ice or ice floes. Ice floes originate due to ice dynamics (i.e. the movement of ice caused by stresses resulting from thermal expansion, wind and currents), waves moving into an ice sheet, ice sheet interactions and ice sheets interacting with objects such as structures, ships, etc. Temperature variation can induce internal stresses in the ice cover and crack propagation can occur, breaking a sheet ice into ice floes.

A.6.5.3.3 Ridged and rafted ice (deformed ice)

The ice cover can deform when subjected to movement caused by external stresses on the ice sheet/floe and interactions with another ice sheet/floe. Two common deformation mechanisms are ridging (the interaction of two ice sheets/floes at their edges) and rafting (the submersion of one ice sheet/floe beneath another). In both cases, deformations are localized where ridging and rafting processes take place.

Ridges are often categorized into pressure ridges and shear ridges. Pressure ridges are in general curvilinear features, but can sometimes be found as straight lines. They are caused by one ice sheet/floe moving into another. They can exist as single features, with a triangular or trapezoidal keel and sail, but they are often found in larger ridge fields. Shear ridges tend to be straight features caused by one ice sheet/floe sliding along another's edge. A common feature of a shear ridge is a vertical side, both above and below the water, where the interaction took place. Shear ridges are often found at the boundary between landfast ice and the moving ice pack.

In general, ridges show a wide range of shapes and sizes. Keel depths up to 50 m and sail heights up to 12,8 m have been measured, but ridge keels deeper than 30 m are rare[A.6-50].

First-year ice ridges are porous features that consist of ice, water, air and snow. The above water part, called the sail, has pores filled with air and snow. The underwater part, called the keel, has pores filled with water and in some cases air pockets can exist. Second-year and multi-year ridges are generally composed of ice with a very low porosity. The keel depth to sail height ratio is an important parameter and is usually between 4 and 5 for first-year ridges and around 3 to 3,5 for second-year and multi-year ridges[A.6-51], [A.6-52].

A ridge keel is further separated into an upper refrozen layer called the consolidated layer and a lower unconsolidated part. The consolidated layer grows through the ridge lifetime as a function of the surrounding meteorological and oceanographic conditions, air and water temperature, snow depth and the velocity of the wind, and surrounding currents are of principal importance. There is no clear indication whether the mechanical properties are similar to or weaker than those of level ice. References on this topic include [A.6-53] through [A.6-59]. For first-year ridges, the ratio of the thickness of the consolidated layer to the level ice thickness that has grown in open water under the same temperatures to which the ridge was exposed is an important factor and is generally between 1,5 and 2. A consolidated layer thickness of 8,5 m has been measured in first-year ice in the Okhotsk Sea[A.6-60]. The distinction between the consolidated and unconsolidated parts of a keel is less clear for multi-year ridges, as it is possible that some can be consolidated all the way through the keel[A.6-61].

A.6.5.3.4 Hummocks and rubble fields

Ridges are linear features created by the interaction between ice sheets/floes. Hummocks are areal features and can be oval, rectangular or square in horizontal plane view. The WMO defines a hummock as “a hillock of broken ice which has been forced upwards by pressure” but does not include the areal aspect.

Hummocks and rubble fields can range in size from tens of metres to kilometres. These features can be found in all water depth ranges.

Another feature that distinguishes hummocks from ridges is their consolidation. As such, the term “hummock” is most applicable to multi-year ice, although the term can be used to describe deformed first-year ice that has consolidated over the course of the winter season.

Statistics on the physical dimensions of hummock type features (both first-year and multi-year) exist for the US Chukchi Sea[A.6-62], for offshore Russia regions[A.6-63], [A.6-64], for offshore Sakhalin Island[A.6-65], and for the Canadian Beaufort Sea[A.6-51].

A.6.5.3.5 Landfast ice

Landfast ice is a continuous, stable ice cover that is frozen to the shore or a grounded feature. The extent of landfast ice from shore depends upon the water depth, the local geography (i.e. islands, bays, shoals, etc.), and wind and water current speeds and can be from a few metres to several hundreds of kilometres. Landfast ice is normally composed of first-year ice, but multi-year landfast sea ice does exist in the northern Canadian arctic islands.

The boundary between landfast ice and pack ice is called the shear zone or transition zone. This zone consists of substantial ice deformation and consequently a high ridge density (defined as the number of ridges per unit length; e.g. per kilometre). When the ice within the shear zone moves, it is part of the pack ice, but when it freezes it becomes part of the landfast ice cover.

Pack ice is any ice cover that is not landfast. The parameters used to characterize it are ice concentration, the floe size distribution, ice velocity and the thickness distribution. One can also characterize ridge dimensions and frequency.

A.6.5.3.6 Icebergs

Where required for the specification of design criteria, quantitative representations for iceberg shape should be established. Typically, these involve interrelationships between easily measurable index dimensions (maximum waterline length, waterline width perpendicular to the length, maximum height and maximum draught), and their relationship with other parameters, such as metacentric height, waterline area, radii of gyration and block coefficient.

NOTE The block coefficient is the ratio of iceberg volume to the volume of a rectangular prism formed from the index dimensions.

A.6.5.3.7 Shelf ice

Shelf ice is ice whose origin is the floating portion of a glacier.

A.6.5.4 Ice movement

A.6.5.4.1 Processes

Under the influence of wind and current, ice can be very dynamic. Although ice drift speeds are generally less than 1 m/s, speeds of over 3 m/s have been observed in regions of high tidal currents, such as Cook Inlet, Alaska. Numerous publications are available that describe the factors that influence ice drift speed, i.e. surface and keel drag coefficients, horizontal areas, wind speed, current speed, etc. If actual measured ice drift data are not available, ice drift speed can be estimated by the use of algorithms adopted in computer simulation models, determination of ice feature encounter frequency, speed of ice impact, etc.

An important phenomenon that results from ice dynamics is ice pressure. Ice pressure is common in coastal regions when onshore winds cause ice to build up along a coast or when the wind or current direction changes rapidly. Changes due to tidal currents can be quite important in this respect. In either case, the ice cannot respond by changing its direction and internal stresses within the ice cover build up, causing ice pressure. The effect of ice pressure is to reduce the capability of a vessel to transit through the ice. In extreme cases, it has been known to cause ice floes to penetrate a vessel hull, causing it to sink. Offshore platforms are generally designed to higher local loads than those caused by ice pressure but a check should be performed.

Wind, waves and currents govern the drift of icebergs. Since most of the iceberg mass is under water, icebergs have a lower wind factor than sea ice, implying that the underlying current has a relatively greater effect on iceberg speed and direction [A.6-23].

A.6.5.4.2 Marginal ice zone

The region of the ice cover that lies close to the open ocean boundary is called the marginal ice zone (MIZ). In this region, the ice cover is broken up into floes by the flexural stress of waves and by the swell penetrating into the ice from the open sea. The width of the MIZ is defined as the depth of penetration to which waves can fracture ice to create floes; it is a function not only of ice thickness and mechanical properties, but also of the regional wave climatology and water depth. The wave spectrum is modified in shallow water to create shorter, steeper waves, which break floes into smaller fragments, but which do not penetrate as far into the ice as the longer, deep water waves.

If the wind is blowing towards the ice edge from the open sea, it compresses the MIZ and produces a compact ice field with a sharp outer boundary of small cakes and brash ice (fragments of broken floes). Atmospherically, an on-ice wind is often associated with warm moist air from the open sea being cooled over the ice so that compact ice margins are often difficult to observe from the air or from visible-range satellite; their structure is best revealed by synthetic aperture radar.

When the wind is blowing away from the edge, most of the MIZ becomes diffuse. The outermost edge, instead of just becoming an open ice field fading away into the open sea, takes on a new organization of its own, with a series of compact ice edge bands forming, separated by completely open water and lying with their long axes roughly perpendicular to the wind. In winter this opening up of the ice edge permits new ice to form in the open water areas, leading to enhanced brine rejection in the MIZ.

In northern oceans, a wind parallel to the ice edge (ice to the left looking downwind) creates an Ekman transport effect (due to the Coriolis force) in the ocean boundary layer that is directed away from the ice edge, resulting in an upwelling that can transport heat from deeper layers into the ice edge zone. A wind parallel to the ice edge (ice to the right looking downwind) interacts with the local ice breeze that is produced by the horizontal temperature gradient between warm air outside the ice edge and cooled air lying over the ice edge. The interaction can produce a surface front outside the ice edge; an example is a front with a temperature jump of 6 °C in 25 km, observed 100 km off the ice edge in the Barents Sea[A.6-66].

A.6.5.5 Ice properties

Guidance with respect to the mechanical properties of ice is provided in A.8.2.8.

A.6.5.6 Ice monitoring

No additional guidance is offered.

A.6.6 Seabed considerations

A.6.6.1 Earthquake

Examples of arctic and cold regions that are known to be seismically active include

- Cook Inlet;
- Okhotsk Sea and Tatar Strait;
- Sea of Japan;
- Bohai Sea;
- certain regions of offshore Canada.

A.6.6.2 Permafrost

No additional guidance is offered.

A.6.6.3 Ice gouge

Ice gouging or scouring (terms used synonymously in the literature) occurs when an ice keel moves while in contact with the sea floor. Ice features associated with gouging include

- first-year ridges within ice floes or in hummock fields driven by pack ice;
- multi-year ridges within ice floes;
- stamukhi being moved or destroyed by movements of the surrounding ice;
- icebergs or ice islands.

Ice gouge depths can range from a few centimetres to several metres, depending on the type of ice feature creating the gouge and the seabed soil type. Ice gouge depths can vary significantly within the footprint area of the gouge itself and also along the length of the gouge.

Ice gouges are generally linear features that can extend for a kilometre or more in length. In the following discussion, the term gouge is used for furrows or linear features, while the term pit is used for areal features. Pits are distinguished from gouges in that they have limited lateral extent, in the range of a few metres to tens of metres.

Generally, it is thought that ice gouges are created by upslope movements of ice keels in contact with the seabed. Downslope ice gouging has also been observed for ridge keels[A.6-67] and for icebergs, where pitch motions can occur during the gouging process. The significance of iceberg motions is also illustrated by the presence of chains of pits that have been seen in the seabed off Canada's Labrador coast[A.6-68]. Isolated pits in the seabed have been observed in various locations such as Canada's east coast[A.6-69] and the Caspian Sea.

Specific detailed knowledge regarding the gouging process is not generally available, and the number of direct observations that have been made in the field is quite limited. Knowledge of the gouging process is derived primarily from the impressions in existing seabeds or in ancient seabeds that are now exposed.

It is generally recognized that the ice-soil interaction process depends on the ice feature and type of interaction. In the Canadian Beaufort Sea, the available literature suggests that gouges are long, linear features with relatively consistent dimensions over their length and width, and perhaps some rise-up of the base of the gouge track. It is generally thought that these features were created by multi-year ridge keels[A.6-70]. Recent information obtained with a multi-beam echo-sounder, which provides a more complete record of the gouge, shows that local variations do occur in the gouge track. Reference [A.6-67] describes cases where the number of gouges within a multi-keeled gouge produced by a multi-year ridge keel varies along the gouge track. They attribute this to changes in ice drift direction, which can alter the orientation of the gouging keels, potentially causing them to be “shadowed” by one another.

Off Canada's east coast and off Greenland, where icebergs are the main ice gouging feature, other characteristic gouge marks have been observed. Deep pits have been observed in the seabed at the end of gouge tracks, where icebergs have ground themselves into the seabed or broken up. The same features have been observed for stamukhi. Isolated iceberg pits that are probably due to the break-up and impact with the seabed have also been observed. The depth of pits formed by icebergs can reach 10 m, with horizontal dimensions several times greater. Linear gouge tracks are occasionally found with periodic impressions in the seabed, likely the result of wave-excited pitch motions of marginally stable icebergs.

Surveys along gouge lengths of several kilometres in the Canadian Beaufort Sea have shown that the gouge track can be divided into well defined phases (increasing gouge depth without rise-up, increasing gouge depth with rise-up and constant gouge depth with rise-up), and that the base of the gouge can rise by several metres over the gouge[A.6-71], [A.6-67]. This can indicate that the ice keel is being uplifted along the gouge track or, alternatively, that the ice keel is being abraded or failing mechanically along the gouge track or perhaps a combination of the two.

A.6.6.4 Strudel scours

Rivers that discharge into arctic coastal waters can thaw well in advance of the bottomfast sea ice along the coast during the spring melt season. The river water flows onto the ice and spreads offshore, flooding substantial portions of the nearshore zone. Drainage occurs through discontinuities in the ice, which typically consist of tidal cracks, thermal cracks and seal breathing holes. In those instances where the drainage rate is high and the water depth relatively shallow (typically less than 7 m), substantial scouring of the sea bottom can occur.

Two types of strudel scours have been observed: circular and linear. Circular scours form beneath either circular drainage features or enlarged segments of crack drains. Linear scours form beneath crack drains.

In general, the distribution and severity of strudel scours are controlled by river discharge and the propagation and drainage of the flood water through discontinuities in the ice canopy.

A.7 Reliability and limit states design

A.7.1 Design philosophy

A.7.1.1 Governing principles

This International Standard aims to ensure the performance of arctic offshore structures through a design approach in which underlying reliability targets are reflected in the partial action factors associated with the various limit states. This International Standard allows the designer to treat individual causes separately and thereby meet overall targets in an approximate sense by applying individual action combinations and partial action factors.

Clause 7 applies provisions, performance-based where possible, for offshore structures in arctic and cold regions. While a degree of prescription has been provided to facilitate practical design, there is also the possibility for probabilistic evaluation of action combinations and factors in order to allow flexibility in the selection of safe, technically feasible and efficient design options.

It is possible that the reliability of a particular structure in some ice environments is not always consistent with the assumptions made during the calibration of the action factors presented in this International Standard. Therefore significant site-specific conditions should be assessed in the context of the state of knowledge relevant to the development of this International Standard. Also, when considering phases such as construction, transportation, installation and removal, it should be noted that the reliability targets and action factors have been explicitly derived for in-place, in-service conditions.

It is also prudent to consider the overall reliability of a structure in addition to whether the reliability associated with individual limit state provisions has been satisfied.

A.7.1.2 Life-safety categories

Three life-safety categories are defined.

a) S1 Manned non-evacuated

   The manned non-evacuated category refers to a platform that is continuously (or nearly continuously) occupied by persons accommodated and living thereon, and from which personnel evacuation prior to the design environmental event is either not intended or impractical.

   A platform is categorized as S1 manned non-evacuated unless the particular requirements for S2 or S3 apply throughout the design service life of the platform.

b) S2 Manned evacuated

The manned evacuated category refers to a platform that is normally manned except during a forecast design environmental event. A manned platform is categorized as a manned evacuated platform only if all of the following are met.

- Reliable forecast of a design environmental event is technically and operationally feasible and the weather between any such forecast and the occurrence of the design environmental event is not likely to inhibit an evacuation.
- Prior to a design environmental event, evacuation is planned.
- Sufficient time and resources exist to safely evacuate all personnel from the platform and all other platforms likely to require evacuation for the same storm.

c) S3 Unmanned

The unmanned category refers to a platform that is manned only for occasional inspection, maintenance, and modification visits. A platform is categorized as unmanned only if all of the following are met.

- Visits to the platform are undertaken for specific planned inspection, maintenance or modification operations on the platform itself.
- Visits are not expected to last more than 24 h during seasons when severe weather is expected to occur.
- All of the evacuation criteria for b) S2 manned evacuated platforms are met.
- A platform in this category can also be described as “not normally manned”.

It is recognized that life-safety category definitions include a degree of judgment. The category that applies to a structure should be determined by the owner of the structure prior to the design of a new structure and should be agreed by the regulator where applicable.

A.7.1.3 Consequence categories

Factors for consideration in determining the consequence category include

- life-safety of personnel on, or near, the platform brought in to react to any consequence of failure;
- damage to the environment;
- anticipated financial losses to the owner, the other operators and the industry in general.

There are three consequence categories.

a) C1 High consequence

The high consequence category refers to platforms with high production rates or large processing capability and/or those platforms that have the potential for well flow of either oil or sour gas in the event of platform failure. In addition, it includes platforms where the shut-in of the oil or sour gas production is not planned, or not practical, prior to the occurrence of the design event (such as areas with high seismic activity). Platforms that support trunk oil transport lines and/or storage facilities for intermittent oil shipment are also considered to be in the high consequence category.

Sour gas is generally defined as natural gas containing a proportion of at least 0,01 % to 1 % hydrogen sulfide. A volume fraction of hydrogen sulfide of 0,1 % or 1 000 ppm (parts per million) by volume is lethal immediately if breathed and is recommended as a reasonable definition for use in this International Standard.

A platform is categorized as C1 unless the particular requirements for C2 or C3 apply throughout the design service life of the platform.

b) C2 Medium consequence

The medium consequence category refers to platforms where production can be shut in during the design event. All of the following criteria apply.

- All wells that can flow on their own in the event of platform failure should contain fully functional, subsurface safety valves that are manufactured and tested in accordance with applicable specifications.
- Oil storage is limited to process inventory and “surge” tanks for pipeline transfer.
- Pipelines have limited hydrocarbon release potential, due to low volume, low pressure or effective check valves or line block valves.

c) C3 Low consequence

The low consequence category refers to minimal platforms where production can be shut in during the design event. These platforms can support production departing from the platform and low volume infield flowlines. All of the following criteria apply.

- All wells that can flow on their own in the event of platform failure should contain fully functional, subsurface safety valves, which are manufactured and tested in accordance with applicable specifications.
- Oil storage is limited to process inventory.
- Pipelines have limited hydrocarbon release potential, due to low volume, pressure, or effective check valves or line block valves.

It is recognized that consequence category definitions include a degree of judgment. The category that applies to a structure should be determined by the owner prior to the design of a new structure and approved by the regulator where applicable.

A.7.1.4 Exposure levels

By analogy to the evacuation of structures in the path of hurricanes in various parts of the world, the evacuation of an arctic offshore structure (and wells secured) can be planned in the case of a predictable extreme action or an abnormal ice event such as an approaching ice island. This can constitute an L2 exposure level design case. Berms and protection structures can potentially be designed as L3 if structures they protect retain their own integrity after the failure of the L3 structures.

When part of a structure is designated with a lesser exposure level (i.e. L2 or L3) than the rest of the structure, the first paragraph of 7.1.4 should be interpreted by replacing “structures” with “parts of structures”. When a component of a structure is designated with a lesser exposure level, the failure of the component should lead to impairment only of a part of the structure with an equivalent or higher exposure level.

A.7.1.5 Limit states

No additional guidance is offered.

A.7.1.6 Alternative design methods

No additional guidance is offered.

A.7.2 Limit states design method

A.7.2.1 Limit states

An important SLS for arctic offshore structures is the habitability during vibration response to dynamic excitation.

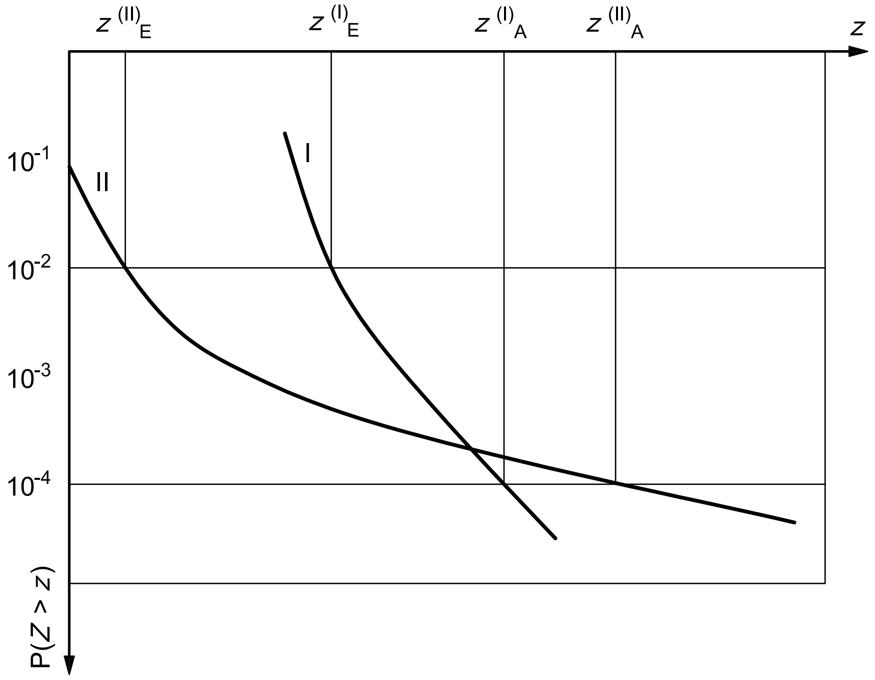
A.7.2.2 Actions

The concepts of “frequent environmental processes” and “rare environmental events” were introduced in other codes[A.7-1] to emphasize the distinction between frequent events (wind, storms, etc.) that have several peak values each year, and rare events such as iceberg collisions that occur only once every several years. The design values for such iceberg collisions can be calculated for annual exceedance probabilities of 10^{-2} and 10^{-4} per year, respectively, for L1 structures.

In this International Standard, the concepts of EL and AL events replace the concepts of “frequent process” and “rare events”. Note that these two sets of concepts are not equivalent.

Both EL and AL events should be calculated for all interaction scenarios, whether they are characterized by frequent environmental processes or rare environmental events. The present approach removes the somewhat arbitrary distinction between the frequencies associated with frequent processes and rare events.

As required in 7.2.2.3 and 7.2.2.4, the 10^{-2} ELIE and 10^{-4} (for L1) or 10^{-3} (for L2) ALIE characteristic action values are calculated for all events; the “rare” value can be close to zero for ELIE, but can dominate ALIE as shown in Figure A.7-1. Conversely, the frequent case can be dominant at the ELIE level. If there are insufficient data to calculate characteristic values, the representative values should be selected by expert judgment. Due account should be made for the differences in the consequences associated with ELIE and ALIE.



Key

z, Z	action
$P(Z > z)$	annual probability that action Z exceeds specified value z (annual probability of exceedance)
I	frequent events
II	rare events
z_E	ELIE action
z_A	ALIE action

Figure A.7-1 — Schematic illustration of ELIE and ALIE, for rare and frequent events

Earthquakes generally have small or insignificant values at the extreme level.

Potential examples of events for which only ALIE applies include iceberg and ice island impacts. If such events occur with an annual probability greater than 10^{-4} (for L1 structures), the ALIE action with an annual probability of exceedance of 10^{-4} can be estimated using the approach outlined in 8.2 and A.8.2.

To satisfy target reliabilities less than 10^{-4} in Table A.7-1 (i.e. for L1 structures), ice events with an annual probability of occurrence between 10^{-4} and 10^{-5} should also be considered. It is not possible to calculate a representative action with probability of exceedance of 10^{-4} for an ice event that has a probability or occurrence of less than 10^{-4}. In such cases, the ALIE design can be assessed using probabilistic methods or by considering nominal values of the action based on the ice events. The target can be achieved by the demonstration of adequate structural resistance, through operational procedures as discussed in 8.2.7, or using a combination of both. Similarly, ice events with an annual probability of occurrence between 10^{-3} and 10^{-4} should be considered for L2 structures with respect to the reliability target of 10^{-4}. However, the reliability target for L3 structures is such that the ALIE is not relevant.

Temperature gradients arising from functional requirements or environmental conditions can be an important action in the design of arctic offshore structures. These may be considered variable actions (Q) when determining action factors and action combinations.

A.7.2.3 Principal and companion environmental actions

Table 7-2 provides guidance on stochastically dependent, stochastically independent and mutually exclusive environmental processes. The first column in Table 7-2 indicates the principal EL or AL environmental action in a particular load combination. The second column shows the actions that are likely to have high or possibly extreme values at the same time as the principal actions in the first column. The third column indicates actions that are stochastically independent of the principal actions, but are not likely to occur at the same time. These should both be included in the action combination under consideration and a probabilistic analysis should be performed with statistical distributions of both the principal and appropriate companion values so that the resulting combined environmental action has the relevant annual probability of exceedance. The fourth column lists actions that should normally be excluded from the action combination with the principal action under consideration.

If a deterministic analysis is performed, then the representative extreme value of each relevant companion action should be factored by the relevant factor provided in Table 7-3 and then combined with the representative extreme or abnormal value of the principal action. The resulting combined environmental action is then used in the action combinations specified in Table 7-4.

The values specified in Table 7-3 are derived from a calibration analysis (see A.7.2.4) so as to be conservative to account for a wide variety of possibilities. For the design of arctic offshore structures, a full probabilistic calculation for companion actions is preferred.

A.7.2.4 Combinations of actions and partial action factors

The action factors for permanent and variable actions presented in Table 7-4 are based on ISO 19902 for fixed steel structures. For fixed concrete structures and for floating structures, ISO 19903 and ISO 19904-1 present different and sometimes lower values of these action factors. Therefore, if using ISO 19902, ISO 19903 and ISO 19904-1 for the respective structure types, the use of their action factors for permanent and variable, but not for environmental, actions is permitted. The calibration analysis for this International Standard demonstrates that the action factor required for environmental actions for arctic offshore structures is not sensitive to small changes in the gravity action factors.

The action factors are specified to be not less than the values in Table 7-4 (or in the structure-specific International Standards, if used) because larger factors can be used if greater reliability is required. In the case of action factors less than unity in Table 7-4 for overturning, uplift and action reversal, lower action factors can provide greater reliability.

Thermal contraction and gravity combinations are defined in ISO 19900. Moving actions can be considered as variable actions.

An action factor of 1,2 for permanent hydrostatic pressure and for physically limited variable actions can be used because of the very low uncertainty in the maximum values of these actions. An example of a physically limited variable action is the contents of a tank for which the variable weight cannot exceed that determined by the maximum volume of the tank.

Action factors have not been included for the L3 exposure level in Table 7-4. Although their specification is usually at the discretion of the owner and subject to national approval processes, some guidance on general values is provided in Reference [A.7-2].

This International Standard allows a user to perform a calibration of action factors for use in place of the action factors presented in Table 7-4, to the reliability targets presented in Table A.7-1, for all exposure levels. This can be necessary due to particular aspects of the physical environment, of the structure type, of the ice-structure interaction scenarios and of other factors such as ice management if these are an integral part of the system design. A methodology for such a calibration is presented in Reference [A.7-2]. The results of such a calibration can be values of action factors that are less than or are greater than the values in Table 7-4. In such a calibration, due account should be made of the relevant resistance factors, as specified in ISO 19902 and ISO 19903, as well as in other International Standards for offshore structures.

Table A.7-1 — Reliability targets for each limit state action combination

Exposure level	Reliability target expressed as annual failure probability
L1	$1{,}0 \times 10^{-5}$
L2	$1{,}0 \times 10^{-4}$
L3	$1{,}0 \times 10^{-3}$

The targets in Table A.7-1 are for single causes, i.e. for each action combination, and apply to both global effects such as overturning and local effects.

The action factors in this International Standard were calibrated according to Reference [A.7-2]. The calibration accounts for weighted combinations of all action effects over all design equations and load combinations, for different resistance models, for different levels of action effect model uncertainties, for different levels of statistical uncertainty, and for different mean action event occurrence rates. The methodology involves a weighted optimization process with the objective function minimizing the deviation from L1, L2 and L3 targets, with checks that upper bound failure probability constraints are not violated. For L1 structures, a target annual failure probability of 10^{-5} was applied as per Table A.7-1, and a constraint was applied to ensure that no limit state annual failure probability exceeded 10^{-4}.

The reliability targets in Table A.7-1 take cognizance of both human safety and environmental protection through the exposure levels L1, L2 and L3. If either the safety class is S1 (manned non-evacuated) or the consequence class is C1 (high environmental consequence), the exposure level is L1 and the greatest reliability applies. Similarly, if the safety class is S3 (unmanned) and the consequence class is C3 (low environmental consequence), the exposure level is L3. Other circumstances are covered by the intermediate exposure level, L2. It is emphasized that the targets in Table A.7-1 are for single causes, intended to be the governing one or ones. It should be noted that the reliability targets do not include operational risks such as transportation to and from the installation. Seismic risk is addressed separately, by reference to ISO 19901-2.

For exposure level L1, a manned installation for which evacuation or shutdown is not planned in the face of extreme or abnormal situations for which it is designed, as distinct from being disconnected in the face of situations for which it is not designed, the reliability target can be considered as being approximately the worst case individual risk to life-safety for each person on the installation, as well as significant environmental damage, for one specific limit state or failure cause. Background to the value of the reliability target associated with exposure level L1 is provided in Reference [A.7-3].

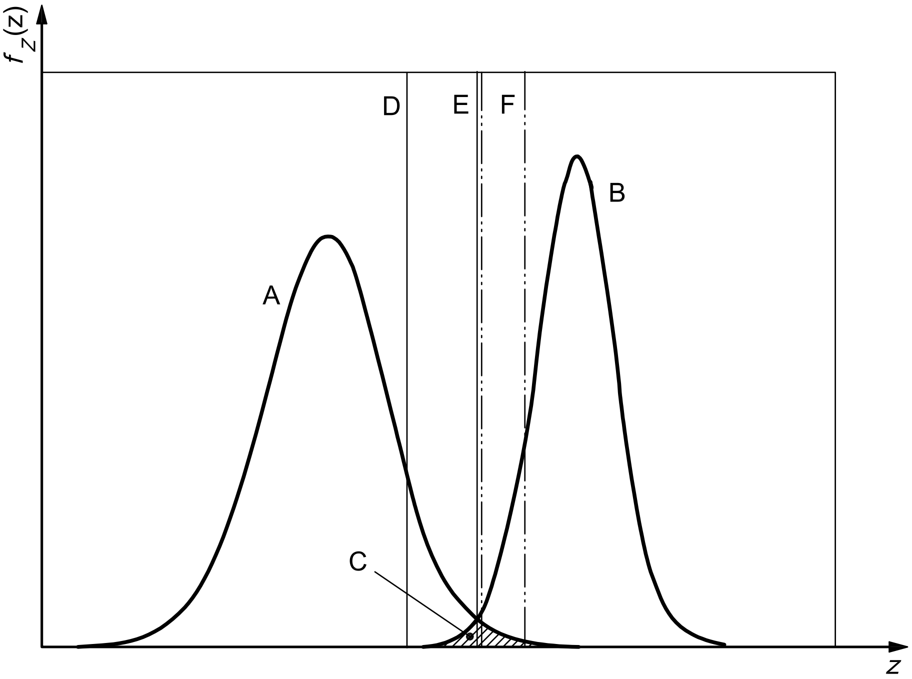
Values of reliability targets have been quantified in CAN/CSA S471 for arctic and other offshore structures, Reference [A.7-1], since its publication in 1992. The "annual reliability target level" of $1 - 10^{-5}$ for CAN/CSA S471 "Safety Class 1", equivalent to ISO 19906 "exposure level L1", served as a basis for the 10^{-5} target annual failure probability used for calibrating the L1 action factors in this International Standard. CAN/CSA S471 has been applied successfully in offshore projects subject to ice actions, such as Terra Nova and White Rose on the Grand Banks off Canada's east coast.

For the lower exposure levels L2 and L3, the annual failure probability target is increased to compensate for the reduced exposure of personnel and to the environment. For exposure level L2, it is reasoned that such exposure can be roughly 10 % of that for L1, on the basis that a precautionary evacuation and shutdown is 90 % likely to occur without casualties or damage, so that the target annual failure probability can be increased to 10^{-4}. Similarly for L3, a further tenfold reduction in exposure is considered appropriate, giving an annual failure probability target of 10^{-3}. This value for ISO 19906 "exposure level L3" is consistent with the "annual reliability target level" of $1 - 10^{-3}$ for CAN/CSA S471 "Safety Class 2".

In view of the track record of successful application of these reliability targets for actual designs, an attempt at greater accuracy has been avoided as an overly precise definition involving smaller subdivisions of orders of magnitude of the probabilities is not considered justifiable. The resulting calibrated action factors are consistent with the other International Standards for offshore structures.

A.7.2.5 ULS and ALS design

For the limit state approach, the total design action effect in a limit state is derived from an analysis of appropriate combinations of the factored representative values of the actions. Representative values should be derived as characteristic values from a probabilistic description of the action, but otherwise can be a nominal value. "Nominal" refers to values of a basic variable determined on a non-statistical basis, typically from acquired experience or physical conditions. Similarly, the characteristic resistances are factored to obtain the design of resistances (for ULS) or are assessed in a wider context (for ALS). The total design action effect should not exceed the design resistance (see Figure A.7-2).



Key

z	action or resistance	C	domain of possible failure
$f_Z(z)$	probability density function	D	representative (characteristic) action
A	action	E	design value: factored action and resistance
B	resistance	F	characteristic resistance

Figure A.7-2 — Schematic showing calculation of design values from representative action and characteristic resistance

Many aspects of modelling actions and resistances can be uncertain, including basic assumptions, incomplete or simplified mathematical/mechanical models, idealizations and the use of insufficiently tested or calibrated variables. A typical example is the assumption of an ice pressure versus area relationship for a specific structure at a specific site, an assumption that, in principle, can only be verified by a dedicated series of full-scale ice-load measurements. While it is generally agreed that these uncertainties should be accounted for in the formulation of design criteria and, by extension, in the calibration of action factors, good practice is for the designer-analyst to adopt a "cautious" deterministic approach using appropriately conservative assumptions; see Reference [A.7-3].

The use of the limit states design method, with its corresponding factors, is intended to achieve an acceptable reliability level in the design, but the method itself does not allow a quantification of that level. While the achieved reliability can vary from one design situation to another, the individual factors are optimized so that deviations from the target reliabilities over a number of situations are minimized. A calibration makes use of a full probabilistic approach whereby the probability of non-performance in each limit state is calculated specifically. The advantage of the factored action and resistance approach is that, because of the optimization of factors achieved by weighting the results for each design situation, the achieved reliability levels are close to the intended targets and show a narrower variation among different design situations, while maintaining practical simplicity.

Once calibrated, the factors are associated with a specific range of design situations, and the design situations are normally specified in a document such as a "basis of design". Partial factors can also be associated with combination of extreme actions to represent the reduced likelihood of the extreme of one action combining with the extreme of another (e.g. maximum ice actions occurring simultaneously with a strong earthquake). The factored action and resistance approach is also known by equivalent names: load and resistance factor design method (LRFD) or partial factor design method (PFD).

A.8 Actions and action effects

A.8.1 General

No additional guidance is offered.

A.8.2 Ice actions

A.8.2.1 General principles for calculating ice actions

The ice design process is illustrated in Figure A.8-1. A key issue is the identification of plausible interaction scenarios based on the structural design, the local ice conditions and the metocean environment.

A.8.2.2 Representative values of ice actions

A.8.2.2.1 Representative values

In this International Standard, representative ice actions are determined for ELIE (extreme-level ice event) and ALIE (abnormal-level ice event) with relevant annual exceedance probability levels, for each ice scenario under consideration and for all scenarios considered together.

Representative ice actions can be estimated using

- probabilistic methods, in which the joint probability distribution of the most important parameters is used to obtain ELIE and ALIE actions;
- deterministic methods, in which extreme (e.g. thickness, for sea ice) or abnormal (e.g. mass or kinetic energy, for icebergs) and nominal values (e.g. pressure) of ice parameters are combined to yield the ELIE and ALIE actions.

For definitions of “representative values”, “ELIE” and “ALIE”, reference should be made to Clause 3, 7.2.2.3 and 7.2.2.4. “Nominal” refers to values of a basic variable determined on a non-statistical basis, typically from acquired experience or physical conditions.

Regardless of the method, the objective is to estimate appropriate ELIE and ALIE actions. More effort is required for probabilistic methods, with the potential benefit of increased efficiency in the design. Where insufficient site-specific data are available for a particular interaction scenario, nominal values of the parameters may be used.

For each ice scenario under consideration, the ice action, Z, is the maximum of the individual actions V_j in a year as given in Equation (A.8-1):

$$Z = \max(V_1, V_2, ..., V_j, ...) \tag{A.8-1}$$

If no events take place in a particular year, Z should be set to zero. Each V_j and, consequently, Z is a function of n, generally random, contributing parameters, X_i, as given in Equation (A.8-2), which is called a load equation:

$$V = V(X_1, X_2, ..., X_i, ..., X_n) \tag{A.8-2}$$

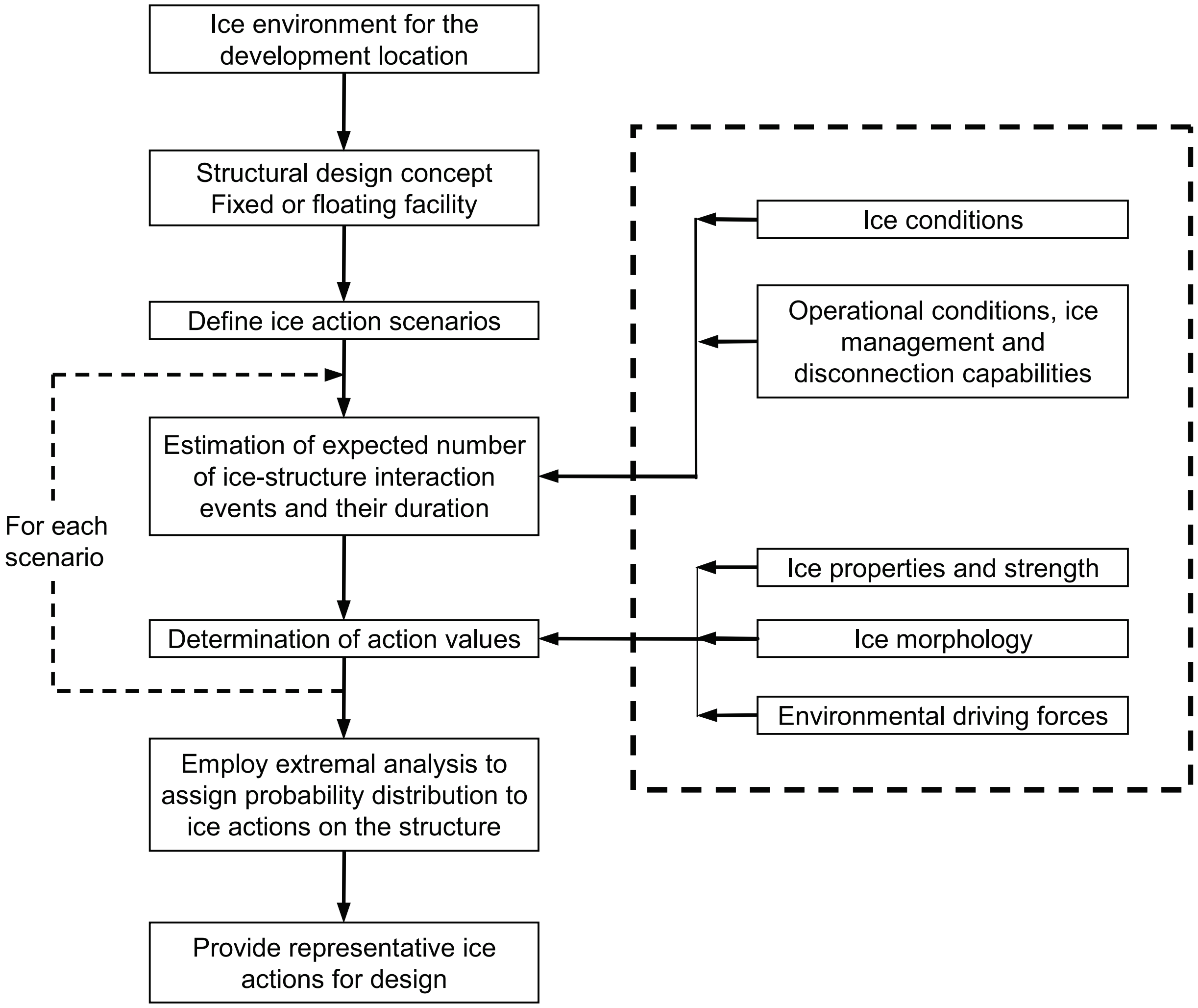


Figure A.8-1 — Flowchart of overall approach for calculating design ice actions

It is not necessary that the relationship between the individual action, V, and the contributing parameters, X_i, be an analytical expression, but it can consist of several relationships for mechanisms acting simultaneously against the structure and within the ice features.

While Z is typically the global horizontal action, it can be an overturning moment, a vertical action or a local action. For sea ice interactions, the parameters X_i can include ice thickness, floe sizes, drift velocity, interaction width, ice crushing pressure, and others. The parameters with the most significant effect on extreme values of the action, Z, are generally the ice thickness and ice strength, whether for level ice, rafted ice or the consolidated layer of a ridge.

A.8.2.2.2 Probabilistic approach

A.8.2.2.2.1 Analysis of individual interaction scenarios

In the probabilistic approach, the representative actions $z_{\mathrm{r,E}}$ and $z_{\mathrm{r,A}}$ are obtained from Equations (A.8-3) and (A.8-4):

$$\mathrm{P}\left(Z > z_{\mathrm{r,E}}\right) = 10^{-2} \tag{A.8-3}$$

$$\begin{aligned}\mathrm{P}\left(Z > z_{\mathrm{r,A}}\right) &= 10^{-4} \text{ (for L1 structures)}\\ &= 10^{-3} \text{ (for L2 structures)}\end{aligned} \tag{A.8-4}$$

where P is the probability.

These can be rewritten equivalently as given in Equations (A.8-5) and (A.8-6):

$$F_Z\left(z_{\mathrm{r,E}}\right) = 0{,}99 \tag{A.8-5}$$

$$\begin{aligned}F_Z\left(z_{\mathrm{r,A}}\right) &= 0{,}9999 \text{ (for L1 structures)}\\ &= 0{,}999 \text{ (for L2 structures)}\end{aligned} \tag{A.8-6}$$

where $F_Z(z)$ is the cumulative distribution function, c.d.f., of the annual maximum, Z.

In many situations, the annual maxima can be used directly to form the distribution of ice actions. If events such as ridge or iceberg impacts are used to define ice actions, then it is reasonable to connect the distribution of the annual maxima $F_Z(z)$ with the c.d.f. of the ice load, $F_V(v)$, reached during *one* event. The relationship between $F_Z(z)$ and $F_V(v)$ depends on the frequency of events and the characteristics of the ice interaction process. Using this relationship and the function $F_V(v)$, one can calculate the desired values $z_{\mathrm{r,E}}$ and $z_{\mathrm{r,A}}$ by solving Equations (A.8-5) and (A.8-6) analytically or numerically. Further discussion on the relationship between individual events, annual maxima and extremes is provided in Reference [A.8-1].

The number of ice events within a given period can often be considered as a Poisson process. For the distribution of annual maxima, the Poisson distribution with arrival rate $\eta[1 - F_V(z)]$ and Poisson parameter $n = 0$ (corresponding to an absence of events in the reference period)[A.8-1] yields the relationship between $F_Z(z)$ and $F_V(v)$ as given in Equation (A.8-7):

$$F_Z\left(z\right) = \exp\left\{-\eta\left[1 - F_V\left(z\right)\right]\right\} \tag{A.8-7}$$

where η is the average annual encounter frequency (see A.8.2.2.5). Equation (A.8-7) is valid for arbitrary values of η, whether large, e.g. of order of thousands for ridges, or small, e.g. of order of 10^{-3} for icebergs.

Due to small values of exceedance levels involved in Equations (A.8-3) and (A.8-4), Equation (A.8-7) yields the approximate relationship given in Equation (A.8-8):

$$F_V\left(z_{\mathrm{r},\alpha}\right) \approx 1-\alpha/\eta \tag{A.8-8}$$

where $z_{\mathrm{r},\alpha}$ is the representative ice action corresponding to an exceedance level α, for ELIE and ALIE. The approximation in Equation (A.8-8) is valid for $\alpha \leqslant 10^{-2}$.

NOTE Equation (A.8-8) does not apply for $\alpha/\eta > 1$, when impact events are very rare and η is small. In this case, the representative ice action corresponding to the exceedance level α is equal to zero. For instance, if the impact frequency of icebergs is $\eta = 10^{-3}$, then one can determine the ALIE representative value ($\alpha = 10^{-4}$, L1 structures), while the ELIE representative value ($\alpha = 10^{-2}$) is zero.

Events can be associated with discrete iceberg, ridge or floe scenarios, they can be associated with a particular mechanism or ice regime, or they can reflect monthly or seasonal maxima.

The distribution of ice actions, $F_V(v)$, should reflect the joint distribution of the parameters X_j. In most circumstances, distributions for all of the parameters are not necessary for calculating representative values of ice action. Some parameters have a small variability and do not have a significant influence on the representative actions, or do not have a large influence in the functional relationships associated with the ice action. This gives rise to widely used semi-probabilistic approaches, in which a probabilistic treatment of actions is performed on a reduced set of parameters by expressing the load Equation (A.8-2) as given in Equation (A.8-9):

$$V = V(X_1, X_2, ..., X_j, X_{j+1,\mathrm{N}}, ..., X_{n,\mathrm{N}}) \tag{A.8-9}$$

where the joint distribution of the main contributing parameters 1, ..., j is considered, while single nominal values for $j+1$, ..., n are used for the remaining ones.

Generally, the main parameters should be characterized such that their combination does not lead to overly conservative or unconservative estimates of representative ice actions. Proper attention should be drawn to the tails of the distributions in question since they have a strong effect on ice loads at small exceedance levels.

When nominal values are used, care should be exercised to ensure that the resulting action approximates the ELIE or ALIE level, as required. To ensure this, nominal values should represent the most likely ones associated with the representative actions. For example, if the ice geometry and interaction scenario are modelled probabilistically, a nominal value for ice pressure should reflect the contact areas, aspect ratios and interaction velocities associated with the representative actions.

A.8.2.2.2.2 Combining different scenarios

For m ice load scenarios in a given time period, say a year, it is necessary to consider a set of loads corresponding to the m scenarios, say Y_1, Y_2, ..., Y_m. The designer is concerned with the maximum of these as given in Equation (A.8-10):

$$Z = \max(Y_1, Y_2, ..., Y_i, ..., Y_m) \tag{A.8-10}$$

If the individual cumulative distributions are F_1, F_2, ..., F_m, and if it is judged that the loads are stochastically independent[A.8-1], then Equation (A.8-11) applies:

$$\begin{aligned} F_Z(z) &= \mathrm{P}(\text{all } Y_i \leqslant z) \\ &= F_1(z) \cdot F_2(z) \cdot ... \cdot F_m(z) \end{aligned} \tag{A.8-11}$$

A.8.2.2.3 Deterministic approach

Deterministic approaches differ from probabilistic methods in that they deal not with distributions of actions, but only with distributions of selected parameters. Such approaches can be used for preliminary design of L1 and L2 structures and for the final design of L3 structures in arctic and cold regions. In deterministic approaches, the representative ELIE or ALIE ice action is generally estimated based on extreme-level or abnormal-level parameter values $X_{1,\mathrm{E}}$ and $X_{1,\mathrm{A}}$, respectively, for the most important parameter (such as ice pressure or thickness) and nominal parameter values, $X_{j,\mathrm{N}}$, for the remaining parameters. Representative action values for relevant interaction scenarios Y_i are obtained from equations of Equation (A.8-12):

$$y_{\mathrm{r}i,\mathrm{E}} \text{ or } y_{\mathrm{r}i,\mathrm{A}} = Y_i\left(X_{1,\mathrm{E}} \text{ or } X_{1,\mathrm{A}}, X_{2,\mathrm{N}}, ..., X_{j,\mathrm{N}}, ..., X_{n,\mathrm{N}}\right) \tag{A.8-12}$$

and the representative values of the ice action are approximated by $z_{\mathrm{r,E}}$ or $z_{\mathrm{r,A}}$ which is equal to $\max\{y_{\mathrm{r1,E}}, y_{\mathrm{r2,E}}, \ldots, y_{\mathrm{r}m,\mathrm{E}}\}$, or $\max\{y_{\mathrm{r1,A}}, y_{\mathrm{r2,A}}, \ldots, y_{\mathrm{r}m,\mathrm{A}}\}$,where E refers to ELIE (i.e. $X_{1,\mathrm{E}}$) and A refers to ALIE (i.e. $X_{1,\mathrm{A}}$).

Nominal values of the parameters, $X_{j,\mathrm{N}}$, should generally be selected to result in conservative values of the actions. To ensure this, the nominal value of each parameter should be a conservative upper bound where it contributes to increase the ice action and a lower bound where it decreases the action.

A commonly employed deterministic approach involves the use of the ELIE sea ice thickness combined with a nominal global pressure for ice crushing. In this case, the ice pressure is not necessarily specified at the extreme-level since this can result in overly conservative actions or be impractical to determine with any accuracy. Nevertheless, the ice pressure should reflect the highest value associated with the ELIE ice thickness. For many level ice interactions annually, the maximum global ice pressure expected in a year is an appropriate nominal value. If only a few interactions occur annually, a lower value can be used. The combination of all parameters at the extreme or abnormal level can produce conservative estimates of actions.

In A.8.2.4.3, A.8.2.4.4 and A.8.2.4.5, the parameters related to ice properties recommended in the text are intended to be used in conjunction with the 10^{-2} annual probability of exceedance (100 year) ice thickness for the ELIE unless stated otherwise.

A.8.2.2.4 Monte Carlo simulation

Because of the complexity of ice action calculations, Monte Carlo simulation methods are generally used in practice. It is appropriate to use different input parameters or distributions for different times within the ice season when sufficient data exist. Allowances for correlations between the different input quantities should be used if they can be established. Sampling can be carried out directly from the distributions or by discretizing the distribution into bins. When using bins, one should ensure that the tails of the distributions are modelled accurately. Specialized methods such as importance sampling can be used.

The number of realizations required for a Monte Carlo simulation depends on the rate at which the event occurs (η, in A.8.2.2.5), the number of parameters in the load equation, Equation (A.8-2), the correlation between the parameters and the annual probability level required. The number of realizations can be estimated from Equation (A.8-13):

$$n_{\mathrm{r}} = q\left(n_{\mathrm{p}}\right)\eta/\alpha \tag{A.8-13}$$

where

$q(n_{\mathrm{p}})$ is a function of the number of parameters for which distributions are specified in the calculation;

η is the annual frequency or rate of events;

α is the annual probability of exceedance (10^{-2} for ELIE and 10^{-4} for ALIE with L1 structures).

The function $q(n_\mathrm{p})$ should be determined, potentially by example, and the reliability of the estimate for the ELIE or ALIE value should be demonstrated. Generally, it is required that $q(n_\mathrm{p})$ be between 10 and 100.

A study is generally performed to investigate the sensitivity of the resulting ice action distribution to the input parameters or to bias in the physical models used. The sensitivity study should include varying the probability of the tails for the most important parameters.

A.8.2.2.5 Encounter frequency

A particular ice scenario can consist of a succession of discrete interactions, for example a series of interactions with ice ridges, areas of rafted ice, multi-year ice floes or icebergs. Scenarios that can be considered in terms of discrete events frequently represent the design condition for arctic offshore structures. The rate of interaction, η, can be determined by comparing the area of possible interaction swept out by the ice feature, taking into account the structure width, with the area of the region under consideration, as shown in Figure A.8-2. The rate of interactions per unit time can be calculated as given in Equation (A.8-14):

$$\eta = \rho_\mathrm{A}\left(\bar{D} + w\right)\bar{v} \tag{A.8-14}$$

where

ρ_A is the areal density of the ice features;

w is the width of the structure, or the average width if it is not circular;

$\bar{D}$ is the average width of the ice features expected in the region;

$\bar{v}$ is the average drift velocity (speed) over the region.

For iceberg interactions with structures having a cross-section that varies with depth, the average sum of the structure and ice feature width at the point of contact should be used.

For ice floes, where coverage is known, the areal density can be determined as given in Equation (A.8-15):

$$\rho_\mathrm{A} = \frac{C_\mathrm{N}}{\bar{A}} \tag{A.8-15}$$

where

$\bar{A}$ is the average floe area;

C_N is the fraction of the sea surface area that is covered by the ice floes.

If only the average floe diameter is known, the mean floe area can be calculated as given in Equation (A.8-16):

$$\bar{A} = \frac{\pi}{4}\left(\bar{D}^2 + \sigma_\mathrm{D}^2\right) \tag{A.8-16}$$

where

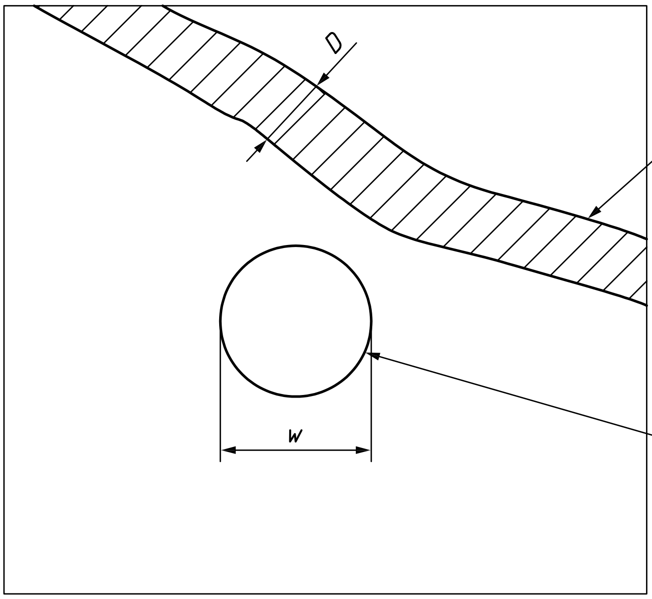
$\bar{D}$ is the average floe diameter;

σ_D is the standard deviation of the floe diameter.

For discrete ice features, the areal density is the average annual (or seasonal, as required) number of features per unit area. Measured areal densities should be corrected to remove spatial and temporal sampling biases where appropriate.

Average values of areal density and drift speed are used to obtain average interaction rates, for example in a month, a season or a year. Ice management and avoidance can be used to modify the interaction rates.

The drift speed is generally determined from measurements of ice movement. It is emphasized that the value used for the calculation of interaction rate should be the average over the region in which the structure is located. It should not be updated in accordance with A.8.2.2.6.



Key

A area swept out by ice feature

B structure

D width or diameter of the ice feature

w width of the structure

Figure A.8-2 — Geometric definitions for determining collision probability

A.8.2.2.6 Updating distributions for encounter

Generic distributions of ice feature size and velocity are those inferred from snapshots of a region over time. The region should be chosen to ensure that the size and velocity distributions are representative of the structure location.

For ice features with a given residence time, the larger ones and those moving faster are more likely to encounter a structure. The velocity distributions used for the encounter are updated from the generic distributions using Bayes' theorem by amending the probability density of velocity f_V to $f_{V|\mathrm{e}}$ as given in Equation (A.8-17):

$$f_{V|\mathrm{e}}(v) = \frac{v f_V(v)}{\int_{\mathrm{all}\,u} u f_V(u)\,\mathrm{d}u} \qquad \text{(A.8-17)}$$

where

e is the encounter or event;

v, V is the ice drift speed;

u is an integration parameter representing drift speed.

Equation (A.8-17) is simply a weighting of the velocity distribution (or histogram) by the velocity, in which larger weights are applied to higher velocities. The denominator is the average drift speed and scales the integral of the probability density function of drift speed to unity.

Regardless of the velocity field, the distribution of the horizontal dimension of the ice features in the region should be updated from f_D to $f_{D|\mathrm{e}}$ using the analogous expression as given in Equation (A.8-18):

$$f_{D|\mathrm{e}}(d) = \frac{(d+w) f_D(d)}{\int_{\mathrm{all}\ u} (u+w) f_D(u)\,\mathrm{d}u} \tag{A.8-18}$$

where

e is the encounter or event;

w is the width of the structure;

d, D is the width of the ice feature;

u is an integration parameter representing the width of the ice feature.

For certain data collection and analysis techniques, the distributions of drift speed and ice feature dimensions can already be updated and should not then be modified. An example is where impact parameters are obtained from drift simulations.

Distributions of drift speeds and ice feature dimensions should be updated only for the consideration of impact or interaction conditions. They should not be updated for the interaction rate calculations in Equations (A.8-14), (A.8-15) and (A.8-16).

A.8.2.2.7 Determination of probability distributions

The choice of parameter distributions is important, particularly when the distribution has a marked influence on extreme values for ice actions. The following should be considered.

- The choice of distribution should reflect the nature of the process, e.g. the draught of ice features should not exceed the water depth, while ice speeds and physical dimensions are strictly positive.
- Field data should be used and best estimates should be made for defining probability distributions of the random parameters.
- The simplest forms for distributions are often best, particularly where the quantity of data is limited.
- Sampling bias should be corrected, e.g. if small features are not sampled, a truncation limit should be specified for the distribution.
- The distributions should reflect uncertainties in the data. Special attention should be made for the tails of parameter distributions that are responsible for higher ice actions. Extrapolation to extreme or abnormal values from limited datasets can result in significant errors in ice actions and potentially lead to unsafe or overly conservative designs. Where direct measurements are insufficient, sound and defensible physical and mathematical reasoning should be made in the application of data from other geographical regions,

when merging available datasets and establishing correlations with other local parameters. The use of conservative deterministic values in such cases is a viable alternative.

- Average parameter values and distributions associated with the representative actions should be verified to ensure they are realistic physically and make sense in combination.

Seasonal variations should be considered for parameters influencing ice actions.

A.8.2.2.8 Ice action data

The guidelines that are provided in A.8.2.3 to A.8.2.6 are based on a large amount of full-scale data and observations that have been compiled between 1965 and 2007. Most expressions that are proposed in A.8.2 for ice action determination have been calibrated by using such data. Further full-scale data can be used to specify methods of determining ice actions, provided that the data are used for conditions that are similar to the conditions under which the data were collected.

A.8.2.3 Ice action scenarios

Ice actions are the result of interactions between various ice features and the structure. The shape and size of the structure, the ice conditions and the environmental driving actions can result in a number of different interaction scenarios, failure modes and resulting ice actions. The relationships among the factors that influence the scenarios are illustrated in Figure A.8-3.

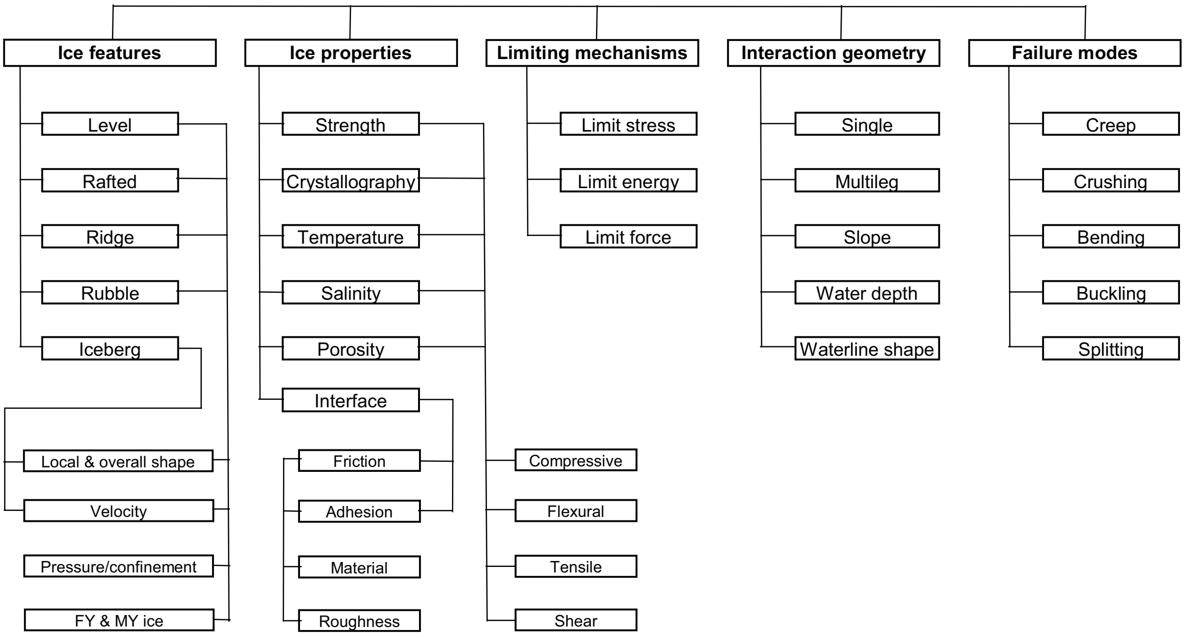


Figure A.8-3 — Factors influencing interaction scenarios

The main physical parameters used to characterize various types of ice interactions are given in Table A.8-1. Level ice is found wherever sea ice is present. First-year ice ridges are found in most areas where the sea ice is mobile. Rafted ice is often found adjacent to ridges. Multi-year ice is found in areas exposed to the arctic ice pack; it is typically colder than first-year ice and has a higher strength due to the lower brine content.

The development of potential interaction scenarios can be assisted through reference to descriptions of the physical environment found in Annex B. Final designs generally require site-specific data collection.

Ice actions for different interaction scenarios can be calculated from information provided in the subclauses listed in Table A.8-2.

Table A.8-1 — Common physical parameters used to describe interaction scenarios

Level ice	ice thickness	First-year ridges	thickness of the consolidated or refrozen rafted ice
	drift speed		keel draught
	floe size		keel geometry
	floe spacing or frequency		surrounding level ice thickness
Rafted ice	total thickness		lateral extent of consolidated layer
	drift speed		ridge orientation relative to structure
	consolidation time or degree of bonding		ridge length
	extent of rafted ice areas		ridge spacing or frequency
	number of layers of ice rafted		drift orientation relative to the structure
	spacing or frequency		drift speed
Multi-year floes	floe thickness	Icebergs	mass
	floe speed		drift speed
			waterline length
	floe size		local shape
	floe edge thickness		
	floe drift orientation relative to the structure		drift orientation to structure
	ridge spacing or frequency		depth of first contact with structure
Multi-year ridges	ridge keel draught		iceberg frequency
	drift speed		
	ridge keel geometry		height above waterline
	ridge orientation relative to structure		draught
	ridge length		waterline width perpendicular to length
	surrounding level ice thickness		
	ridge sail height ridge spacing or frequency		

Table A.8-2 — Subclause references for various interaction scenarios

Ice scenario[a,b]	Fixed structures					Floating structures			Artificial islands	
	Vertical		Conical or sloping		Multi-leg	Ship-shaped	Spar/ buoy vertical	Spar/ buoy conical	Vertical	Sloped
	Wide	Narrow	Wide	Narrow						
FY[c] level	A.8.2.4.3 A.8.2.4.10		A.8.2.4.4 A.8.2.4.10		A.8.2.4.3 A.8.2.4.4 A.8.2.4.9	A.8.2.4.3 A.8.2.4.4 A.8.2.4.8	A.8.2.4.3	A.8.2.4.4	A.8.2.4.3 A.8.2.4.10	A.8.2.4.4 A.8.2.4.10
FY ridges and rubble fields	A.8.2.4.5, A.8.2.4.6				A.8.2.4.5 A.8.2.4.9 A.8.2.4.6	A.8.2.4.5, A.8.2.4.6, A.8.2.4.8			A.8.2.4.5, A.8.2.4.6	
FY discrete floes	A.8.2.4.7				A.8.2.4.7 A.8.2.4.9	A.8.2.4.7				
MY[d] level	A.8.2.4.3		A.8.2.4.4		A.8.2.4.3 A.8.2.4.9	A.8.2.4.3 A.8.2.4.4 A.8.2.4.8	A.8.2.4.3 A.8.2.4.8	A.8.2.4.4 A.8.2.4.8	A.8.2.4.3	A.8.2.4.4
MY ridges and hummock fields	A.8.2.4.5, A.8.2.4.6				A.8.2.4.5 A.8.2.4.9 A.8.2.4.6	A.8.2.4.5, A.8.2.4.6, A.8.2.4.8				
MY discrete floes, icebergs and ice islands	A.8.2.4.7, A.8.2.4.6				A.8.2.4.7 A.8.2.4.6 A.8.2.4.9	A.8.2.4.6, A.8.2.4.7, A.8.2.4.8				

[a] A.8.2.2, A.8.2.4.3, A.8.2.5, A.8.2.7 and A.8.2.8 can apply for all interaction scenarios.

[b] A.8.2.4.11 can apply for fixed structures and artificial islands in first-year level ice.

[c] FY refers to first-year ice.

[d] MY refers to multi-year ice.

A.8.2.4 Global ice actions

A.8.2.4.1 Limiting mechanisms

For many interaction scenarios, it is useful to consider limit stress, limit energy and limit force mechanisms, each of which should be investigated in the assessment of design ice actions.

The limit stress mechanism is when ice failure processes adjacent to the structure (compressive, shear, tensile, flexure, buckling, splitting) govern the ice action. A characteristic of limit stress conditions is that the ice feature has sufficient driving force to fail the ice and completely envelop the structure. In many circumstances, limit stress mechanisms are associated with the design ice actions. Ice floe splitting is a limit stress mechanism that can come into play prior to full envelopment of the structure.

The limit energy mechanism, sometimes called the limit momentum mechanism, occurs when the kinetic energy (or momentum) of the ice feature limits the ice action. Examples include large isolated floe (e.g. multi-year ice in summer), ice island or iceberg impacts.

The limit force mechanism occurs when actions from winds, currents and the surrounding pack ice on an ice feature in contact with the structure are insufficient to fail the ice against the structure.

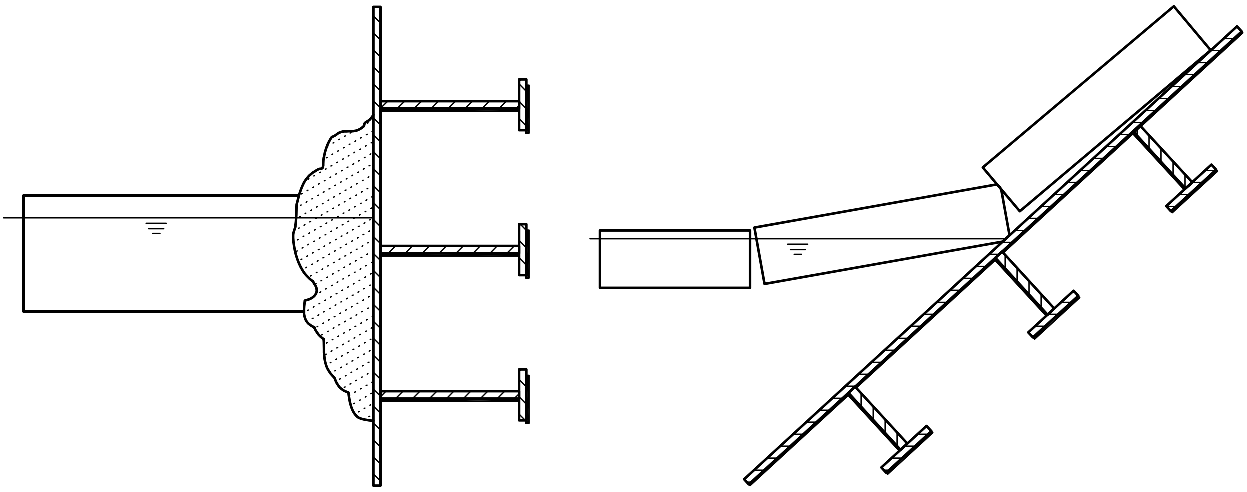
For some scenarios, one can consider a combination of the above mechanisms. Whenever limit force mechanisms are verified, it is always necessary to verify that the action is less than that calculated according to the limit stress mechanism. Ice features can split (limit stress mechanism) in a limit situation. When floes contain ridges, limit stress conditions should be checked at the structure interface. Other failure processes should be verified for the ridges and at the interface between the ridge and the level ice behind it, and limit force actions associated with ridge building should be assessed for the edge of the floe. The ice action on the structure can be the minimum arising from each of these mechanisms. Generally, if more than one limiting mechanism can occur simultaneously, the one that gives the lowest ice action should govern the design. These issues are discussed further in A.8.2.4.2.

A.8.2.4.2 Ice failure modes

A.8.2.4.2.1 Overview of failure modes

The mode of ice failure against the structure has a significant effect on the magnitude of the ice action. The failure mode for sea ice (e.g. crushing, shear, flexure, creep) depends on parameters such as ice thickness, presence of ridges, ice velocity, ice temperature and structure shape. Conditions that induce ice failure by flexure generally result in smaller ice actions than for crushing. Different modes of ice failure can occur on the same structure type depending on ice conditions and interaction velocity, even during the same event. Dynamic structural response is generally associated with ice crushing failure.

Structure geometry is an important factor in determining ice actions. Key design features include the structure type (multi-leg, monopod or caisson), vertical or sloping waterline geometry (see Figure A.8-4), the plan shape of the structure and the plan dimensions. Braces or appendages should not be exposed to ice actions.



a) Crushing failure (vertical structure) **b) Bending failure (sloping structure)**

Figure A.8-4 — Failure modes

The profile of the structure is a key issue. Structures with vertical walls in the waterline region generally experience larger ice actions than sloping ones for similar waterline dimensions. Ice actions are generally less for sloping structures, except in situations where large amounts of ice rubble accumulate on the sloping surface. If this occurs, flexural failure can be impeded and different modes or mixed modes of failure can occur with potentially larger actions.

The plan shape of a structure is less important, except in situations where a corner of a rectangular structure is oriented towards the preferred ice motion direction. Generally, the waterplane form of a structure has a 10 % to 15 % influence on the magnitude of global ice actions[A.8-2].

The plan dimensions of the structure influence the magnitude of ice actions. Many experiments and observations demonstrate the existence of a size effect, whereby the global or effective pressure (total action divided by the nominal contact area) for a narrow structure is higher than for a wide one.

Break-out of an ice feature frozen around a structure can potentially generate large ice actions. Such behaviour is more likely in areas of very small tidal range. While experience has shown that this situation is not generally critical for the design of large offshore structures, the issue should be addressed.

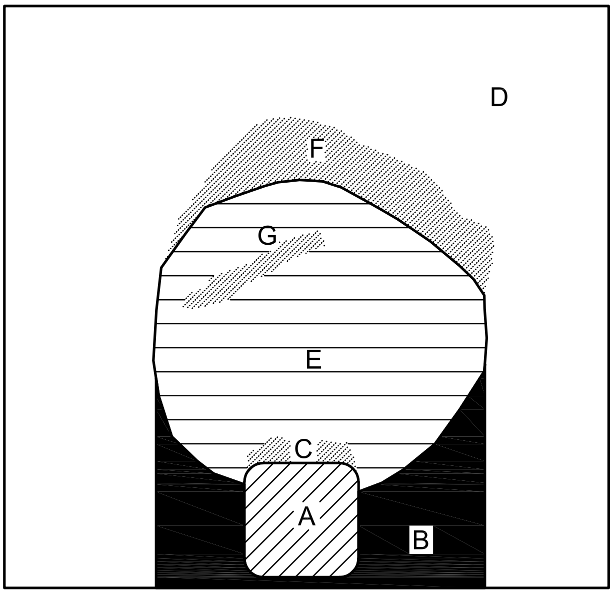
A.8.2.4.2.2 Level ice failure

When a sheet of level ice or rafted ice acts on a vertical structure the ice can fail in different modes. These include flexural failure modes such as bending and buckling, vertical (radial) splitting and crushing. Crushing failure usually dominates ice actions for vertical structure scenarios. If the structure has a sloping face, the ice often fails in flexure as it rides up or down the face.

In shallow water, rubble accumulations on the face of the structure can alter the mode of failure from crushing or flexure to a mixed mode or rubbling failure. Large rubble accumulations interacting with the seabed can buffer the ice action and eventually prevent the transfer of actions to the structure.

A.8.2.4.2.3 Ice failure processes for floes

When a thick first-year (FY) floe or a multi-year (MY) floe comes to rest against the structure, ridge building behind the ice floe and ice failing locally at the structure can take place, as shown in Figure A.8-5. When these occur simultaneously, the minimum of the actions resulting from the two processes is used for design.

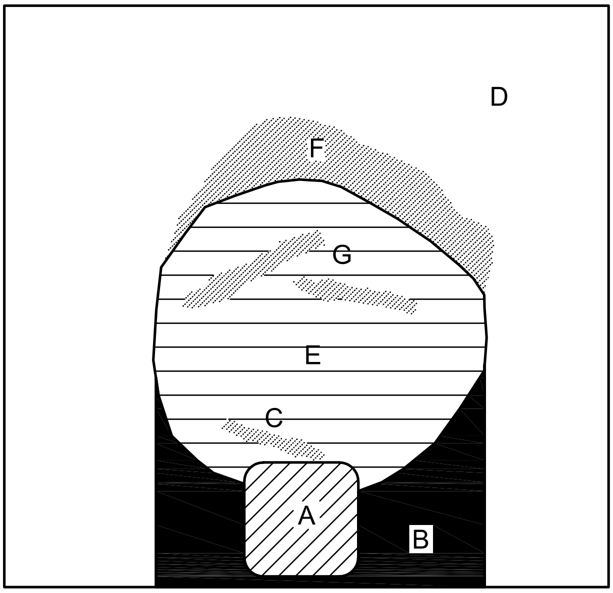


Key

A structure
B open water in wake of ice floe
C local failure
D FY ice
E MY floe or thick FY ice floe
F ridge building
G ridge embedded in ice floe

Figure A.8-5 — Ridge building and local ice failure processes

When a ridge within a floe makes contact with the structure, as shown in Figure A.8-6, a number of failure processes can take place within and adjacent to the ridge in addition to crushing or flexure against the structure. Potential failure processes, such as shear failure of the ridge, ridge break-out from the surrounding ice sheet with rubble building behind the ridge, in-plane failure of the ridge, and out-of-plane failure of the ridge, are shown in Figure A.8-7. Out-of-plane ridge failure can be the result of ridge grounding on the seabed or on a berm adjacent to the structure. Once again, as long as the failure processes can take place simultaneously, the minimum action from the various processes should be considered.



Key

A	structure
B	open water in wake of ice floe
C	ridge failure
D	FY ice
E	MY floe or thick FY ice floe
F	ridge building
G	ridges embedded in ice floe

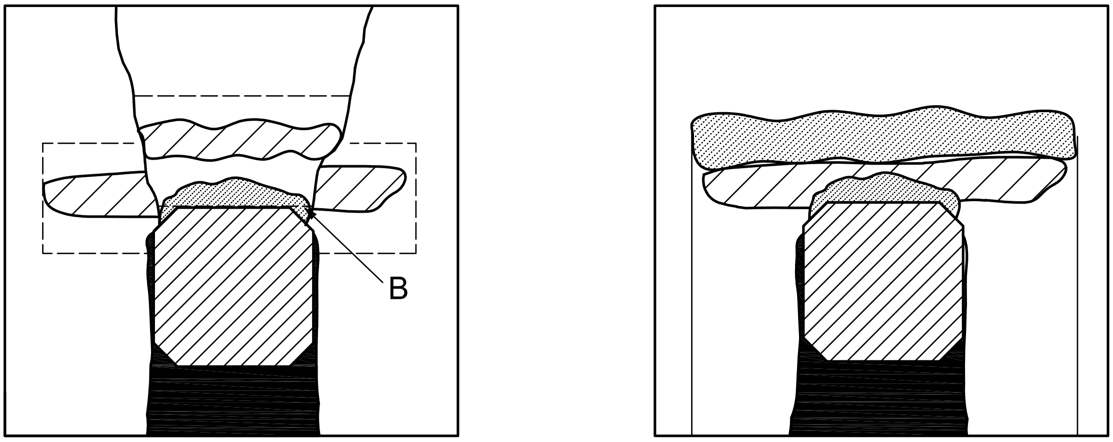
Figure A.8-6 — Ridge building and ridge failure adjacent to the structure

A.8.2.4.3 Vertical structures

A.8.2.4.3.1 Compression failure of an ice sheet

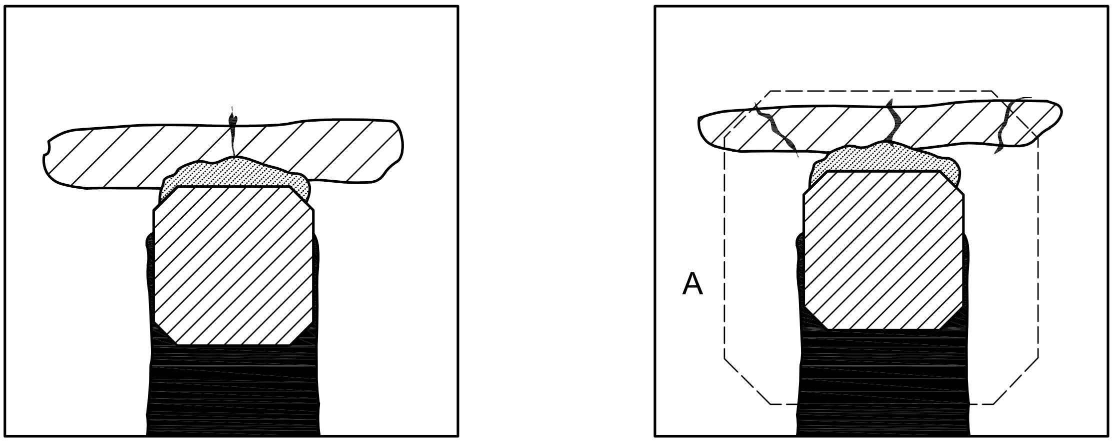
The term crushing refers to a complex compressive failure process, involving the development of a damaged layer as well as sequential development of flakes or spalls, see Figure A.8-8, and horizontal splits or cleavage cracks.

Observations on ice-structure events at full scale and medium scale show that the response of ice to higher rates in these interactions is profoundly irregular. Medium scale field tests, with interaction areas on the order of a square metre, have shown that damage processes such as creep occur in ice action at movement rates of less than 1 mm s^{-1}. At higher rates, fractures and spalls occur, resulting in the formation of high pressure zones (hpz's) in the contact area between the ice and the structure, as well as the fracturing of large pieces of ice resulting in areas of little or no pressure. The result is that some small patches or narrow line-like areas are subjected to high pressures and others to little or no pressure. These high pressures have an important effect on local ice actions, as discussed in A.8.2.5.



a) Ridge shear failure (dashed line shows displacement of ridge)

b) Ridge break-out



c) In-plane ridge failure

d) Out-of-plane ridge failure

Key

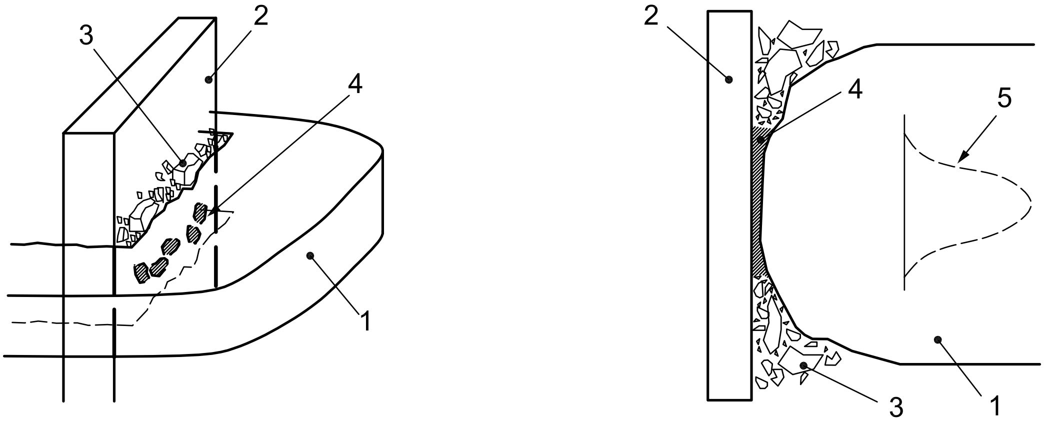
A sea floor footprint of sloping structure
B ice rubble lodged against structure

Figure A.8-7 — Ridge failure processes

Figure A.8-8 shows the structure of an hpz, and the appearance of these within a plane of interaction. Within the hpz's, the state of stress in the ice is tri-axial, varying from low confinement near the edges to high values of contact pressure near the centre.

The pressures within the areas where compressive actions are transmitted from the structure to the ice fluctuate considerably both in space and in time, with most of the contact pressure concentrated intensely in the hpz's. These entities produce crushed ice consisting of large quantities of quite small pieces. Hpz's tend to occur in the most confined regions, away from the free surfaces. This results in the “line-like” action appearance near the centre of ice sheets. The hpz's move about in response to the occurrence of fractures, sometimes moving away from the “most likely” locations. Field data on this failure process are used in A.8.2.5.2 to define equations for local pressures due to level ice actions.

For low speed laterally confined interactions of level first-year ice with a vertical structure, horizontal splits or cleavage cracks can develop as a result of vertical strain in the ice cover. Starting at the hpz's, the horizontal extension of the cracks can reach several times the ice thickness and contribute to the compression failure of the ice sheet.



a) Ice sheet interaction with the flat surface of a narrow vertical structure

b) Profile of ice sheet interaction with vertical structure

Key

1	ice sheet
2	structure
3	spalls and extrusion
4	high pressure zones in a), layer of crushed ice of high pressure zone in b)
5	pressure distribution over the contact surface

Figure A.8-8 — Schematic showing localization of action in compressive ice-structure interaction

The failure process just described means that local ice pressures are much more variable than those on global areas. For global areas, the local pressures average out and the variability is consequently reduced.

A.8.2.4.3.2 Global actions due to ice crushing

When ice crushing occurs against a structure, the global ice action normal to the surface, F_G, can be expressed as given in Equation (A.8-19) regardless of the limiting mechanism:

$$F_\mathrm{G} = p_\mathrm{G} \cdot A_\mathrm{N} \qquad \text{(A.8-19)}$$

where

p_G is the ice pressure averaged over the nominal contact area associated with the global action;

A_N is the nominal contact area.

The nominal contact area is the projected area of the intact ice feature on the structure.

Because the nominal contact area, A_N, for level ice, for rafted ice or for the consolidated layer of a ridge, is the product of the ice thickness, h, and the width, w, Equation (A.8-19) for the global ice action can be rewritten as Equation (A.8-20):

$$F_\mathrm{G} = p_\mathrm{G} \cdot h \cdot w \qquad \text{(A.8-20)}$$

For glacial ice or massive feature interactions, the nominal contact area is the projected contact area of the ice feature on the surface of the structure for a given penetration into the ice.

When limit stress or limit driving force mechanisms govern, the nominal contact area can be constant through the interaction or can assume some maximum value. For limit energy and limit force situations, the projected area typically increases during the course of the interaction according to the shapes of the ice feature and the structure.

Ice pressure, p_{G}, is often the most important parameter when designing structures against ice actions. The pressure associated with the global action is influenced by the ice temperature, the nominal contact area, the shape or aspect ratio of the contact area, the nature of the contact, the relative speed and displacements between ice and structure, as well as the compliance of the structure. Since ice pressure can vary significantly in time, peak values typically depend on the averaging time.

A.8.2.4.3.3 Global pressure for sea ice

Data obtained from full-scale measurements in Cook Inlet, the Beaufort Sea, Baltic Sea and Bohai Sea have been used to determine upper bound ice pressure values for scenarios where a first-year or multi-year ice acts against a vertical structure. The data have also been used to analyse how the ice thickness and the width of the structure influence the global ice action. Based on these studies, the global ice pressure can be determined as given in Equation (A.8-21):

$$p_{\mathrm{G}} = C_{\mathrm{R}} \left(\frac{h}{h_1} \right)^n \left(\frac{w}{h} \right)^m \tag{A.8-21}$$

where

p_{G} is the global average ice pressure, expressed in megapascals;

w is the projected width of the structure, expressed in metres;

h is the thickness of the ice sheet, expressed in metres;

h_1 is a reference thickness of 1 m;

m is an empirical coefficient equal to $-0{,}16$;

n is an empirical coefficient, equal to $-0{,}50 + h/5$ for $h < 1{,}0$ m, and to $-0{,}30$ for $h \geqslant 1{,}0$ m;

C_{R} is the ice strength coefficient, expressed in megapascals.

Equation (A.8-21) applies for rigid structures with aspect ratios w/h greater than 2, where the waterline displacement, obtained as a static response to the representative ice action, is typically less than 10 mm. Equation (A.8-21) does not explicitly include temperature effects[A.8-3].

Equations (A.8-20) and (A.8-21) can be used in a probabilistic analysis by first determining probability density functions for the ice thickness and the strength parameter C_{R}. A characteristic value of the global ice action can then be determined by using guidelines described in A.8.2.2. In a deterministic analysis, the strength parameter for ELIE can be assumed as $C_{\mathrm{R}} = 2{,}8$, based on first-year and multi-year data from the Beaufort Sea[A.8-4] through [A.8-6]. This C_{R} value can be conservative as it potentially includes some magnification due to the compliance of the structure in the referenced data from the Beaufort Sea[A.8-7].

According to another data series from a stiff structure in the Baltic Sea, the ELIE ice strength parameter has been obtained as $C_{\mathrm{R}} = 1{,}8$[A.8-8] in conditions where the ice speed was higher than 0,1 m/s and the maximum waterline displacements in the direction of ice action of the structure were about 0,4 % of the ice thickness. Under these conditions, the strength value C_{R} obtained does not exhibit magnification due to the compliance of the structure. The same data set indicates that C_{R} is about 15 % to 20 % higher for ALIE, so ELIE generally governs level ice actions on vertical structures.

Data obtained both in the field and in the laboratory show that for slender or flexible structures, large magnitude actions can also occur for speeds in the range of 0,003 m/s to 0,1 m/s, which might include creep and crushing actions. Further magnification in the apparent ice strength can arise at a low ice speed if the structure is compliant and an ice-structure interaction process known as intermittent crushing occurs; see A.8.2.6.1. This phenomenon should be considered both in probabilistic and deterministic analyses. Laboratory data[A.8-9] and full-scale data[A.8-7] can be used to determine the amount of ice action amplification. Special numerical methods[A.8-9], [A.8-10] can also be used.

It should also be noted that Equations (A.8-19) to (A.8-21) do not take into account the effects of ice-induced vibrations, which can arise in compliant structures. Guidelines provided in A.8.2.6.1 can be used to check whether the static analysis should be supplemented by a dynamic analysis.

A.8.2.4.3.4 Influence of local ice conditions on ice pressures

Different geographical areas have different ice conditions due to climatic conditions, and due to the mobility and morphology of the ice. Some areas such as the Beaufort Sea have multi-year ice while others such as the Okhotsk Sea, Cook Inlet, Baltic Sea or Bohai Sea have none. As a guide to action calculations and to defining regions of different climate and relative ice strengths, one can consider the following divisions:

- arctic, having about 4 000 freezing degree days per winter season (e.g. Beaufort Sea);
- sub-arctic, having about 2 000 freezing degree days per winter season (e.g. Okhotsk Sea – off northeast Sakhalin Island);
- temperate, having about 1 000 freezing degree days per winter season (e.g. Okhotsk Sea – Aniva Bay, North Caspian Sea, Cook Inlet, Baltic Sea, Bohai Sea).

NOTE The method for calculating freezing degree days is given in A.6.5.1.

The freezing index (freezing degree days; see A.6.5.1) is an important parameter in assessing the thickness of refrozen rafted ice and of the consolidated ice thickness of pressure ridges. While first-year ice can raft to similar thicknesses in areas with differing freezing degree days, the thickness of solid, continuous ice or the consolidated layer differs due to the varying ability of the atmosphere to remove heat from the ice.

As described above, the ice strength parameter C_R has been estimated as 2,8 MPa for arctic areas and 1,8 MPa for temperate areas. When evidence indicates that the ice strength is different in the area of interest, three possible approaches that can be used to specify the ice strength parameter C_R are described below.

In the first approach, the value of $C_R = 2{,}4$ can be used for sub-arctic regions. As an alternative approach, the ice strength parameter can be expressed as given in Equation (A.8-22):

$$C_R = C_{R0} \cdot \frac{\sigma}{\sigma_0} \qquad \text{(A.8-22)}$$

where

C_R is the strength parameter for the area of interest;

C_{R0} is the strength parameter for the reference area, e.g. 2,8 MPa for arctic areas and 1,8 MPa for Baltic Sea;

σ is a measured or inferred strength index for the area of interest;

σ_0 is the strength index for the reference area.

The strength index can involve a variety of compressive strength measures, including borehole jack measurements, uniaxial or multiaxial strength measurements, continuous indentation experiments, and relationships between temperature, brine volume and compressive strength. It is emphasized that proper justification should be made for the use a relationship of the form presented in Equation (A.8-22). Considerable caution should be exercised in scaling the C_R parameter, particularly when large differences exist between ice conditions and temperatures for the area of interest and the reference area.

Scaling based on small-scale uniaxial compressive strength measurements should be done with caution. If *in situ* strength measurements are used, these measurements should cover a sufficiently broad geographical region to be representative. Further discussion on compressive strength is provided in A.8.2.8.2.

When scaling strength indices, it should be recognized that characteristics of the structure can influence the measured data. Ice pressures due to continuous crushing obtained on a rigid structure in one region should not be used directly for compliant structures. Pressures on compliant structures can be significantly higher than on rigid structures.

Borehole jack strengths (see A.8.2.8.2) can be used to obtain a global pressure ratio for two regions. The borehole strengths depend on temperature and salinity in the same manner as for uniaxial compressive strength. If a reference borehole strength is unavailable, the average borehole strength obtained at the site of interest can be divided by 3 to obtain an estimate of the uniaxial compressive strength.

The third approach proposed in Reference [A.8-11] can also be used as a practical means of estimating or scaling C_R. The strength index is evaluated by dividing the ice sheet into a number of layers. for which typical temperature and salinity profiles are obtained. In this method, a time-averaged value is first determined for the temperature at the snow-ice interface. For a constant air temperature, the maximum time for an ice temperature profile to reach equilibrium is 5 days for $h = 0{,}5$ m, 11 days for $h = 0{,}75$ m, 19 days for $h = 1{,}0$ m, 43 days for $h = 1{,}5$ m and 77 days for $h = 2{,}0$ m. The distribution of the brine volume, ν_b, can be determined from Equation (A.8-75) by assuming a linear temperature profile within the ice sheet.

The average strength index is then obtained as given by Equation (A.8-23):

$$\sigma_0 = \left[\frac{1}{n}\sum_{i=1}^{n}(C_i)^2\right]^{1/2} \tag{A.8-23}$$

where

n is the number of layers ($n \geqslant 5$);

C_i is the strength coefficient obtained from Table A.8-3 for a layer.

Table A.8-3 — Ice strength coefficient, C, as a function of the brine volume[a]

ν_b	0,001	0,010	0,025	0,050	0,100	0,200
C MPa	8,4	6,0	3,4	1,6	1,0	0,8

[a] See Equation (A.8-75).

Using this method, the reference value for the index strength σ_0 is 2,86 MPa for the conditions where the strength parameter has been obtained as $C_R = 2{,}8$. Correspondingly, the strength index is $\sigma_0 = 2{,}07$ MPa for temperate areas where the strength parameter has been obtained as $C_R = 1{,}8$.

A.8.2.4.3.5 Global ice pressures from ship ramming tests

Data from ship rams into multi-year ice indicate that the global action is random, even for seemingly identical rams. This is associated with random fracture events in the ice as it fails. Because of size effects, the average global pressure generally decreases as a function of nominal contact area. The pressure-area relationship as given by Equation (A.8-24) has been developed for impact scenarios:

$$p_\mathrm{G} = C_\mathrm{P} {A_\mathrm{N}}^{D_\mathrm{P}} \tag{A.8-24}$$

where

A_N is the nominal contact area;

C_P, D_P are random coefficients.

The coefficients C_P and D_P have been calibrated using a large database of ship rams with multi-year ice (Kigoriak, Polar Sea, MV Arctic, Manhattan and Oden). The projection of the original shape of the ice feature onto the structure at the appropriate penetration and the resulting maximum actions for each simulation were then ranked and compared on a probability of exceedance basis with ship ram trial data. A goodness-of-fit criterion was used to decide which combination best represented the coefficients. The preferred combination was a mean and standard deviation of 3,0 and 1,5, respectively, for C_P (lognormal distribution) and a mean and standard deviation of –0,4 MPa and 0,2 respectively, for D_P (normal distribution)[A.8-12].

When extrapolated to large contact areas, the pressure-area function [Equation (A.8-24)] can yield unrealistically low pressures for the instantaneous ice pressure. A lower bound cut-off for the pressure-area curve should be considered in such cases. Guidance can be obtained from Equation (A.8-22) for low aspect ratio interactions.

A.8.2.4.3.6 Point of action

For sea ice actions on a vertical structure, the point of action can be taken as the mid-depth of the ice. For structures with some deviation from the vertical, the point of action can be taken as the mid-point of the ice in contact with the structure at maximum penetration.

For the interaction of icebergs or other massive features, the point of action can be taken as the point of first contact or the mid-point of the ice in contact with the structure at maximum penetration. For certain geometries of structures, e.g. stepped structures, multiple points of contact should be verified with increasing penetration, particularly if a higher point of contact results.

Water level changes as a result of waves, tides, storm surges and long-term fluctuations should be taken into account. Where appropriate, the correlation between ice thickness, ice velocity and water level should be considered when calculating ice actions.

When torsional actions are considered, the centroid of the contact area can generally be used as the point of action. In such cases, the orientation of the action should reflect the tangential frictional action.

A.8.2.4.4 Sloping structures

A.8.2.4.4.1 Description of the failure process

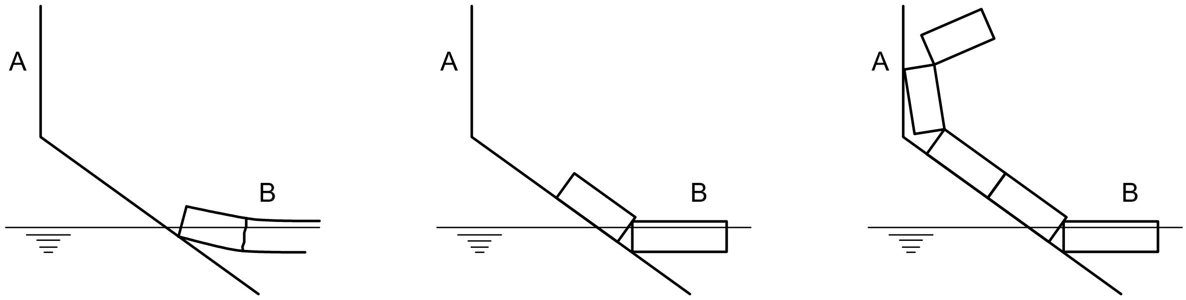
Offshore structures with a sloping surface can be considered as an alternative to a vertical structure. Level ice interacting with a sloping structure is more likely to fail in a flexural failure mode. Ice actions in such failure modes can be significantly lower than in a crushing failure mode, which is typical for vertical-sided structures. Sloping icebreaking surfaces can also reduce ice actions from ice ridges.

There are several possible types of sloping structures. A conical shape is often the preferred shape for offshore structures due to its symmetrical plan shape. In addition to smooth conical structures with circular waterlines, multi-faceted cones with flat, sloping faces have also been investigated. Ice actions on conical or multi-faceted sloping structures have been extensively investigated theoretically and in numerous small-scale laboratory test programmes. Ice action on sloping structures was also studied during several field programmes including Kemi-1 lighthouse in 1983-86 in the Gulf of Bothnia, two piers of the Confederation Bridge since 1997, jacket production platforms in the Bohai Sea, the Kulluk downward breaking floating caisson in the Beaufort Sea, and an experimental tower at Mombetsu, Japan. These structures experienced a wide variety of first-year ice conditions including level ice, first-year ice ridges and rubble fields. Results and observations from these field measurement programmes were used as benchmarks for verification of theoretical models[A.8-13] and ice design criteria for newly built conical and sloping structures. Alternatively, when the full-scale data are not available, small-scale model test data have been used to verify the validity of theoretical models and design criteria.

A side geometry that is formed of two sloping flat surfaces can be used in areas where the ice movement has a dominant direction. Studies have also been done on sloping flat panels to obtain fundamental understanding of the ice actions due to sheet ice. Flat sloping panels can also be used as a part of a structure.

Sloping structures break the oncoming sheet ice by deflecting it either upwards or downwards. The resulting ice action has both a vertical and horizontal component. The horizontal and vertical components of ice action on a downward breaking structure are lower relative to those acting on an upward breaking structure of the same size and slope angle. In the case of a downward breaking structure, the vertical component of the ice action is directed upwards, reducing the effective shear resistance at the structure-seabed interface.

Ice interaction with a sloping surface is a complicated process that includes failure of intact ice, ride-up of broken ice pieces, accumulation of ice rubble on the slope, and subsequent clearing of the rubble accumulation; see Figures A.8-9 and A.8-10.



a) Ice sheet approaches structure

b) Ice begins to fail and ride up face of structure

c) Ice blocks ride up face of structure and are turned back at vertical face

Key

A sloping structure

B encroaching ice sheet

Figure A.8-9 — Processes in the interaction between a sloping structure and sheet ice

Ice rubble can also accumulate under the ice sheet, further complicating the interaction process. The maximum ice action on a sloping structure is hence a function of several different parameters including bending, compressive and shear strengths of the ice sheet, friction coefficient between structure surface and ice, presence of snow, density of ice, and the height and geometry of ice rubble.

Figure A.8-11 depicts level ice action components for a two-dimensional interaction with an upward breaking structure. The horizontal and vertical components of ice action are as given by Equation (A.8-25):

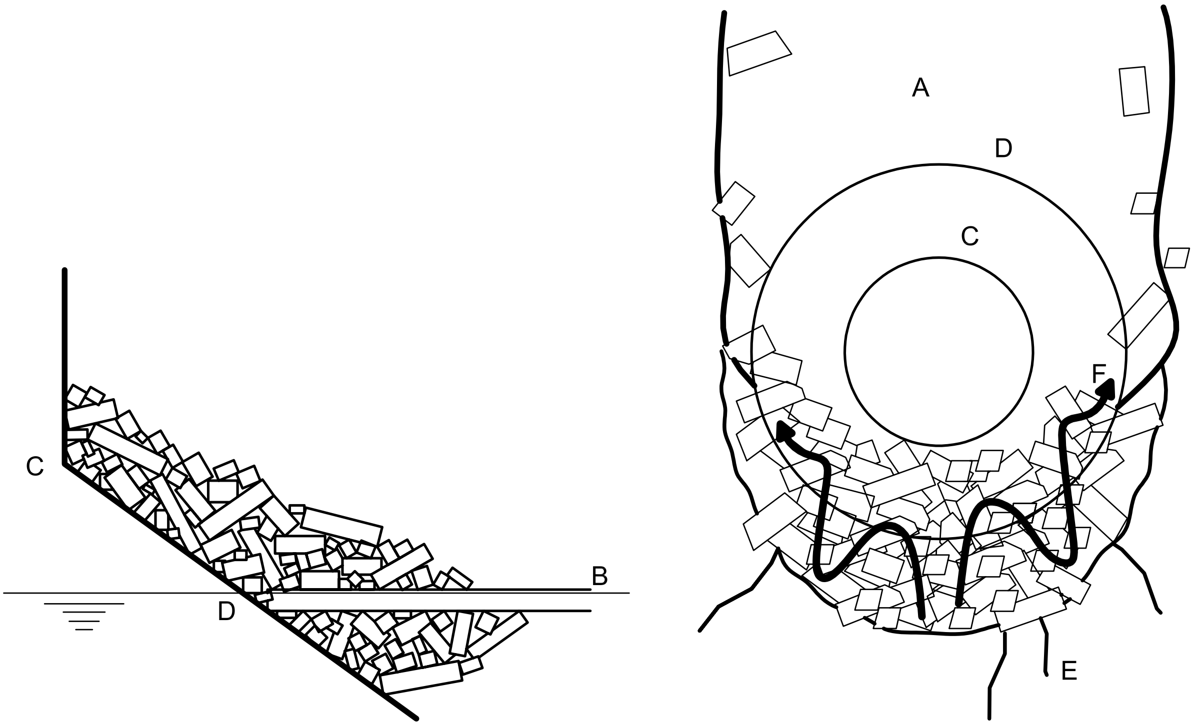
$$\begin{aligned} F_\mathrm{H} &= N\sin\alpha + \mu N\cos\alpha \\ F_\mathrm{V} &= N\cos\alpha - \mu N\sin\alpha \end{aligned} \qquad \text{(A.8-25)}$$

where

N is the component normal to the structure surface;

α is the inclination angle of the structure surface from the horizontal, expressed in radians;

μ is the coefficient of kinetic friction between the ice and structure surface (for values, see A.8.2.8.7).



a) Ice rubble pile-up against a sloping structure **b) Ice failure and clearing of rubble around an upward breaking conical structure**

Key

A open water in wake of structure
B encroaching ice sheet
C top of sloping face of structure
D waterline of structure
E cracks forming in encroaching ice sheet
F clearing of ice rubble blocks around structure

Figure A.8-10 — Ice rubble pile-up and clearing around a sloping structure

The relationship between the vertical and horizontal components is given by Equation (A.8-26):

$$F_{\mathrm{V}} = \frac{F_{\mathrm{H}}}{\xi} \tag{A.8-26}$$

where $\xi = \dfrac{\sin\alpha + \mu\cos\alpha}{\cos\alpha - \mu\sin\alpha}$.

Theoretical models developed to calculate level ice actions on sloping structures can provide reasonably accurate estimates of ice action, as long as the input data and assumptions are appropriate.

A number of methods of determining ice actions on cones and sloping structures have been developed, two of which are described below. The first, as described in A.8.2.4.4.2, is based on the theory of plasticity, and the second, as described in A.8.2.4.4.3, is based on elastic beam bending.

Besides the parameters used in Equations (A.8-25) and (A.8-26), the following parameters are used in the two models, with the various parameters expressed in consistent units:

H_B is the horizontal action on the cone due to ice breaking;

V_B is the vertical action on the cone due to ice breaking;

H_R is the horizontal action on cone due to ride-up;

V_R is the vertical action on cone due to ride-up;

σ_f is the flexural strength of the ice sheet;

h is the thickness of the ice sheet;

w is the waterline diameter of the cone or width of a sloping structure;

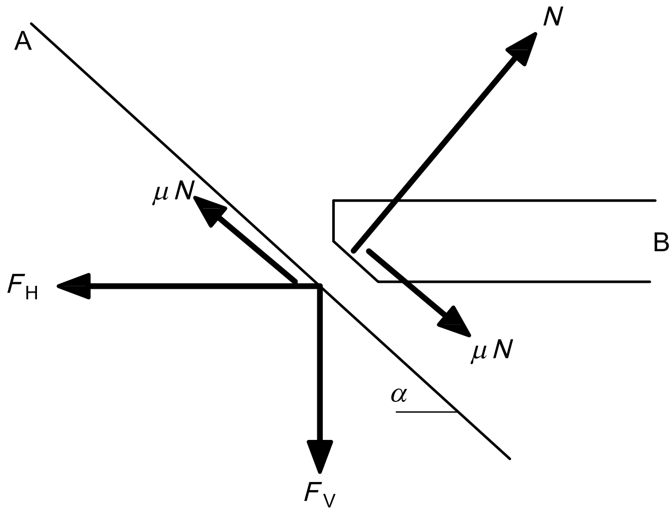
ρ_i is the density of ice, see A.8.2.8.10;

ρ_w is the density of water;

g is the acceleration due to gravity;

ν is the Poisson ratio for ice, typically equal to 0,3.

The flexural strength depends on the size of the ice specimen that is used to obtain this parameter. Therefore, the values of this parameter should be adopted from field tests where the specimen size is comparable to the design condition (see A.8.2.8.3).



Key

A sloping face of structure

B encroaching ice sheet

N normal component of reaction to ice action on structure

μ ice-structure friction coefficient

α slope of structure face from horizontal

F_H horizontal component of ice action

F_V vertical component of ice action

Figure A.8-11 — Ice action components on a sloping structure for a two-dimensional condition

A.8.2.4.4.2 Plastic method for cones

This method is based on a limit analysis solution for level ice actions on upward and downward breaking cones[A.8-14]. The model considers actions due to the flexural failure of the ice sheet and the ride-up actions due to ice pieces. The derivation is for an upward breaking cone and is also valid for a downward breaking cone if ρ_i is replaced with $(\rho_\text{w} - \rho_\text{i})$.

The functions as given by Equations (A.8-27) to (A.8-30) are defined for the solution:

$$f = \sin\alpha + \mu\, E_1 \cos\alpha \tag{A.8-27}$$

$$g_\text{r} = \frac{\sin\alpha + \dfrac{\alpha}{\cos\alpha}}{\dfrac{\pi}{2}\sin^2\alpha + 2\mu\alpha\cos\alpha} \tag{A.8-28}$$

$$h_\text{v} = \frac{f\cos\alpha - \mu\, E_2}{\dfrac{\pi}{4}\sin^2\alpha + \mu\,\alpha\cos\alpha} \tag{A.8-29}$$

$$W = \rho_\text{i}\, g\, h_\text{r}\, \frac{w^2 - w_\text{T}^2}{4\cos\alpha} \tag{A.8-30}$$

where

α is the slope of the structure measured from the horizontal, expressed in radians;

w_T is the top diameter of the cone;

h_r is the ice ride-up thickness ($h_\text{r} \geqslant h$).

The effects of a rubble accumulation on the cone can be considered by using a value that exceeds the single sheet thickness for the ride-up thickness. The parameters E_1 and E_2 are the complete elliptical integrals of the first and second kind, defined as given by Equations (A.8-31) and (A.8-32):

$$E_1 = \int_0^{\pi/2} \left(1 - \sin^2\alpha\,\sin^2\eta\right)^{-1/2} \mathrm{d}\eta \tag{A.8-31}$$

$$E_2 = \int_0^{\pi/2} \left(1 - \sin^2\alpha\,\sin^2\eta\right)^{1/2} \mathrm{d}\eta \tag{A.8-32}$$

Assuming a single sheet thickness of ride-up ice, the horizontal ride-up action, H_R, and the vertical ride-up action, V_R, are obtained as given by Equations (A.8-33) and (A.8-34):

$$H_\text{R} = W\,\frac{\tan\alpha + \mu E_2 - \mu f g_\text{r}\cos\alpha}{1 - \mu g_\text{r}} \tag{A.8-33}$$

$$V_\text{R} = W\cos\alpha\left(\frac{\pi}{2}\cos\alpha - \mu\alpha - f h_\text{v}\right) + H_\text{R}\, h_\text{v} \tag{A.8-34}$$

The horizontal breaking action H_B and the vertical breaking action V_B are given by Equations (A.8-35) and (A.8-36):

$$H_B = \frac{\sigma_f\, h^2}{3}\, \frac{\tan\alpha}{1-\mu\, g_r} \left[\frac{1 + Y\, x \ln x}{x-1} + G\,(x-1)(x+2) \right] \tag{A.8-35}$$

$$V_B = H_B\, h_v \tag{A.8-36}$$

where

Y is equal to 2,711 for Tresca yielding or equal to 3,422 for Johansen yielding;

G is equal to $(\rho_i\, g\, w^2)/(4\sigma_f h)$;

x is given by Equation (A.8-37):

$$x = 1 + \left(3G + \frac{Y}{2} \right)^{-1/2} \tag{A.8-37}$$

The total action components in the horizontal and vertical directions are given, respectively, by Equations (A.8-38) and (A.8-39):

$$F_H = H_B + H_R \tag{A.8-38}$$

$$F_V = V_B + V_R \tag{A.8-39}$$

A.8.2.4.4.3 Model based on elastic beam bending

When an ice sheet acts on a wide slope or cone, the flexural failure component can be evaluated considering the ice sheet as an elastic beam on elastic foundation. In addition, three-dimensional effects can be considered as well as the presence of rubble on the face of the structure in the model outlined in Equations (A.8-40) to (A.8-47)[A.8-15], [A.8-16]. This method can also be used for downward breaking slopes by replacing ice weight in air by ice buoyancy in water. The present model accounts approximately for axial forces in the ice sheet and other more comprehensive approaches (see, for example, [A.8-17]), are recommended in order that they be dealt with correctly.

According to this model[A.8-16], the horizontal action component is determined as given by Equation (A.8-40):

$$F_H = \frac{H_B + H_P + H_R + H_L + H_T}{1 - \dfrac{H_B}{\sigma_f\, l_c\, h}} \tag{A.8-40}$$

where

H_B is the breaking load;

H_P is the load component required to push the sheet ice through the ice rubble;

H_R is the load to push the ice blocks up the slope through the ice rubble;

H_L is the load required to lift the ice rubble on top of the advancing ice sheet prior to breaking it;

H_T is the load to turn the ice block at the top of the slope.

The load component H_B is obtained as given by Equation (A.8-41):

$$H_B = 0{,}68\, \xi\, \sigma_f \left(\frac{\rho_w\, g\, h^5}{E} \right)^{0{,}25} \left(w + \frac{\pi^2\, L_c}{4} \right) \tag{A.8-41}$$

where

$$L_c = \left[\frac{E\, h^3}{12\, \rho_w\, g \left(1 - \nu^2\right)} \right]^{1/4}$$

where

E is the elastic modulus;

ν is the Poisson ratio;

other parameters as above.

The load component H_P is expressed as given by Equation (A.8-42):

$$H_P = w\, h_r^2 \mu_i\, \rho_i g\, (1 - e) \left(1 - \frac{\tan\theta}{\tan\alpha} \right)^2 \frac{1}{2 \tan\theta} \tag{A.8-42}$$

where

h_r is the rubble height;

μ_i is the ice-to-ice friction coefficient;

e is the porosity of the ice rubble;

θ is the angle the rubble makes with the horizontal.

The load component H_R is given by Equation (A.8-43):

$$H_R = w\, P \frac{1}{\cos\alpha - \mu \sin\alpha} \tag{A.8-43}$$

where

$$P = 0{,}5 \mu_i \left(\mu_i + \mu \right) \rho_i g \left(1 - e \right) h_r^2 \sin\alpha \cdot \left(\frac{1}{\tan\theta} - \frac{1}{\tan\alpha} \right) \cdot \left(1 - \frac{\tan\theta}{\tan\alpha} \right) + \ldots$$

$$\ldots + 0{,}5 \left(\mu_i + \mu \right) \rho_i\, g \left(1 - e \right) h_r^2 \frac{\cos\alpha}{\tan\alpha} \left(1 - \frac{\tan\theta}{\tan\alpha} \right) + h_r h \rho_i g \frac{\sin\alpha + \mu \cos\alpha}{\sin\alpha}$$

The load component H_L is given by Equation (A.8-44):

$$H_\mathrm{L} = 0{,}5 w\, h_\mathrm{r}^2 \rho_\mathrm{i}\, g\, (1-e)\, \xi \left(\frac{1}{\tan\theta} - \frac{1}{\tan\alpha}\right)\left(1 - \frac{\tan\theta}{\tan\alpha}\right) + \ldots$$
$$\ldots + 0{,}5\, w h_\mathrm{r}^2 \rho_\mathrm{i}\, g\, (1-e)\, \xi \tan\phi \left(1 - \frac{\tan\theta}{\tan\alpha}\right)^2 + \xi c w h_\mathrm{r} \left(1 - \frac{\tan\theta}{\tan\alpha}\right) \tag{A.8-44}$$

where

c is the cohesion of the ice rubble;

ϕ is the friction angle of the ice rubble.

The final load component, H_T, that is required for Equation (A.8-40) is given by Equation (A.8-45):

$$H_\mathrm{T} = 1{,}5 w h^2 \rho_\mathrm{i}\, g \frac{\cos\alpha}{\sin\alpha - \mu\cos\alpha} \tag{A.8-45}$$

Equation (A.8-40) has been modified from the original equation[A.8-16] to account for compressive stress in ice sheet as a result of the applied horizontal load, accounting for the denominator in Equation (A.8-40). This is considered by using the calculated value of the horizontal action to modify the flexural strength as given by Equation (A.8-46):

$$\sigma_\mathrm{f}^{(1)} = \frac{F_\mathrm{H}}{l_\mathrm{c} h} + \sigma_\mathrm{f} \tag{A.8-46}$$

where l_c is the total length of the circumferential crack, estimated as given by Equation (A.8-47):

$$l_\mathrm{c} = w + \frac{\pi^2}{4} L_\mathrm{c} \tag{A.8-47}$$

The corresponding vertical load is determined by Equation (A.8-26).

A.8.2.4.4.4 Effect of ice rubble

It should be noted that the predictions obtained from the two models provided in A.8.2.4.4.2 and in A.8.2.4.4.3 depend significantly on the amount of rubble on the slope. Depending on slope angle and the width of the cone, the volume of ice rubble can vary in different situations. Frictional effects due to snow or the roughness of the ice sheets also influence the height of the rubble pile. The frictional effects can vary in different ice regimes. Field measurements in the Bohai Sea have shown that the clearing process of the ice rubble can be very effective on narrow cones, especially in the absence of snow cover. In such conditions, the horizontal component of the ice action consists mainly of the icebreaking component.

In the model described in A.8.2.4.4.3, the loads are also very sensitive to the angle of repose chosen for the rubble pile. Combined with the rubble height, the angle of repose determines the volume of ice rubble on the slope of the structure. The force to drive the oncoming ice through this rubble pile and up the slope increases rapidly with this volume. This force is then transmitted to the structure and is a component of the total ice action. The choice of angle of repose should be based on experience and observations from actual structures. Model tests can also provide a guide. In general, the angle of repose should not be less than the structure slope angle minus 10°. For very high rubble piles, as can occur on a wide structure, an angle of about 5° less than the slope angle gives a realistic volume of rubble on the slope. It should be recognized that an angle of repose equal to the slope angle ($\theta = \alpha$) implies a single layer of ice riding up the slope. Angles of repose steeper than the slope angle cannot be accounted for in this model because this leads to a negative volume of ice rubble on the slope.

It is recognized that, in nature, an idealized uniform angle of repose for the rubble on the slope does not necessarily occur. In fact, investigators of ice action on the Kemi-1 cone in Finland and the Confederation Bridge in Canada have observed a variety of bilinear, curved or straight rubble slope angles[A.8-18], [A.8-13]. The geometry of the rubble formation seems to depend on ice strength, velocity, thickness, friction (snow on top of the ice) as well as on the cone angle and waterline diameter. When using the model described in A.8.2.4.4.3, the selection of the rubble angle of repose should approximate the correct volume of ice rubble that can occur on the slope.

A wide structure, especially with a flat face in shallow water, encourages high rubble heights on the structure because the ice cannot clear around it. In this situation, rubble heights in the 12 m to 20 m height range can occur. In fact, once sufficient rubble has accumulated on and in front of the structure, the ice load required to continue to push oncoming ice through the rubble to the slope of the structure, and then up its slope, becomes so large that the ice failure mode eventually switches to failure of the oncoming ice against the rubble pile in front of the structure. The ice action is then determined using methods valid for ice acting against ice rubble. For wide structures, the ridge building actions described in A.8.2.4.5 can be applied. If the ice rubble in front of the structure is grounded and has time to consolidate, then the crushing equations given in A.8.2.4.3.2 and A.8.2.4.3.3 provide a conservative estimate of global ice pressures. It should also be recognized that if the ice is acting on grounded ice rubble in front of the structure, the actual load transmitted to the structure is reduced by the sliding resistance of the grounded ice rubble. This sliding resistance can be estimated from the footprint of the ice rubble and the cohesive strength of the soil. For a granular soil, the weight of the ice rubble acting on the sea floor multiplied by the tangent of the friction angle of the soil gives a reasonable estimate.

A.8.2.4.4.5 High speed interactions

Laboratory and full-scale observations indicate that the failure mode of sheet ice on sloping structures can change from bending to shear at high interaction speeds. Full-scale observations have shown further that the ice thickness has less of an influence for shear failure than for bending failure, making shear failure more prevalent at higher ice thicknesses. The change in mechanism is due to inertial effects, which can potentially increase the global ice action.

Particularly for narrow cones, the extent of rubble build-up is generally less at high interaction velocities, which acts to reduce the global ice action.

As a result of the above processes, ice actions on sloping structures depend on the drift velocity. The velocity effect is rather complex and its magnitude depends on the slope angle, sloping surface roughness and the ratio between ice thickness and waterline structure width.

Whenever available, relevant full-scale data should be used to determine the degree and the sense of the velocity effect for ice actions on sloping structures. In the absence of such data, it is recommended that ice actions be increased for ice velocities in excess of 0,5 m/s. Some guidance with respect to velocity effects based on model test results can be found in Reference [A.8-19].

A.8.2.4.5 Ice rubble and ridges

A.8.2.4.5.1 First-year ridges

First-year ridges and hummock fields are found anywhere where first-year ice forms and is mobile enough to create them. In sea areas where there is only first-year ice, ice ridges are often the governing interaction scenario for design ice actions.

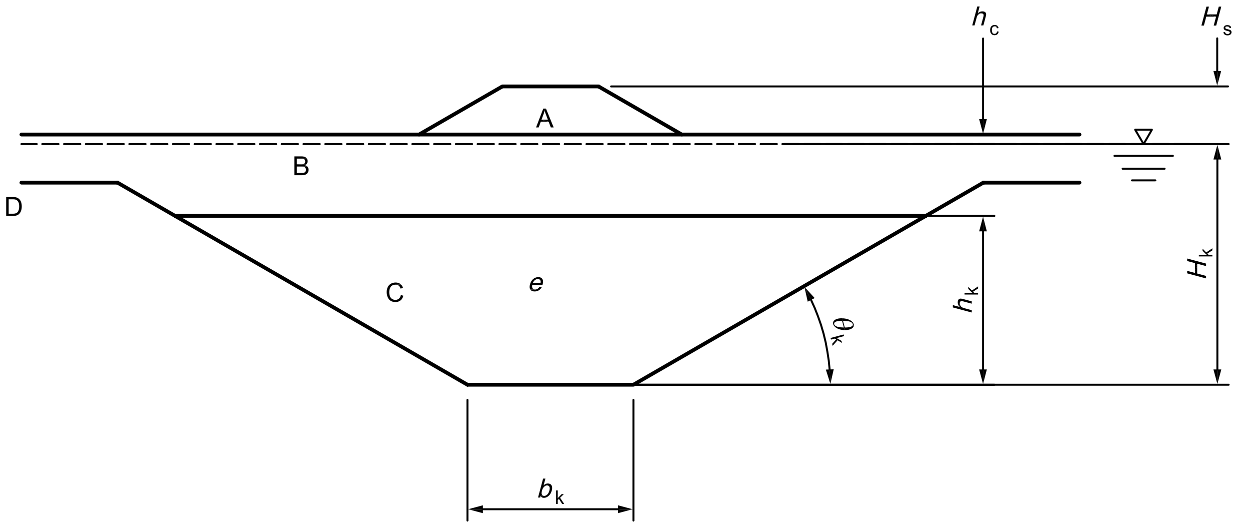
First-year ridges are composed of a sail, a consolidated layer and a keel of lower strength. The keel consists of partly consolidated ice blocks or loose ice blocks with friction only between the blocks. A major part of the consolidated layer is a rafted ice sheet where several thinner sheets of parent ice are refrozen one above the other. The geometrical forms of ice ridges vary in nature. In design, it can be assumed that the cross-section of an ice ridge is symmetric, as illustrated in Figure A.8-12.

The sail height and the level ice thickness are often used as key parameters to define other geometrical shape parameters. For the ridge profile shown in Figure A.8-12, typical relationships are given as $h_c = 1{,}6h$, $H_k = 4{,}5H_s$ and $\theta_k = 26°$. The width parameter can vary from $b_k = 0$ to $b_k = 5H_s$. The porosity of the ridge keel depends on the age of the ice ridge and varies in different sea areas. Some key indices of ridge shape are outlined in Reference [A.8-20].

The thickness parameters h_c and H_k depend on geographical location. Thicker consolidated layers and keels develop in highly dynamic sea areas due to the rafting process. Therefore, it is suggested that field data be used to specify statistical characteristics of the consolidated layer. Existing field data suggest that the parameters h_c and H_k are not correlated with each other. In the absence of field data, it can be assumed in a deterministic analysis that h_c is 2,0 times the thickness of an ice sheet that has grown in open water under the same conditions as the ice ridge.

The thickness h_c of the consolidated layer of an ice ridge is locally variable in the vicinity of the structure during an ice action. This can be considered if field data are available to create a probability distribution for the consolidated layer thickness. Using this probability distribution, an average value of the consolidated layer thickness can be determined for each event. The average value can be determined by considering the thickness variability in an area of $A = w^2$, where w is the width of the structure.

If detailed data are not available, the keel porosity can be assumed to have a uniform probability distribution with a lower bound of 0,1 and an upper bound of 0,4.



Key

A	ridge sail
B	ridge consolidated layer
C	ridge keel
D	level ice
H_s	sail height
H_k	keel depth
h_c	consolidated layer thickness
h_k	vertical distance between the base of the consolidated layer and the base of the keel
b_k	width of the base of the keel
e	keel porosity
θ_k	keel angle

Figure A.8-12 — Idealized geometry of a first-year ridge

An accurate, theoretical determination of the actions caused by ice ridges is difficult. An upper bound estimation of the horizontal action caused by a first-year ridge, F_R, can be obtained as given by Equation (A.8-48):

$$F_R = F_c + F_k \tag{A.8-48}$$

where

F_c is the action component due to the consolidated part of the ridge;

F_k is the keel action component.

Since the volume of the sail is small compared to that of the keel, the effects of the ridge sail can be neglected in the case of first-year ridges. The action component, F_c, can be determined, as an estimate, using instructions given in A.8.2.4.3 and A.8.2.4.3.3 for parameters of the consolidated layer of an ice ridge, or A.8.2.4.4 for sloping structures by substituting h_c for h.

Several models are available for the determination of the unconsolidated keel action component F_k. Passive failure models are generally used to determine the unconsolidated keel action component acting on vertical or inclined structures. Measurements indicate that the keel cohesion often varies from zero at the base of the keel to a maximum immediately beneath the consolidated layer. Under such conditions, the keel action can be determined for vertical structures (see Reference [A.8-21]), with suitable modification (see Reference [A.8-22]) as given by Equations (A.8-49) and (A.8-50):

$$F_k = \mu_\phi h_k w \left(\frac{h_k \mu_\phi \gamma_e}{2} + 2c \right) \left(1 + \frac{h_k}{6w} \right) \tag{A.8-49}$$

$$\mu_\phi = \tan\left(45^\circ + \frac{\phi}{2} \right) \tag{A.8-50}$$

where

μ_ϕ is the passive pressure coefficient;

ϕ is the angle of internal friction;

c is the apparent keel cohesion (an average value over the keel volume should be used);

w is the width of the structure;

γ_e is the effective buoyancy, in units consistent with c.

The effective buoyancy is given by Equation (A.8-51):

$$\gamma_e = (1 - e)(\rho_w - \rho_i)\, g \tag{A.8-51}$$

where

e is the keel porosity;

ρ_w is the water density;

ρ_i is the ice density.

Guidance for the specification of ridge keel parameters is provided in A.8.2.8.8.

Alternative equations can be derived to obtain the unconsolidated keel action component, F_k, on a sloping structure. Measurements indicate that the keel cohesion varies from zero at the base of the keel to a maximum immediately beneath the consolidated layer. An average value over the keel depth is appropriate for use in Equation (A.8-49).

The application point for the action of a first-year ridge keel can be assumed to be at one third of the keel depth below the base of the consolidated layer.

To calculate the keel action on a multi-leg structure, the sum of the keel action from each individual leg should be checked against the action on the effective width of the structure and the lower action selected. In addition, the vertical action of ice rubble should be considered if the ice acts against a submerged portion of the structure.

Equations (A.8-49) to (A.8-51) represent a limit stress approach for actions due to ice ridges. Other failure modes, such as the ridge building process, plug shear failure and out-of-plane ridge failure (see A.8.2.4.2), can limit the design action. The plug failure case tends to occur when the ice blocks are loose or when the cohesion is uniformly distributed in the vertical direction. The model described in References [A.8-15] and [A.8-23] can be used in such conditions.

A.8.2.4.5.2 Multi-year ridges

The size and shape of multi-year ridges vary considerably. Multi-year ridges are more rectangular in shape than first-year ridges. The ratio of the keel depth to sail height is approximately 3,3 for Beaufort Sea multi-year ridges. The keel angle is approximately 30°, and the sail angle is about 20° from the horizontal. Ridge shape parameters should be specified according to geographical location. Total ice thickness, sail and keel, should be used when determining MYI ridge thickness.

Conceivable failure modes for multi-year ridges interacting with vertical structures include crushing, shearing and in-plane bending (see A.8.2.4.2). The action exerted by the ridge is the minimum for these modes of failure.

When the structure is wide relative to the ice thickness, the crushing pressure for multi-year ice failing directly on the structure is determined using Equation (A.8-21). For ice failing within the floe and behind a ridge, the same equation and parameters are used for the pressure. Some practitioners have multiplied these pressures by 1,5 to account for the frozen-in condition.

When shear failure modes are considered for multi-year ridges, an average bulk shear strength value of 0,25 MPa with a range of 0,15 MPa to 0,4 MPa has been used by some practitioners. Correspondingly, the flexural strength of a multi-year ice feature can be taken as 0,40 MPa, although values ranging to 1 MPa are used by some practitioners.

Multi-year ridge actions against conical structures can be estimated using a variety of methods[A.8-15], [A.8-24], [A.8-25]. Scale effects are not considered in these models. If scale effects on flexural strength are considered, potentially lower actions values can be calculated for extreme-level ice actions. An example is provided in Annex C of Reference [A.7-2].

A.8.2.4.6 Limit force actions due to the ridge building process

To calculate the ice actions due to ridge building, two key parameters are needed as inputs (Figure A.8-13). One is the ridge building action per unit of length, p_D, on the back of the floe. The other is the ice feature width, D, over which the pack ice is acting. The limit ridge building action is given by Equation (A.8-52):

$$F_B = p_D D \tag{A.8-52}$$

Observations of ridge building and ice rubble building in front of structures indicate that the ice fails out-of-plane in bending. The first estimates of the limit actions are based on analytical models for ridge building. Experiments were conducted in the 1980s and 1990s in the Beaufort Sea. In some test series, pressure instruments were embedded in the ice floes. The results from these tests[A.8-26], [A.8-27] show that the ridge building action depends on the width, D, of the ice feature as illustrated in Figure A.8-14.

A general expression for the ridge building action is given by Equation (A.8-53):

$$p_\mathrm{D} = R\,h^{1{,}25} D^{-0{,}54} \tag{A.8-53}$$

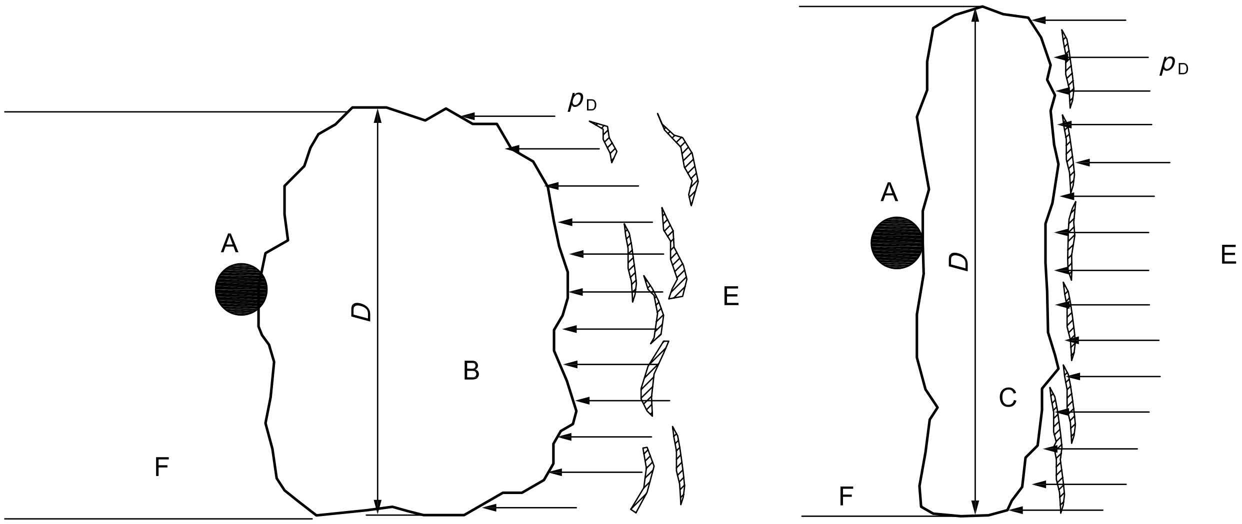
where

p_D is the ridge building action per unit width, expressed in meganewtons per metre;

h is the thickness of the ice sheet acting on the thicker ice feature, expressed in metres;

D is the width of the thicker ice feature, expressed in metres;

R is a coefficient, see Figure A.8-14.



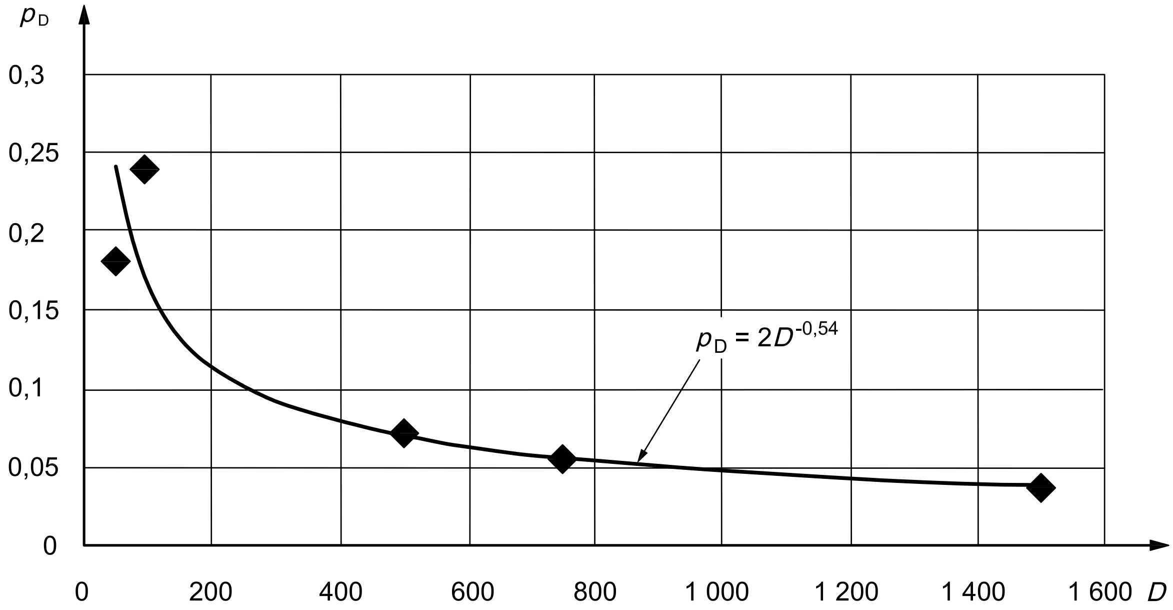
a) Ridge building action for thick floe

b) Ridge building action for consolidated ridge

Key

A structure
B thick ice floe
C thick consolidated ice ridge
E surrounding ice sheet
F open water in wake of structure
D width of the ice feature, expressed in metres
p_D line load imposed on the width of the ice feature

Figure A.8-13 — Ridge building action behind thick floe or ridge



Key

p_D ridge building action, expressed in meganewtons per metre

D width of thicker ice feature, expressed in metres

Figure A.8-14 — Ridge building action versus width
(normalized using thickness to the power 1,25)

Based on a review of the theories for rubble building and the measured data, it is suggested that, for widths less than 100 m, rubbling failures cannot be relied on, and the methodology for crushing actions (see A.8.2.4.3 and A.8.2.4.3.3) should be used. For this reason, an upper bound relationship has been adjusted from the field data to approximately match the crushing equation at 100 m width and 1 m of ice. The few data for widths greater than 1 500 m suggest a levelling-out of the line actions with width, and applied ridge building line actions should not generally be less than the value corresponding to a width of 1 500 m.

Based on these considerations, an upper bound estimate at the 99 % confidence level is obtained by selecting $R = 10$. Based on judgment, a 50 % confidence level ridge building line action is given by the Equation (A.8-53) with $R = 6$. If a probabilistic methodology is used, it is recommended that the parameter R be uniformly distributed between 2 and 10.

Equation (A.8-53) is based mainly on data for first-year ice actions. This equation can also be used where 2 m thick first-year ice surrounds a multi-year floe with diameter of 300 m or greater. A recommended value of the scaling parameter is $R = 10$. The frozen-in condition can be considered by application of a multiplicative factor of 1,5 to the ridge building action. If the diameter of the multi-year floe is less than 300 m, Equation (A.8-21) can be used.

A.8.2.4.7 Limit energy global ice actions

A.8.2.4.7.1 Full-scale data

Relevant full-scale measurement programmes where the kinetic energy of the ice feature limited the ice actions include:

- Hans Island multi-year floe impact programme in 1980-83;
- several well documented impacts of multi-year ice floes against the Molikpaq structure in the spring of 1986;

- measurements of ice floe impacts against an artificial island in the Tatar Strait in 1992;
- small iceberg impact test in Antarctica in 1990;
- Bergy bit impact tests at Newman's Cove in 1992 and Grappling Island in 1995;
- Bergy bit impact tests with the icebreaker Terry Fox in 2001.

Except for the multi-year floe impacts, most of the field data are obtained from experiments with relatively small ice features, on the order of hundreds to several thousand tonnes. Uncertainty should be considered when extrapolating these data to design situations involving features of several hundred thousand to several million tonnes.

A.8.2.4.7.2 Kinetic energy lost due to rotations of the ice feature

A large portion of the initial kinetic energy can be transferred into rotation of the ice feature during eccentric impacts, thereby mitigating the action relative to head-on impacts. If E_0 is the initial kinetic energy of the ice feature, the reduced kinetic energy after rotation for impact with a fixed structure is given by Equation (A.8-54)[A.8-28]:

$$E_\mathrm{K} = \frac{E_0}{1 + \dfrac{\varepsilon_\mathrm{z}^2}{r_\mathrm{z}^2} + \dfrac{\varepsilon_\mathrm{y}^2}{r_\mathrm{y}^2}} \tag{A.8-54}$$

where

ε_z, ε_y are the eccentricities in the vertical and horizontal planes respectively;

r_z, r_y are the corresponding radii of gyration of the ice feature.

The eccentricities represent offset distances between the point of contact and the centre of mass of the ice feature relative to the direction of motion immediately prior to impact. The radii of gyration should reflect added inertia effects. For ice floe impacts, the $\varepsilon_\mathrm{z}^2/r_\mathrm{z}^2$ term can generally be ignored.

For probabilistic and semi-probabilistic analyses, eccentricities and radii of gyration should be random parameters reflecting the range of ice feature sizes, contact geometries and ice drift directions relative to the structure. A reduction in the impact energy due to ice feature rotation can be made for deterministic analyses when adequately substantiated or when dictated specifically by the structure and ice feature geometries.

A.8.2.4.7.3 Impact actions

The ice actions resulting from impacts can be calculated using numerical algorithms or closed-form analytical solutions. The underlying assumption in both cases is that the impact action reaches its maximum value when the penetration stops and the nominal contact area reaches its maximum.

Both analytical, closed-form solutions and numerical models require that the instantaneous impact action be expressed as a function of penetration depth. Such a function can be presented as a combination of the pressure-area relationship, which describes strength properties of ice and the contact area, with the penetration depth relationship, which depends only on the structure and the ice feature geometries.

A closed-form solution[A.8-28] can be obtained when each of these relationships is represented as a power law. The pressure-area relationship for general ice feature shapes can be expressed as given by Equation (A.8-55):

$$p = C_\mathrm{P}\, A_\mathrm{N}^{\,D_\mathrm{P}} \tag{A.8-55}$$

where

A_N is the nominal contact area;

C_P, D_P are coefficients.

The contact area-penetration depth relationship is given by Equation (A.8-56):

$$A_N = C_A \, \delta^{D_A} \tag{A.8-56}$$

where

δ is the penetration depth of the structure into the ice;

C_A, D_A are coefficients.

The maximum action at the end of the interaction is given by Equation (A.8-57):

$$F_E = a\left[\frac{b+1}{a} E_K\right]^{\frac{b}{b+1}} \tag{A.8-57}$$

where

E_K is the impact energy after correction for ice feature rotation;

$a = C_P C_A{}^{D_P+1}$;

$b = D_A(D_P + 1)$ for $b \geqslant 0$[A.8-28].

For floes or ice features of relatively constant thickness, the pressure relationship can be expressed as given by Equation (A.8-58):

$$p = C_h \, h^{D_1} \, w^{D_2} \tag{A.8-58}$$

where

h is the ice thickness;

w is the interaction width.

The corresponding contact area relationship is given by Equation (A.8-59):

$$A_N = h \; C_w \, \delta^{D_w} \tag{A.8-59}$$

where C_w and D_w are coefficients.

In this case, the coefficients in Equation (A.8-57) are $a = C_h C_w{}^{D_2+1} h^{D_1+1}$ and $b = D_w(D_2 + 1)$. The coefficients C_w and D_w should be determined from the geometry of the structure and ice features. In the absence of site-specific ice feature geometry, simple geometric shapes can be used.

The contact area relationships shown above can be used to represent a variety of structure and ice feature shapes, and are not limited to small penetration depths as long as the power law forms are appropriate. For floes, the parameters C_w and D_w should be based on measurements of the plan shape of floes in the region of interest and from the shape of the structure. For massive ice features such as icebergs, the parameters C_A

and D_A should be based on measurements of the local shape of the ice features and from the shape of the structure. In the absence of site-specific data, simple geometric shapes can be used to represent the local ice shape. For circular floes and flat or circular structure faces, the power law is a good approximation for small penetrations relative to the floe and structure radii.

For deterministic solutions, the pressure, contact area and contact width coefficients are constant. As a first approximation for sea ice floe interactions, the parameter C_h can be assumed to be equal to C_R in Equation (A.8-21). For certain parameter combinations, values less than C_R can potentially yield larger actions and it is recommended that a range of values up to and including C_R be verified. In the absence of measured data, a correspondence can be made between exponents D_1 and D_2 and the parameters of Equation (A.8-21) as $D_1 = n - m$ and $D_2 = m$.

For probabilistic solutions, the contributing parameters can be random, and the contact areas or widths should reflect the distributions of measured ice feature shapes and ice impact orientations with respect to the structure. The distribution of pressures should reflect the average impact pressure over each interaction. For impact situations, random values of the pressure coefficients, C_P and D_P, can be used; see Equation (A.8-24).

A.8.2.4.7.4 Hydrodynamic effects

Hydrodynamic effects associated with ice feature motions in the vicinity of the structure can be considerable, especially in conditions where the ice concentration is low and relatively small ice features are impacting wide structures. Due to hydrodynamic effects, smaller ice features can slow down as they approach and tend to move around the structure. Consideration should be given to added mass of the impacting ice feature, with due account for the presence of the seabed and the structure[A.8-29]. When the structure moves sufficiently during the course of the interaction, its added mass should also be considered.

A.8.2.4.7.5 Structural compliance

Structural compliance has a complex effect on the impact action. The maximum impact action is smaller for a compliant structure because part of the kinetic energy of the impacting ice feature is spent in structural deformation or displacement. On the other hand, actions on the mooring system or the structure foundation can increase due to the inertial effects if the duration of the impact is comparable to the first natural period of the structure.

Equations (A.8-54) to (A.8-59) do not take account of the structural compliance. Special consideration should be made in such cases.

A.8.2.4.8 Floating structures

Floating structures in iceberg and sea ice environments are unique in that they generally have disconnection capability and operate with ice management support. These are coordinated using an ice management plan that includes an alert system for staged shutdown as outlined in Clauses 13 and 17, and A.13, and A.17.

When the floating structure is connected, it is necessary to consider global ice actions for the stationkeeping system and hull for the parameter distributions associated with managed ice. Of particular concern are those features at the upper end of the managed ice distribution for which the actions approach the capacity of the stationkeeping system. It is also necessary to consider ice actions on the hull for disconnected states and when in transit. Factors influencing ice actions on floating structures are provided in 13.4.

For iceberg environments, design ice actions can be determined from the frequency of impacts, and the joint distribution of iceberg size, relative speed between iceberg and floater at impact, ice pressure, contact area and other subsidiary conditions. While ice management and disconnection influence the frequency of impacts and the distributions of impact parameters, the procedure for calculation of ice actions on floating structures is similar to that for fixed structures. A key difference is that the flexibility of the stationkeeping system should be factored into the relationship for dissipation of kinetic energy on impact. Other provisions for stationkeeping are addressed in 13.7.

For sea ice environments, ice management and disconnection can reduce the frequency of severe ice events. The ice reaching the structure is typically a slurry of broken ice pieces containing some larger floes and possibly glacial or multi-year ice. Design actions are generally governed by thick ice features that cannot be detected within the surrounding ice cover or that prove more difficult to manage than anticipated, and interactions on the side of ship-shaped structures when weathervaning is impeded.

Actions from managed sea ice are best determined from full-scale data. Reference [A.8-30] outlines a method that uses full-scale load data from the Kulluk conical drilling platform in the Beaufort Sea, for which ice actions have been associated with the size and thickness of the managed ice. This method is also described in Reference [A.8-31]. While other methods based on full-scale icebreaking vessel performance trials have been developed, they have not yet been described in the open literature.

Despite the empirical prediction methods[A.8-30], [A.8-31] for ice actions in managed ice conditions, the requirement for more full-scale measurements should be clearly recognized.

A.8.2.4.9 Multi-leg structures

The calculation method shown below is based mainly on laboratory tests. The global limit stress action on a multi-leg structure can be determined by first using the guidelines provided in A.8.2.4.3 or A.8.2.4.4 to obtain a quasi-static action on one leg. The global action is then as given by Equation (A.8-60):

$$F_\mathrm{S} = k_\mathrm{s}\, k_\mathrm{n}\, k_\mathrm{j}\, F_1 \qquad \text{(A.8-60)}$$

where

F_1 is the ice action on one leg;

k_s accounts for the interference and sheltering effects;

k_n accounts for the effect of non-simultaneous failure;

k_j accounts for the ice jamming.

The ice action depends on the clear distance, L, between the legs in the front row of legs interacting with ice. If this distance is large, each leg interacts with the ice sheet independently of the other legs. In this case, the sheltering factor, k_s, approaches the number, n, of the legs. Where all legs are on a line perpendicular to the drift direction, data from limited model tests suggest that the legs act independently of each other if the ratio of the clear distance, L, between the legs and the width, w, of an individual leg is greater than 5. Field evidence from the Confederation Bridge suggests some interaction between piers for L/w ratios of about 10. For a typical multi-leg structure where the legs are not in a single line, the legs become independent at a higher value of L/w. For a typical multi-leg structure with four legs, the maximal sheltering factor varies from 3,0 to 3,5. The angle of incidence of the ice drift influences the ice action. Some guidance on the distribution of loads between legs for multi-leg structures based on model tests is found in Reference [A.8-32].

The peak values of the actions on different legs are not likely to occur simultaneously unless the structure is very compliant. This can be considered by the reduction factor k_n. In the absence of test data, this parameter can be assumed as $k_\mathrm{n} = 0{,}9$.

Ice jamming between the legs can be expected if L/w is less than 4. This can, but not necessarily always, lead to an increase in the ice action. Experimental data can clarify the influence of ice jamming in a particular design case. Where there is any chance that ice can jam between the legs, both the jammed and unjammed cases should be considered and the maximum value of ice action selected. In the analysis of the jammed case, the limit stress load should be checked for each leg to ensure the load path is feasible. Ice jamming is more likely with a first-year ridge because of the associated ice rubble in the keel. The critical spacing can be wider.

It should be recognized that the ice actions arising in the limit stress conditions described above can be limited due to other failure mechanisms described in A.8.2.4.2. While evaluating these mechanisms, one should consider the possibility that an isolated ice floe stops after interacting with the leading leg. Stopping can also occur at a later stage, before all legs interact with the ice sheet. Guidelines provided in A.8.2.4.6 can be used to estimate the limit kinetic energy action, F_E. Based on this analysis, an initial estimate of the representative action value is selected as the minimum of F_E and F_S obtained from Equations (A.8-57) and (A.8-60).

If the ice floe stops after an initial interaction with the multi-leg structure, the penetration can still continue if a ridge building process (see A.8.2.4.2 and A.8.2.4.6) becomes active and the limit force action, F_F, obtained from Equation (A.8-52), i.e. $F_F = F_B$, is greater than F_E. In such a condition, the representative action on a multi-leg structure is selected as the minimum of F_S and F_F. Further guidance on multi-leg structures can be found in Reference [A.8-33].

A.8.2.4.10 Adfreeze action effects

A.8.2.4.10.1 Adfreeze to piles and supports

Ice can freeze to a structure as an ice bustle in areas where the tidal amplitude is sufficient to fail the ice around the structure with each cycle (see Figure A.8-15). Usually, the new ice formation spreads from the maximal to minimal levels of flood/ebb tides. The rate of the ice growth can be as high as 2,5 cm per cycle and the thickness of this formation can reach several metres. If the spacing between the structure's piles or supports is insufficient, then ice can begin to grow between piles.

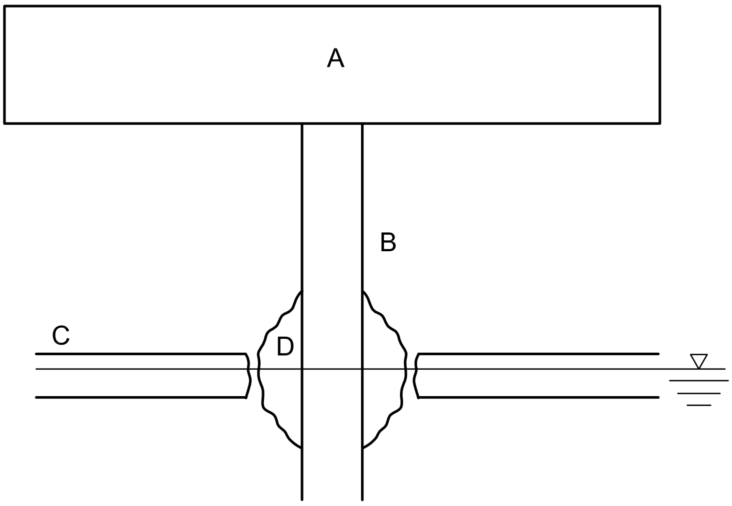
For further information, see Reference [A.8-34].

A.8.2.4.10.2 Horizontal actions due to adfreezing

Ice bustles can cause an increase in the magnitude of horizontal ice actions. This can occur first of all due to an increase in the contact area. Secondly, ice accumulations on the surface of sloping structures can make the contact angle of the oncoming ice steeper, also resulting in increasing vertical and horizontal action due to possible ice crushing instead of flexural failure of the ice.

Another adfreeze phenomenon is the condition where the structure freezes within a level ice sheet. This can occur in the following situations:

- when the structure is located in a sheltered area;
- when the structure is located in an open sea, but the change of the water level during the tide/ebb action or the air pressure variation is very limited, and the ice moves very slowly or is stationary for a long time.



Key

A	quay structure	C	ice surface
B	pile	D	ice bustle

Figure A.8-15 — Schematic of ice bustle formed on quay piles

When the ice begins to move, horizontal actions can exceed those of the drifting level ice with the same parameters because the ice thickness of the adfrozen ice in the vicinity of the structure is greater. An increase in the ice action can occur also after a stopping condition when the ice does not freeze to the structure. This can happen due to healing of the cracks that exist in the ice edge.

The rubble formed during interactions between an ice sheet and an upward sloping structure can freeze together and adfreeze to the structure. This kind of rubble can create a false bow ahead of the structure. False bows with a thickness of 2 m and a width of 3 m have been observed in the field on a pile with a diameter of 1,8 m. Subsequent ice failure events can create actions that cannot be predicted by models derived for sloping structures. When sufficient adfreeze strength is present, the effective structure diameter should include the adfrozen ice mass in calculations.

A.8.2.4.10.3 Vertical actions due to adfreezing

An ice bustle formed on the piles of a structure can impede vessel access and create additional vertical actions that should be verified in the design. Ice bustle thickness tends to reach a limit after some time as the formation process is controlled by the water surface at high tide. When the water level changes, the ice cover that is attached to a structure bends and creates a vertical action. The limits of ice adfreeze bond strength or ice flexural strength restrict the magnitude of this action.

During water level fluctuations, pile uplift can be of concern for light structures. Adfrozen ice pulls the pile upwards, soil sloughs into the cavity under the pile bottom and prevents the pile from sinking to its original depth after the water level recedes. Adhesion or bending failure breaks the ice free from the pile. During repeating adfreeze and water level fluctuations, the pile can be gradually jacked up. Pile motions of over 2 m have been observed for water level fluctuations of less than 20 cm.

Natural processes that reduce the break-out load are

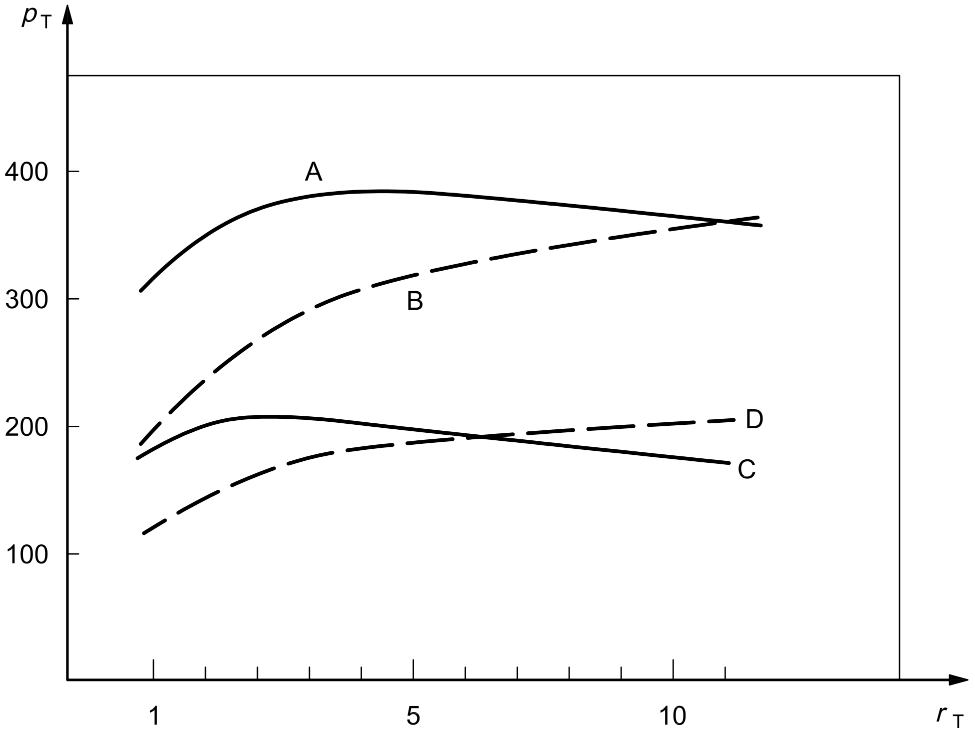
- the slow initial load build-up, which limits the ice action;
- the progressive non-simultaneous adfreeze failure.

A.8.2.4.11 Thermal action effects

In sheltered areas and areas near the shore, ice actions can occur due to rising temperatures when ice expansion is restricted by fixed structures or other obstructions. Based on full-scale measurements made in Russian and Canadian sea areas, sea ice does not expand appreciably for ice temperatures above −10 °C for salinities greater than 3 ‰ or above −7 °C for salinities greater than 1 ‰.

The thermal ice action depends mainly on the initial ice surface temperature and the rate of temperature increase. This is shown in Figure A.8-16 for freshwater ice sheets with complete lateral restraint.

For a preliminary assessment of thermal actions, indicative values in the range of 150 kN/m to 300 kN/m can be used regardless of the ice thickness[A.8-35] to [A.8-37]. Thermal actions in freshwater ice are larger in magnitude than those in sea ice.



Key

A	T = –30 °C and h = 1,0 m	p_T	thermal ice pressure, expressed in kilonewtons per metre
B	T = –30 °C and h = 0,5 m	r_T	rate of temperature increase, expressed in degrees Celsius per hour
C	T = –20 °C and h = 1,0 m	h	ice thickness
D	T = –20 °C and h = 0,5 m		

Figure A.8-16 — Thermal ice load versus the rate of temperature increase of the ice surface[A.8-35]

A.8.2.5 Local ice actions

A.8.2.5.1 Overview of local ice actions

While global actions are calculated from average pressures over the nominal contact area, there can be many areas within the nominal contact area that are subjected to higher local pressures, see Figure A.8-8. Consequently, global average pressures should not be used for local design and a separate consideration of local pressures is necessary. Local pressures should be used, for example, in the design of shell or stiffening elements as illustrated in Figure A.8-17. The same concept for loaded area applies to concrete structures.

Ice interactions can produce local pressures that can be considered as constant over an area as given by Equation (A.8-61):

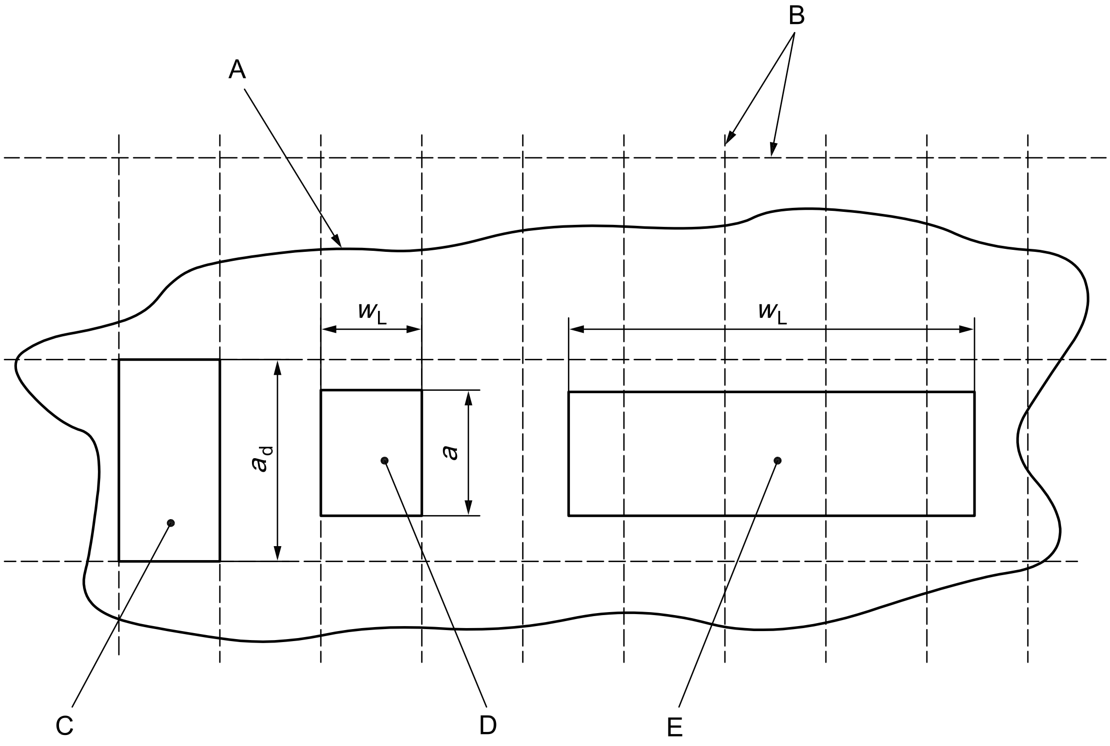
$$A = a \cdot w_L \tag{A.8-61}$$

where

a is the height of the loaded area;

w_L is the width of the loaded area.

Maximum action effects usually occur when the height, a, of the loaded area equals the height of the local design area, a_d (Figure A.8-17). For level ice, w_L is greater than 4 times the ice thickness[A.8-38].



Key

A	global interaction area (grows as interaction proceeds)	a	loaded height
B	frames and stiffeners	a_d	frame spacing
C	local area for plate design	w_L	loaded width
D	loaded area for plate design		
E	loaded area for stiffener design		

Figure A.8-17 — Definition of loaded areas for local actions

Local ice pressures differ depending on the thickness of the ice encountering a structure. For sea ice up to about 1 m thick, the proximity of the upper and lower free surfaces of the ice limits the ice pressure (see A.8.2.5.2). In contrast, thick multi-year ice and icebergs are capable of providing the confinement required to produce higher pressures for the same loaded area (see A.8.2.5.3). Methods are presented in A.8.2.5.2 to A.8.2.5.5 for evaluating local pressures in each case. The methods described in A.8.2.5.2 and A.8.2.5.3 provide pressures in ELIE conditions while the method described in A.8.2.5.4 can be used to obtain pressures both in ELIE and ALIE conditions. For impact pressures from discrete ice features or glacial ice, reference should be made to A.8.2.5.4. It is emphasized that the relationships in A.8.2.5.2 and A.8.2.5.3 are based on datasets with different environmental conditions. As a result, their correspondence is not exact and they might not yield the same local pressures for the same ice thicknesses. Sound judgment should be used in their application.

A.8.2.5.2 Local actions from thin first-year ice

A.8.2.5.2.1 Overview

A method is described in A.8.2.5.2 for determining local pressures from first-year ice up to approximately 1 m thick. This method applies to level ice, rafted ice and consolidated layers of first-year ice ridges. Considerable data exist from full-scale local pressure measurements for level and rafted ice conditions. Pressure panels were used to measure the average pressure on an area approximately 1 m wide over the full ice thickness. Based on these data, the largest actions on vertical structures tend to occur at low ice velocities. In such situations, local ice failure occurs simultaneously over a major proportion of the ice thickness because of the ductile behaviour of the ice. The approach described in A.8.2.5.2 is based on Reference [A.8-38].

A.8.2.5.2.2 Representative values of local actions

Local action effects can be assessed by the application uniformly over a local design area of the action, F_L, expressed in meganewtons, as given by Equation (A.8-62) for a_d greater than 0,14:

$$F_\mathrm{L} = 3{,}72 \cdot \sqrt{a_\mathrm{d}} \cdot w_\mathrm{L} \qquad \text{(A.8-62)}$$

where

a_d is the height of the local design area, expressed in metres;

w_L is the width of the local design area, expressed in metres;

Equation (A.8-62) is valid for the following conditions:

a) $w_\mathrm{L}/a_\mathrm{d} \leqslant 10$;

b) $a_\mathrm{d} \leqslant 0{,}4\ h_\mathrm{E}$, where h_E is the characteristic ice thickness for ELIE.

If the height of the local design area exceeds 0,4 h_E, Equations (A.8-63) and (A.8-64) can be used to determine the local actions. It is not necessary to consider local actions for $w_\mathrm{L}/a_\mathrm{d}$ greater than 10.

A.8.2.5.2.3 Full thickness local pressure

Full thickness local ice pressure is associated with the full ice sheet (floe) thickness. Equation (A.8-62) is based on an interpretation of data from the Gulf of Bothnia[A.8-39]. Its derivation is based on an upper bound value for the full thickness pressure, p_F, expressed in megapascals, as given by Equation (A.8-63):

$$\begin{aligned} p_\mathrm{F} &= 2{,}35\ h^{-0{,}50} && \text{for } h > 0{,}35\ \text{m} \\ p_\mathrm{F} &= 4{,}0 && \text{for } h \leqslant 0{,}35\ \text{m} \end{aligned} \qquad \text{(A.8-63)}$$

where h is the ice thickness, expressed in metres.

In a deterministic design, the local pressure acting on the loaded area [see Equation (A.8-61)] is given by Equation (A.8-64):

$$p_\mathrm{L} = \gamma_\mathrm{L}\ p_\mathrm{F} \qquad \text{(A.8-64)}$$

where

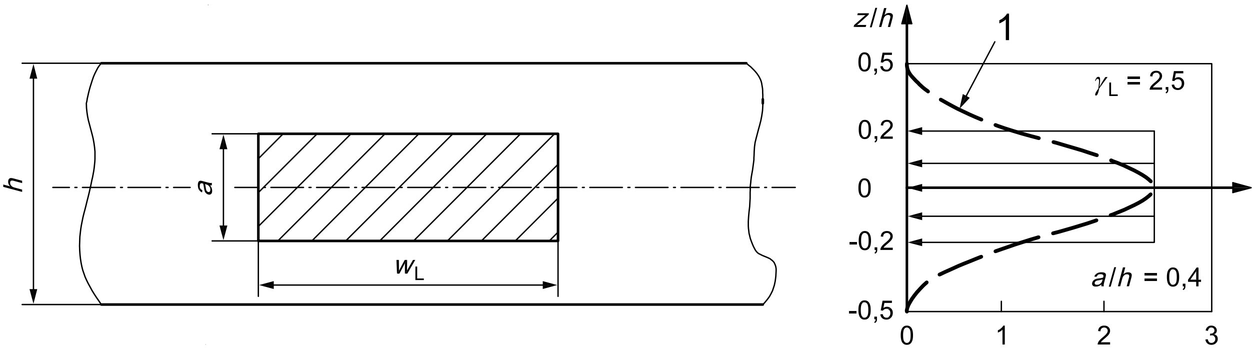
γ_L is equal to 2,5;

p_F is the full thickness pressure defined by Equation (A.8-63), equal to $p_\mathrm{F}(h)$.

The coefficient, γ_L, reflects a simplified vertical distribution of the full thickness pressure on the loaded area, A, which is equal to $a \cdot w_\mathrm{L}$, as illustrated in Figure A.8-18.

A.8.2.5.2.4 Local design at discontinuities in the structure

Local stress concentrations can occur close to discontinuities such as the corners of a rectangular structure. In these areas, the magnitude of full thickness pressures can reach 2,5 to 3,0 times the usual full thickness pressure. Higher design pressures should be considered over a horizontal distance from the corner equal to the ice thickness[A.8-40].



a) **Loaded area** b) **Pressure distribution**

Key

1	data obtained from field measurements
h	ice thickness
z	distance from mid-depth of ice
γ_L	pressure distribution coefficient
a	loaded height
w_L	loaded width

Figure A.8-18 — Distribution of the full thickness pressure on the loaded area

A.8.2.5.2.5 Probabilistic local design

The method described in A.8.2.5.2 can also be used for probabilistic analyses by determining a joint probability density function for the ice thickness and the full thickness local pressure, and then applying the guidelines of A.8.2.2.

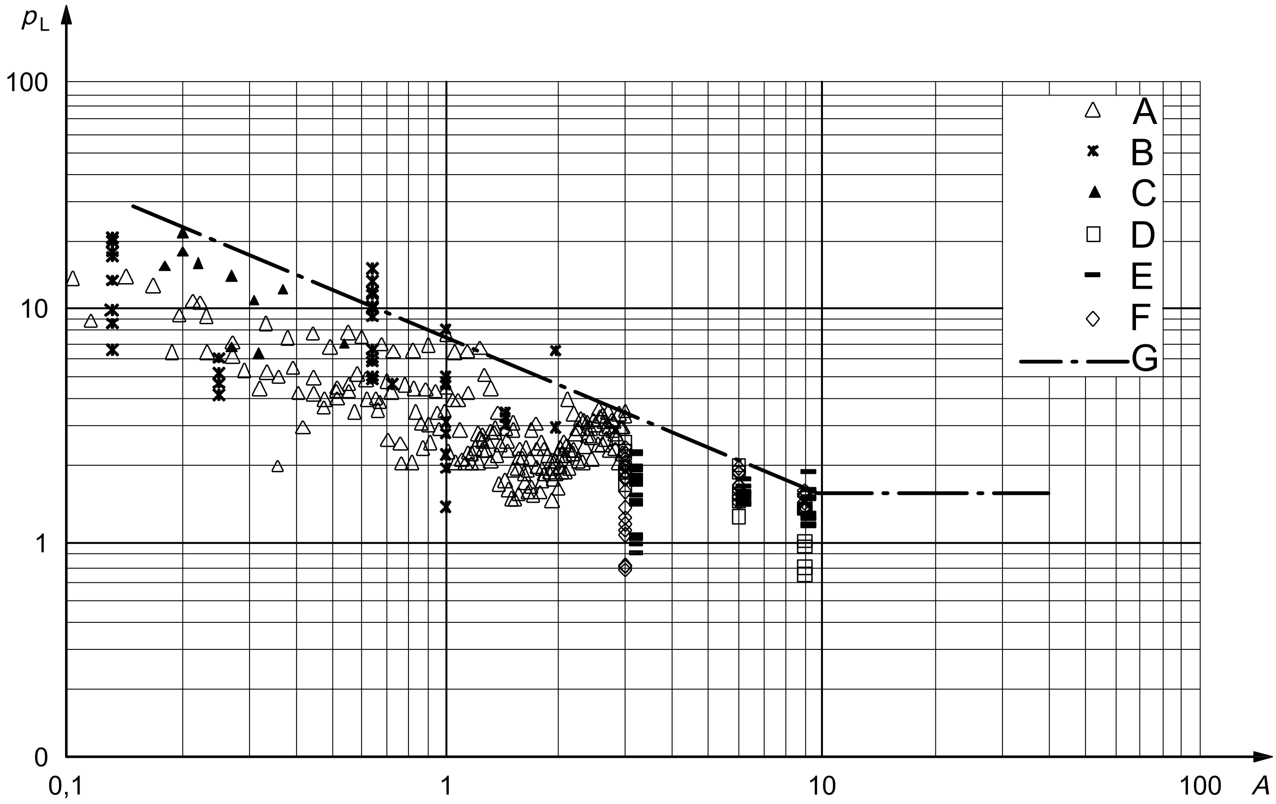
A.8.2.5.3 Local pressures for thick, massive ice features

Local pressures due to massive ice features having a thickness in excess of 1,5 m can be determined using data shown in Figure A.8-19[A.8-41]. These data have been derived from indentation tests in the Beaufort Sea and from measurements made on the ice pressure panels of the Molikpaq structure in the same area.

Based on these data, the local pressure, p_L, expressed in megapascals, acting on the loaded area can be determined as given by Equation (A.8-65):

$$\begin{aligned} p_L &= 7{,}40\ A^{-0{,}70} && \text{for } A \leqslant 10\ \text{m}^2 \\ &= 1{,}48 && \text{for } A > 10\ \text{m}^2 \end{aligned} \tag{A.8-65}$$

where A, expressed in square metres, is the local design area (see Figure A.8-17).



Key

A 3 m^2 Pond Inlet test data

B flat jack test data

C 1989 Hobson's Choice test data

D Molikpaq BW data

E Molikpaq N face data

F Molikpaq E face data

G $p_L = 7{,}40A^{-0{,}70}$ (mean plus three times the standard deviation), $A \leqslant 10$ m^2; $p_L = 1{,}48$, $A > 10$ m^2

p_L local ice pressure, expressed in megapascals

A contact area, expressed in square metres

Figure A.8-19 — Compilation of data for ice pressures as a function of the loaded area

A.8.2.5.4 Probabilistic model for local ice pressures

A probabilistic local pressure model has been developed based on data from ship impacts with multi-year ice floes[A.8-42]. Data are primarily from measurements of the Kigoriak ramming tests on multi-year ice and these are supplemented with data from other vessels. The model gives a probability distribution for the maximum annual pressure, p, corresponding to an annual exposure, μ. Exposure is expressed as a proportion of the average duration of 0,7 s for rams in the Kigoriak trial.

EXAMPLE For an annual exposure of 7 s, the exposure factor, μ, is equal to 7 s divided by 0,7 s, or 10.

The cumulative probability distribution given by Equation (A.8-66) can be used for the local pressure p, representing the decrease of pressure, expressed in megapascals, acting on an area A, expressed in square metres:

$$F_P(p) = \exp\left[-\mu \exp(-p/\alpha)\right] \qquad \text{(A.8-66)}$$

where

$$\alpha = A^{-0,7} \tag{A.8-67}$$

Equation (A.8-66) is appropriate when considering a single panel as is usual in design. If the maximum action on n panels is required, an exposure of $n\mu$ should be used instead of μ.

The approach is appropriate for a number of discrete impacts per year, and can be applied for impacts of bergy bits with floating structures and for multi-year ice interactions. A possible speed effect on local pressures can be included when relevant field data become available.

A.8.2.5.5 Local ice pressure combinations

Local ice actions on a structure hull occur at different locations for different contact areas over time, as has been discussed previously. Figure A.8-17 illustrates the principle. A local ice pressure, p_L, is applied over an area, A_L, while there is a pressure p_0 over a much larger portion of the hull with an area, A_0. In general, this pressure is the global ice pressure obtained from Equation (A.8-21). A higher local pressure, p_L, sometimes referred to as a hot spot, is obtained from Equations (A.8-58), (A.8-59) or (A.8-61). The pressure, p_L, is the total pressure at this location and is not added to p_0.

The pressure, p_0, can also be determined from Equations (A.8-58), (A.8-59) or (A.8-61) and applied over an area larger than A_L. For example, an average pressure, p_0, can be applied over the space between bulkheads of a structure and the local pressure, p_L, can then be the pressure on plating spanning between stiffeners.

Considering force equilibrium, the pressure surrounding the local area is less than p_0, and can be determined as given by Equation (A.8-68):

$$p_0^\mathrm{p} = \frac{p_0 A_0 - p_\mathrm{L} A_\mathrm{L}}{A_0 - A_\mathrm{L}} \tag{A.8-68}$$

Figure A.8-20 illustrates the method of combining the local pressure with a pressure acting on a larger area. It is necessary to use judgment in determining the combination of pressures for use in the design. Some combinations are more critical than others, and the process of determining these is one of trial and error. Because of the considerable variability of hull configurations, no prescriptive set of combinations can be specified.

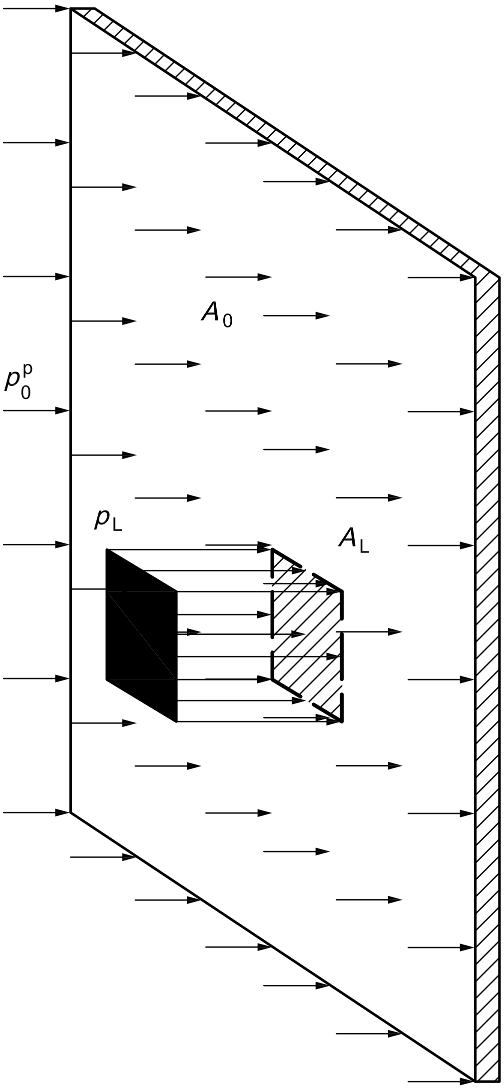
A.8.2.6 Dynamic ice actions

A.8.2.6.1 Dynamic actions on vertical structures

A.8.2.6.1.1 General

The guidelines provided in A.8.2.6.1 are based mainly on full-scale data for narrow structures. These include intermittent ice crushing, frequency lock-in and random vibrations due to continuous ice crushing. The main aim of a dynamic analysis is to ensure that the structure does not encounter a frequency lock-in condition.

The dynamic ice-structure interaction known as frequency lock-in, or self-excited vibration, can arise when sheet ice acts continuously on a vertical structure at a moderate ice speed, ranging typically from 0,04 m/s to 0,1 m/s. The steady-state vibrations that arise due to the lock-in phenomenon can cause low cycle fatigue in steel structures and can also cause liquefaction in the soil beneath the structure. Vibrations can also affect topsides structures, such as flare booms, see 15.1.1.3. Consequently, a static design should be supplemented with a dynamic analysis if there is a risk of frequency lock-in for a particular structure. Based on field experience, structures with a fundamental frequency in the range of 0,4 Hz to 10 Hz have experienced self-excited vibrations when the total structural damping (as a fraction of critical) has been lower than about 3 %.



Key

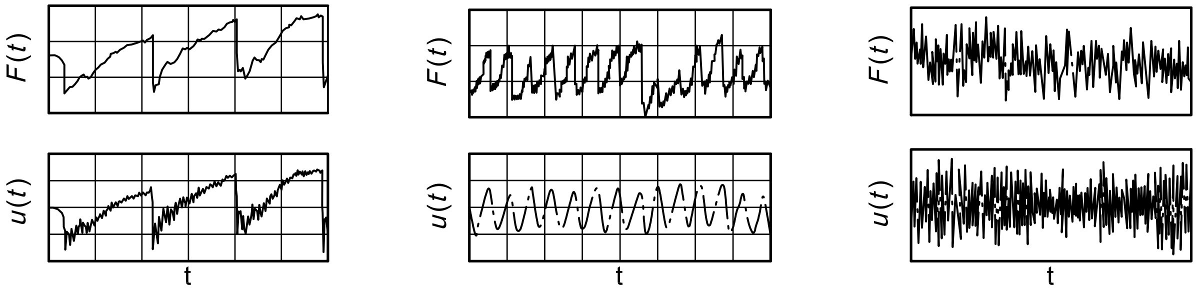
p_L	local ice pressure patch
A_L	local contact area, expressed in square metres
p_0^p	background ice pressure
A_0	background area

Figure A.8-20 — Method of combining the local pressure with a pressure acting on a larger area

Detailed studies should be conducted for the assessment of vibrations for wide structures. Narrow vertical structures can be sensitive to several kinds of dynamic ice-structure interactions.

A.8.2.6.1.2 Time-varying interaction processes

The dynamic ice-structure interaction process is influenced by the ice velocity and the waterline displacement of the structure. Figure A.8-21 illustrates the three primary modes of interaction in terms of ice force, $F(t)$, and the corresponding displacement, $u(t)$, as measured in full-scale structures in the Bohai Sea.



a) Intermittent ice crushing **b) Frequency lock-in** **c) Continuous brittle crushing**

Key

t time

F ice action

u structure displacement

Figure A.8-21 — Modes of time-varying action due to ice crushing and the corresponding dynamic component of structure response

An interaction phenomenon known as intermittent ice crushing, depicted in Figure A.8-21 a), can arise if a compliant structure is exposed to ice action at a low speed. The interaction involves a loading phase and an unloading phase. In the loading phase, the structure moves in the same direction as the ice. The ice edge experiences ductile deformations and the ice action gradually increases. The external ice action and the internal forces of the structure are usually in a static balance when the ice action reaches a maximum value. At the peak value of ice action, brittle crushing starts at the ice edge, leading to relaxation vibrations in the structure that decay during the unloading phase. The rate of decay depends on the total damping provided by the soil and the structure.

Frequency lock-in, depicted in Figure A.8-21 b), can occur at intermediate ice speeds as the time-varying ice actions adapt to the frequency of the waterline displacements of the structure. The vibrations of the structure are typically sinusoidal in this condition. Similar to intermittent crushing, the ice-structure interaction exhibits alternating phases of ductile loading and brittle unloading. The time history of the ice action depends on the characteristics of the ice and the structure.

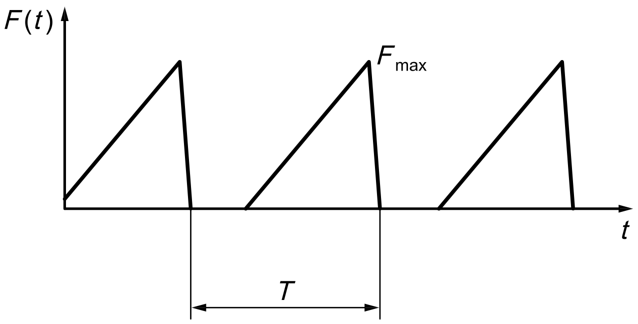
Figure A.8-21 c) shows typical records of the ice action and the structural response for continuous brittle crushing. This occurs at higher ice speeds, typically when $v > 0{,}1$ m/s. Both the ice action and the response are random. If required, the response of the structure can be calculated in the frequency domain using a power spectral density function to characterize the ice action.

A.8.2.6.1.3 Dynamic response to intermittent crushing

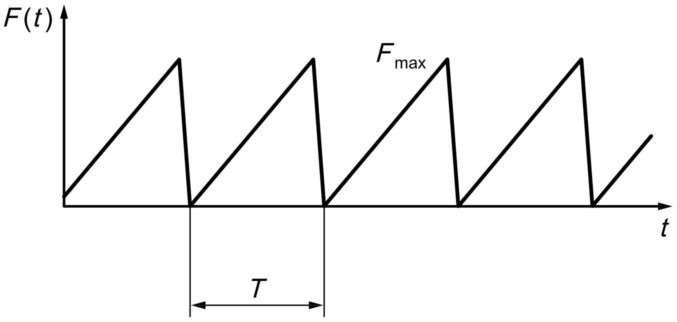
Figure A.8-22 shows idealized time histories of ice actions that can arise due to intermittent crushing. The period, T, of the ice action is much longer than the longest natural period of the structure. The time history shown in Figure A.8-22 a) can also arise from a splitting failure mode where the period, T, of the ice action is longer than the duration of the loading/unloading cycle.

General-purpose finite element software can be used to calculate the response of the structure due to the ice actions. The peak action, F_{max}, can be determined by the method described in A.8.2.4.3 as the static global ice action, F_{G}.

The dynamic analysis is focused on effects of the relaxation oscillations. It is, therefore, often sufficient to determine the response to a single loading cycle.



a) Period of ice action greater than duration of loading/unloading cycle



b) Period of ice action equal to duration of loading/unloading cycle

Key

t	time
F	ice action
F_{max}	maximum value of ice action
T	period of ice action

NOTE Both F_{max} and T can vary randomly.

Figure A.8-22 — Idealized time histories of the ice action due to intermittent crushing

A.8.2.6.1.4 Susceptibility to frequency lock-in

Based on field measurements and observations, the ice failure frequency typically locks in to some of the lowest natural modes of the structure. For complex structures, lock-in frequency is not always immediately apparent and an eigenvalue analysis is required to determine the lock-in frequency. The condition of dynamic stability can be used to assess which natural modes are sensitive to ice-induced vibrations [A.8-43], [A.8-44]. To ensure dynamic stability of a natural mode, n, the relative damping coefficient, ξ_n, of the structure should be larger than the opposite contribution of ice action to dynamic instability. The damping coefficients, ξ_n, of the lowest natural modes of the structure should be large enough to dissipate the energy inflow due to ice action by satisfying Equation (A.8-69):

$$\xi_n \geqslant \frac{\phi_{n\text{c}}^2}{4\pi f_n M_n} \cdot h \cdot \theta \qquad \text{(A.8-69)}$$

where

ξ_n is the total damping of the eigenmode as a fraction of critical;

$\phi_{n\text{c}}$ is the non-normalized modal amplitude at the ice action point;

M_n is the true modal mass, expressed in kilograms;

f_n is the natural frequency of the eigenmode, expressed in hertz;

h is the ice thickness, expressed in metres;

θ is a coefficient, the suggested value of which is 40×10^6 kilograms per metre-second.

The suggested value for θ was obtained from studies with stiff and narrow structures in the Baltic Sea. For wide or compliant structures, an appropriate value of θ should be estimated.

The design procedure for frequency lock-in vibrations consists of the following steps.

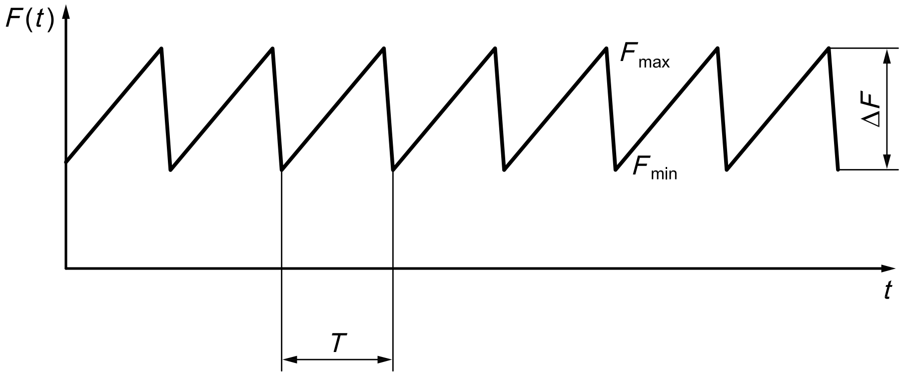
a) Solve the eigenvalues and modes of vibration.

b) Identify the lowest modes that are susceptible to frequency lock-in.

c) Calculate the dynamic response using the method described in A.8.2.6.1.5.

A.8.2.6.1.5 Dynamic response to frequency lock-in

The simplified forcing function shown in Figure A.8-23 can be used to determine the structural response in the case of vibrations with frequency lock-in. In this method, the frequency, $f = 1/T$, of the forcing function is assumed to be equal to the frequency of one of the unstable natural modes that has a natural frequency below 10 Hz, as derived from Equation (A.8-69). The peak values, F_{max}, as well as the double amplitude, $\Delta F = F_{\text{max}} - F_{\text{min}}$, can be assumed as constant. The peak values can be determined as the global ice action, F_{G}, on the structure (see A.8.2.4.3). In the analysis, the forcing function should be long enough such that a steady-state response is obtained.



Key

t	time
F	ice action
F_{max}	maximum value of ice action
F_{min}	minimum value of ice action
ΔF	difference between maximum and minimum values of ice action
T	period of ice action

Figure A.8-23 — Assumed ice load history for frequency lock-in conditions

The double amplitude, ΔF, which depends on the natural modes of the structure and the ice velocity, can be expressed as a fraction, q, of the peak action, F_{max}, as given by Equation (A.8-70):

$$\Delta F = qF_{\text{max}} \tag{A.8-70}$$

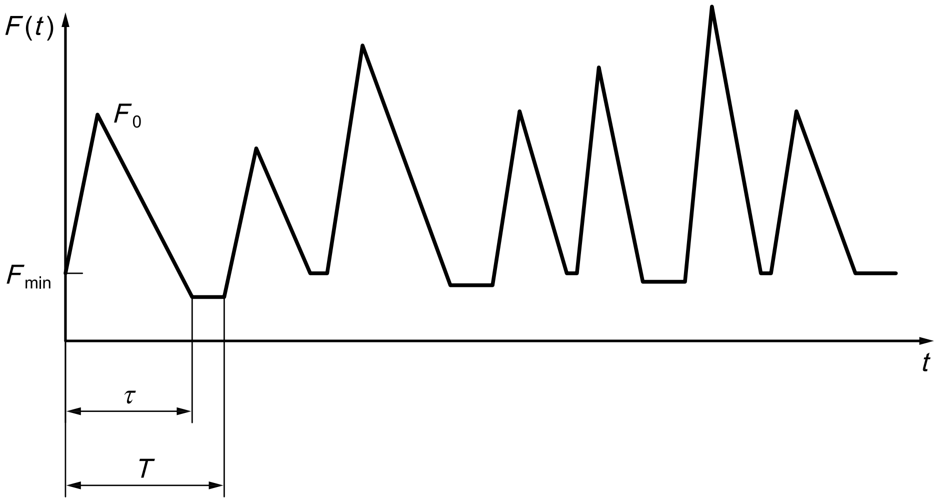
An initial value can be adopted for the coefficient, q, in the range between 0,1 and 0,5. Based on results of the response analysis, the coefficient, q, should then be scaled so that the velocity response at the waterline amounts to a value that is 1,4 times the highest ice velocity, v_t, at which a lock-in condition can occur. This velocity can be obtained as given by Equation (A.8-71):

$$v_\mathrm{t} = \gamma_\mathrm{v} f_n \tag{A.8-71}$$

where $\gamma_\mathrm{v} = 0{,}060$ m. This relationship is based on field data for slender structures with natural frequencies up to 5 Hz.

A.8.2.6.2 Dynamic actions on conical structures

Full-scale experience from the Bohai Sea has shown that a conical waterline geometry of the structure reduces the magnitude of ice-induced vibrations relative to the analogous vertical structure. On the other hand, the same data indicate that structures with a narrow cone at the waterline can still experience ice-induced vibrations. The vibrations are enhanced when stable ice rubble does not form on the front face of the cone. The time history for this kind of ice action is illustrated in Figure A.8-24. The dynamic response of the structure due to this kind of random forcing function is less than due to frequency lock-in on a similar vertical structure.



Key

t	time
F	ice action
F_0	peak value of ice action
F_min	minimum value of ice action
τ	duration of loading/unloading cycle
T	period of ice action

Figure A.8-24 — Idealized time history of the horizontal action on a conical structure

The time-varying action, $F(t)$, is a function of several parameters, including the width of the structure, slope angle and the frictional actions involved. The stationary action component F_min arises mainly from the ice rubble that is present on the face of a conical or sloping structure. Vibrations have been recorded in the Bohai Sea ice regime on multi-leg structures that have cones with a waterline diameter of 4 m. Due to an effective clearing of the ice rubble, the stationary action component has been in the range of $F_\mathrm{min} < 0{,}1F_{0,\mathrm{max}}$ on these structures. For other measurements in the Baltic Sea, severe vibrations did not occur for a conical structure with a waterline diameter of 10 m. The prevailing stationary action component was found to be around $F_\mathrm{min} = 0{,}45F_{0,\mathrm{max}}$ in this case.

The peak action, F_0, can be considered as a random parameter that follows a normal distribution. The maximum value, $F_{0,\text{max}}$, of this parameter can be estimated using instructions given in A.8.2.4.4. According to field data on narrow cones where the action component, F_{min}, is very small, the coefficient of variation of the peak values can vary from 0,20 to 0,60 in different events. Consequently, it is suggested that the coefficient of variation for the double amplitude, $\Delta F = F_0 - F_{\text{min}}$, of the time-varying action be 0,40. Assuming that the maximum value corresponds to a non-exceedance probability of 0,95, the mean value of the random peak action can be estimated as given by Equation (A.8-72):

$$F_{0,\text{mean}} = F_{\text{min}} + 0{,}56\,(F_{0,\text{max}} - F_{\text{min}}) \tag{A.8-72}$$

The period between action peaks can be calculated as given by Equation (A.8-73):

$$T = \frac{l_\text{b}}{v} \tag{A.8-73}$$

where

l_b is the breaking length of the ice sheet;

v is the ice velocity

The ice breaking length, l_b, is a function of ice thickness, ice strength, structure diameter and ice drift velocity. It varies in the range of 3 to 10 times the ice thickness, and this ratio typically decreases with increasing ice thickness and ice velocity. The period between two individual peaks is a random parameter with a coefficient of variation of 0,40 to 0,70. As an average, the standard deviation can be assumed to be 0,50 times the mean value of the action period.

The ratio between the duration of the actual action pulse, τ, and the average period, T, can vary between 0,3 and 1,0.

A.8.2.6.3 Fatigue accumulation due to ice actions

The fatigue of an offshore structure and its foundation (see 9.4.7, 11.8 and 12.3.5.3) results from the cumulative effect of wave, wind and ice actions. Fatigue resulting from ice actions should be analysed to the same level of detail as that from metocean actions. Fatigue should be assessed over the design service life based on the difference between the maximum and minimum stresses over continuous time records.

For the assessment of fatigue life, a basic service period of one year can be considered. The different kinds of ice actions that occur within this period are classified by defining a set of action processes $F^k(t)$ for $k = 1,2,\ldots$. Typical action processes include

- time-varying quasi-static actions due to flexural failure of ice;
- ridge actions;
- time-varying actions due to intermittent ice crushing;
- dynamic actions due to continuous ice crushing;
- vibrations due to ice crushing or flexural failure of level ice or rafted ice.

Each of the action processes is analysed on a statistical basis. The analyses yield a set of ice action spectra $\Delta F(\eta^k)$, where η^k is the number of ice actions that vary at an amplitude ΔF during the service period of one year. The amplitude, ΔF, of the ice action is defined as the difference between a peak value and the subsequent minimum value. The effects of dynamic magnification should be considered in the determination of the spectrum when vibrations arise due to action processes.

The accumulation of fatigue damage is determined separately for each of the action spectra. The total damage due to ice actions is then obtained as a linear accumulation of the damage due to the individual action spectra as given in Equation (A.8-74):

$$D_{\text{ice}} = \sum_{k} D^{k} \tag{A.8-74}$$

where

D^k are the damage accumulations due to the individual ice action spectra;

D_{ice} is the total damage due to ice actions.

Specific guidelines for determining the cumulative damage depend on the structure characteristics under consideration.

A.8.2.7 Operational procedures to reduce ice actions

A variety of operational procedures can be used to modify the frequency and the magnitude of ice actions. Active ice management techniques are considered in Clause 17, while passive techniques (such as spray ice or other barriers) are considered in Clause 16. These can have a major influence on the representative actions used for design and can allow floating production structures and lightly reinforced structures to operate in ice environments.

When operational procedures are used to reduce ice actions, a key aspect is the quantification of success of such procedures. It can be difficult to assess success *a priori* and the best measure is likely to be past success under operational conditions. Kulluk ice action data show that actions in managed ice with good clearing were 5 to 10 times less than actions in unbroken conditions.

Ice actions due to managed sea ice can require special treatment because of the presence of large quantities of broken ice. The best approach is to use full-scale data and the analysis of ice actions should reflect the particular ice environment and expected management resources.

A.8.2.8 Physical and mechanical properties of ice

A.8.2.8.1 Overview of physical and mechanical properties of ice

Physical and mechanical properties of ice are useful for the calculation of ice actions on structures. Furthermore, their knowledge is required in order to compare different full-scale measurements on ice actions and to simulate full-scale conditions in model tests.

Mechanical properties of ice have been studied for many decades and reliable dependencies have been established between physical properties (temperature, salinity, density) of ice and its strength parameters. Engineers can choose to use these dependencies instead of new strength tests. If a designer decides to perform new strength tests anyway, these new tests should be conducted following the International Association of Hydraulic Engineering and Research (IAHR) procedures for strength tests[A.8-45].

Depending on the action scenario, knowledge of the following physical and mechanical properties can be required for the calculation of ice actions on marine structures:

- compressive strength;
- tensile/flexural strength;
- fracture toughness;
- friction, adhesion;

- shear strength and cohesion of fragmented ice;
- elastic modulus;
- density.

Some action scenarios can create a shear failure across an ice sheet. Compressive strength and the tensile strength can be used in such cases to establish the failure criterion. Therefore, shear strength is not considered herein as an independent material parameter.

Locally grown ice covers consist of vertical columns with a random horizontal c-axis. At consistent current direction, the c-axis can be oriented, which has an effect on strength properties. The size of the columns increases with the ice cover depth.

Besides columnar-grained ice, the ice cover can consist of granular ice. In contrast to freshwater ice, sea ice crystals have a substructure that consists of parallel platelets, between which brine pockets are distributed. These brine pockets reduce the strength of sea ice relative to that of freshwater ice. The volume of the brine pockets are temperature dependent, which causes the ice strength to increase as the ice temperature decreases. The brine volume fraction of sea ice can be determined by the relationship given by Equation (A.8-75)[A.8-46]:

$$\nu_{\mathrm{b}} = S\left(\frac{49{,}18}{|T|} + 0{,}53\right) \tag{A.8-75}$$

where

ν_{b} is the brine volume fraction;

S is the salinity as a fraction of the ice melt volume;

T is the ice temperature, expressed in degrees Celsius.

For most of the mechanical properties of sea ice, the strength has been related by experiments to the brine volume or the volume of brine and air. This means that some of the strength properties can be calculated when the salinity, air content and temperature in the ice have been measured.

A.8.2.8.2 Compressive strength

A.8.2.8.2.1 General

The compressive strength of sea ice depends on the brine volume, the content of air bubbles, the action direction relative to the sample and/or crystal orientation, grain size, strain rate, temperature and ice type (columnar or granular).

Most common in ice mechanics is the uniaxial compressive strength, which is used for theoretical calculations of ice actions on marine structures. As real ice-structure interaction causes a three-dimensional state of stress, a more relevant concept for these theoretical calculations is the three-dimensional failure criterion, in which bi-axial and tri-axial compressive and tensile strength data are also considered.

A.8.2.8.2.2 Uniaxial compressive strength of first-year ice

The uniaxial compressive strength has its maximum at a strain rate of approximately $\dot{\varepsilon} = 10^{-3}/\mathrm{s}$, where the ice fails at the transition between ductile and brittle deformation.

The influence of the crystal structure and action direction on uniaxial compressive strength of first-year sea ice has been tested extensively. For horizontally loaded columnar ice (composed of columnar crystals), the uniaxial strength, σ_c, expressed in megapascals, is given by Equation (A.8-76)[A.8-47]:

$$\sigma_c = 37\dot{\varepsilon}^{0,22}\left(1-\sqrt{\frac{v_t}{0,27}}\right) \tag{A.8-76}$$

For vertically loaded columnar ice, the uniaxial strength, σ_c, is given by Equation (A.8-77):

$$\sigma_c = 160\dot{\varepsilon}^{0,22}\left(1-\sqrt{\frac{v_t}{0,20}}\right) \tag{A.8-77}$$

For granular sea ice (composed of granular crystals usually with a random c-axis orientation), the uniaxial strength, σ_c, is given by Equation (A.8-78):

$$\sigma_c = 49\dot{\varepsilon}^{0,22}\left(1-\sqrt{\frac{v_t}{0,28}}\right) \tag{A.8-78}$$

In Equations (A.8-76) to (A.8-78), v_t is the total void volume fraction (brine and air) and $\dot{\varepsilon}$ is the strain rate per second. These equations yield slightly conservative values when the total void volume is replaced by the brine volume fraction, v_b. The range of strain rates, $\dot{\varepsilon}$, for which these equations are valid is from 10^{-7}/s to 10^{-3}/s.

NOTE When it is necessary to obtain the maximum compressive strength, $\dot{\varepsilon}^{0,22}$ can be replaced by the factor 0,22, corresponding to a strain rate of 10^{-3}/s . Also, Equation (A.8-78) can be used generally since sea ice is granular.

A.8.2.8.2.3 Uniaxial compressive strength of multi-year ice

Measurements on the compressive strength of multi-year ice have shown that

- strength values of multi-year ice range from 4 MPa to 12 MPa, depending upon the strain rate;
- the strength of multi-year ice is similar to the strength of first-year ice when the ice is very cold (i.e. –20 °C); but
- multi-year ice is considerably stronger than first-year ice when the ice is warmer.

A.8.2.8.2.4 Ice borehole strength

The borehole jack test has been used extensively to characterize the *in situ* strength of ice and to determine a relative strength index. The jack consists of a high strength, stainless steel hydraulic cylinder with a double-acting piston that pushes on the sidewalls of an augured hole in the ice.

In situ borehole compression tests provide information of the ice strength in a three-dimensional stress state. Limited experiments have shown that the ultimate strength value, p_u, obtained in a borehole jack test is bounded as given by Equation (A.8-79):

$$s_{\text{min}}\sigma_c \leqslant p_u \leqslant s_{\text{max}}\sigma_c \tag{A.8-79}$$

where

σ_c is the unconfined compressive strength of the ice, in units consistent with p_u;

s_{min} is a lower bound factor;

s_{max} is an upper bound factor.

Reference [A.8-48] provides a range for s_{min} to s_{max}, of 2 to 4, while Reference [A.8-49] provides a range of 3,5 to 5. The relationship can be reassessed with site-specific data.

Borehole jacks have been used to study how the compressive strength changes during the spring and summer as the ice becomes warmer[A.8-50]. The device has also been used to investigate the strength profile of thickened sea ice roads[A.8-51] and the consolidation of pressure ridges.

A.8.2.8.3 Flexural strength

The flexural strength of ice sheets, rafted ice and the consolidated layer of ridges is used for estimating ice actions on sloping structures. The flexural strength is defined as the extreme fibre stress in tension. There are two different test methods in use:

- the simple beam test with four-point action application;
- the preferred cantilever beam test, in which the *in situ* ice cover is cut along three sides and loaded at the free end of the cantilever.

Based on a large number of small-scale tests, the flexural strength, σ_{f}, expressed in megapascals, of sea ice decreases with increasing brine volume, which includes the effect of the ice temperature[A.8-52], as given by Equation (A.8-80):

$$\sigma_{\text{f}} = 1{,}76 \exp\left(-5{,}88 \nu_{\text{b}}^{1/2}\right) \qquad \text{(A.8-80)}$$

where ν_{b} is the brine volume fraction.

For sea ice, the downward breaking *in situ* flexural strength, σ_{f}, has typical values of 0,3 MPa to 0,5 MPa for winter, while values of 0,2 MPa are typical for warmer conditions[A.8-53]. If site-specific tests or small-scale tests are conducted, the size effect on flexural strength should be accounted for[A.8-45].

A.8.2.8.4 Tensile strength

The tensile strength is measured directly with a dumbbell specimen, where the larger end surfaces are frozen to end cups, which are connected to the testing machine. The tensile strength is nearly independent of the strain rate in the range of 10^{-5}/s to 10^{-3}/s.

The tensile strength in the growth (vertical) direction of columnar-grained ice is about twice as high as in the horizontal direction (see Table A.8-4). The tensile strength depends on the brine volume of the sea ice. For information on the tensile strength of granular ice, see Reference [A.8-54].

Table A.8-4 — Tensile strength values

Temperature °C	**Ice type**	**Salinity** ‰	**Action direction**	
			Vertical MPa	**Horizontal** MPa
−10	sea ice	4 to 6	1,7	0,9
−10	Baltic ice	0,2	2,2	1,0

Based on the data shown in Table A.8-4, the tensile strength can be expressed as given by Equation (A.8-81) for the vertical direction and Equation (A.8-82) for the horizontal direction[A.8-55], [A.8-56]:

$$\sigma_{\text{t}} = 2{,}2[1-\left(\nu_{\text{b}}/0{,}31\right)^{1/2}] \qquad \text{(A.8-81)}$$

$$\sigma_t = 1{,}0[1-(\nu_b/0{,}14)^{1/2}] \tag{A.8-82}$$

where

ν_b is the brine volume fraction;

σ_t is the tensile strength, expressed in megapascals.

A.8.2.8.5 Shear strength

Shear failure can be a relevant action limiting mechanism for which an example is shown in Figure A.8-7. Ice is seldom in a state of pure shear while acting on a structure and the effect of tensile and compressive normal stresses should be assessed when calculating ice failure actions.

Reported values of shear strength vary in a range from 0,2 MPa to 2,5 MPa. This range is wide due to the difficulty in excluding the effects of the normal stress from the shear strength values. Limited but consistent data indicate that the shear strength varies in the range from 0,4 MPa to 1,3 MPa.

Full-scale experimental data are scarce. “Bone-shaped” torsion test beams produce pure shear without side effects due to normal stresses or stress concentrations. *In situ* beams with a cross-section of approximately 0,4 m × 0,4 m for Baltic Sea ice (1 % salinity) had a shear strength of 0,6 MPa[A.8-57].

The shear strength also depends on brine volume or total porosity. Small-scale tests described in Reference [A.8-58] indicate that the shear strength can be expressed as given by Equation (A.8-83):

$$\tau = 1{,}5\left(1-\sqrt{\frac{\nu_t}{3{,}9}}\right) \tag{A.8-83}$$

where

ν_t is the total void volume fraction (brine and air);

τ is the shear strength, expressed in megapascals.

A.8.2.8.6 Fracture toughness

The fracture toughness, K_{Ic}, of ice depends on the size of the piece of ice that is being fractured, the length of the crack, the temperature, the composition of the ice, and the action rate. A commonly quoted value of K_{Ic} for ice at laboratory scale is 100 kPa·m$^{1/2}$. *In situ* fracture tests on sea ice samples larger than 3 m have shown that K_{Ic} is about 250 kPa·m$^{1/2}$. Since K_{Ic} is only weakly scale dependent at larger scales, fracture toughness can be used directly in calculations if the K_{Ic} values used are measured at a suitable scale[A.8-59]. If not, a viscoelastic cohesive crack model can be used to predict K_{Ic} as a function of crack length for any geometry[A.8-60].

A.8.2.8.7 Friction coefficient

Frictional effects influence the ice actions acting on sloping and conical structures. Friction tests have been carried out in laboratories as well as in the field in order to establish the friction coefficient between ice and material surfaces, such as concrete and steel of various conditions (corroded, smooth, painted, low friction coatings).

The influence of the following parameters has been investigated in laboratory conditions: static versus kinetic friction, normal action, relative velocity, surface roughness, ice temperature and surface lubrication by the seawater. Test results show that

- the static friction coefficient can be up to five times greater than the kinetic friction coefficient at 0,1 m/s;

- the kinetic friction coefficient decreases with increasing contact pressure;
- the coefficient of kinetic friction increases with a decrease of the sliding velocity and also with a decrease of temperature;
- the seawater that can be present at the ice-structure interface does not materially influence the kinetic friction.

Kinetic friction coefficients for ice against steel and concrete based on laboratory measurements are shown in Table A.8-5 (based on References [A.8-61] and [A.8-62]). Other values can be used if supported by experimental data.

Table A.8-5 — Measured values of kinetic friction coefficient

Construction material	**Influence of sliding velocity**					
	$v_s \leqslant 0{,}01$ m/s		$v_s = 0{,}1$ m/s		$v_s = 0{,}5$ m/s	
	mean	**st. dev.**	**mean**	**st. dev.**	**mean**	**st. dev.**
Smooth steel	0,10	0,02	0,05	0,01	0,05	0,01
Smooth concrete	0,12	0,02	0,05	0,015	0,05	0,01
Corroded steel	0,15	0,03	0,10	0,03	0,10	0,03
Rough concrete	0,22	0,05	0,10	0,03	0,10	0,03

A.8.2.8.8 Material parameters for ridge keels

The strength of a ridge keel can be characterized as a Mohr-Coulomb material with internal friction and cohesion parameters. The majority of laboratory and full-scale tests have been interpreted in this way.

The range of published rubble internal friction angle varies from 10° to 80°. The reason for this large variation is the consolidation of the keel, since it is very hard to distinguish the relative contributions of internal friction and cohesion to the shear strength. Consolidation can increase the cohesion in a short time after the floes are brought together and put under pressure. Generally accepted values range between 20° to 40°.

Reported rubble cohesion values vary from 0 kPa to 100 kPa. Both extremes can be justified in special conditions. Zero cohesion in rubble ice occurs, for example, after the keel fails while the rubble is clearing the structure. Higher values are associated with a partly consolidated layer, e.g. the rubble in a stamukha. Full-scale data suggest that the average value of the cohesion of a first-year ridge keel is around 5 kPa to 7 kPa, when a non-zero friction angle is estimated simultaneously.

The internal temperature of ice ridges determines the depth of the consolidated layer and its strength, which depends on the brine volume and the temperature.

The keel porosity is directly proportional to the buoyancy induced pressure between floes, and hence to the keel shear failure strength. In compression, the higher the porosity, the more volumetric compaction is encountered. The reported values of keel porosity range from 10 % to 50 %. The keel porosity typically increases with depth, starting usually from 20 % just under the consolidated layer and increasing to 50 % at the keel bottom.

A.8.2.8.9 Elastic modulus

The elastic modulus of ice depends on the total void volume, v_T, as given by Equation (A.8-84):

$$E = E_\mathrm{fi}\left(1-\sqrt{v_\mathrm{T}}\right)^4 \tag{A.8-84}$$

where

v_T is expressed as the total brine and/or void volume fraction;

E_fi is the elastic modulus of freshwater ice, which has a value in the range of 9 GPa to 10 GPa.

Representative elastic moduli for design ice actions in natural ice sheets range between 2 GPa and 6 GPa. The elastic modulus increases with decreasing temperature.

A.8.2.8.10 Density

There are several different methods to measure the density of ice. The most common technique is the mass/volume technique by which an ice block is cut from an ice sheet and trimmed to a standard size, which provides the volume, V. Weighing the sample provides the mass, M. The ice density is then calculated as given by Equation (A.8-85):

$$\rho_\mathrm{i} = \frac{M}{V} \tag{A.8-85}$$

Measurements done by a large number of researchers[A.8-63] show that

- the sea ice density ranges between 720 kg/m^3 and 920 kg/m^3;
- *in situ* densities are different above and below the waterline;
- above the waterline, the density ranges from 840 kg/m^3 to 910 kg/m^3 for first-year ice and from 720 kg/m^3 to 910 kg/m^3 for multi-year ice;
- below the waterline, the density is more consistent, ranging from 900 kg/m^3 to 920 kg/m^3 for both types of ice.

A.8.3 Metocean related actions

A.8.3.1 Metocean actions on structures

A.8.3.1.1 General

Guidance and requirements concerning the actions of winds, waves and currents on steel framed structures, large volume and gravity structures, and floating structures and moorings are given in ISO 19901-1 (metocean), ISO 19902 (fixed steel structures), ISO 19903 (fixed concrete structures), and ISO 19904-1 (floating structures).

A.8.3.1.2 Ice accumulation on the structure

A.8.3.1.2.1 General

Guidance with respect to atmospheric and salt water spray ice accumulations is provided in A.6.3.5.

Pieces of floating ice can accumulate and lodge between the members of a structure where they intersect the water surface. Hydrodynamic actions on the ice are transmitted into the structure and add to the horizontal action.

The growth of ice on piles (ice bustle) can also increase the waterline area and, thus, cause an increase of the horizontal actions from waves and currents. When the water level decreases, water left on the pile freezes and ice accumulates. Similarly, ice accumulations on the surface of sloping structures make these structures steeper, and possibly increase the non-linear amplification of water surface elevations. Ice actions associated with ice bustles are covered in A.8.2.4.10.

A.8.3.1.2.2 Wave and current actions

No additional guidance is offered.

A.8.3.1.2.3 Wind actions

No additional guidance is offered.

A.8.3.1.2.4 Dynamic and static responses

Information on static, dynamic and stability analyses is contained in the International Standard relevant to the structure type, i.e. ISO 19902, ISO 19903 and ISO 19904-1. Additional information on the stability of floating structures in intact and damaged conditions is contained in 13.6.

The presence of ice can lead to unexpected action effects, for example, torsion in members due to an eccentric accumulation of ice.

The mass of the icing adds additional static vertical actions that can be considerably offset from the centre of gravity of the ice-free structure. The vertical actions can influence static position, stability, resistance to other actions and dynamic response. For a floating system, the consequent list, increase in draught and reduction of freeboard can increase the possibility of green water (or floating ice) impacting the deck. Changes in the metacentric height can have consequences for stability, roll and pitch stiffness, and responses.

A.8.3.1.3 Particular considerations for large volume structures

Information on model testing in general and large volume structures in particular can be found in ISO 19903. Some of the non-linear features associated with the interactions of waves with large volume structures are described in Reference [A.8-64].

Hydrodynamic effects on ice impact conditions are addressed in A.8.2.4.7.

A.8.3.1.4 Freeboard and deck elevation

No additional guidance is offered.

A.8.3.2 Wave-induced velocity of ice features

The addition of wave and current velocities is a vector process. The largest sum is obtained by combining the current with the particle velocity, either at the wave crest or at the wave trough. The relative magnitude of the two cases depends on the difference in direction between the wave and the current.

For pieces of floating ice with horizontal dimensions of 1/15 of the incident wavelength and greater, velocities can be obtained by solving their equations of motion. Diffraction analysis (including linear and slow-drift effects) can be used to calculate wave actions on the ice. Wind, current and wave drag actions can be obtained from drag models. Computational fluid dynamics or model testing can also be used.

Slopes and changes in water depth can focus and steepen incident waves through refraction. This increases velocities at the water surface and, thereby, the impact velocities of floating ice. The effect has been described in Reference [A.8-65].

A procedure has been described for calculating the probability distribution of the velocity of an ice mass in the presence of waves[A.8-66]. This approach assumes that the ice mass follows the water particle velocity, that the wave-induced velocity follows a standardized normal distribution, and that the surge velocity at impact is proportional to the sum of the drift and wave-induced velocities. Based on these assumptions, it can be determined that the ice collision velocity follows a “Special Rayleigh” distribution.

In the evaluation of the structural consequences of ice impact, reference can be made to the sections on collision and impact damage in codes for the type of structure of interest.

A.8.4 Seismic actions

No additional guidance is offered.

A.9 Foundation design

A.9.1 General

No additional guidance is offered.

A.9.2 Site investigation

A.9.2.1 Purpose and scope of the investigations

Reference should be made to ISO 19901-4 for further guidance on site investigations in temperate waters. In the following sections, no further guidance is given unless arctic and cold region specific.

A.9.2.2 Bathymetry survey

No additional guidance is offered.

A.9.2.3 Geophysical survey

No additional guidance is offered.

A.9.2.4 Geotechnical investigation

Guidelines for the description of frozen soils are provided in Table 2.1 of Reference [A.9-1]. This table provides an approach to describe visible and non-visible ice in soil samples, for use in addition to the standard soil description and classification methods; see, for example, Reference [A.9-2].

Permafrost and ice layers can be detected using the cone penetration test, CPT[A.9-3]. Frozen soil generally shows a very high tip resistance. Temperature measurements during cone penetration can be helpful to identify frozen soils[A.9-4] but it is necessary that the temperature be adjusted to compensate for warming of the penetrometer and surrounding soil as a result of the penetration process[A.9-5]. Reference [A.9-6] gives an example of the use of a CPT through a sand/silt tailings deposit with buried ice layers. When the layer is pure ice, the tip resistance and pore pressures are high while the sleeve friction is negligible.

Special sampling and handling techniques can be required for certain sediment conditions, such as gaseous sediments, permafrost and soft surface sediments. Gas in sediment, either in solution or as bubbles, can expand and cause sample disturbance. Warm permafrost is also difficult to sample undisturbed because the sediment is close to its freeze-thaw boundary temperature of between 0 °C and −2 °C.

Reference [A.9-7] contains a section on site investigation practice for permafrost conditions. Further background to the techniques and methods can be obtained from proceedings of several speciality conferences related to cold regions. Examples of such conferences include

- the ASCE International Conferences on Cold Regions Engineering;
- the Canadian Conferences on Permafrost;
- the International Permafrost Conferences;
- the International Conferences on Port and Ocean Engineering under Arctic Conditions (POAC);
- the Annual International Offshore and Polar Engineering Conferences (ISOPE);
- the ASCE "Arctic 85" Conference, San Francisco, California, 25-27 March, 1985.

Of particular note is that thermal disturbance to permafrost samples at temperatures close to freezing is almost impossible to prevent. *In situ* testing using the CPT and the pressuremeter is, therefore, commonly used to evaluate the behaviour of piles in permafrost. Because of the rate sensitivity of frozen soils, the standard 20 mm/s CPT is not appropriate. Special test methods are required to determine creep parameters, such as incremental load controlled tests in which the load on the cone is increased in steps and held constant at each step for a given time[A.9-8]. More recently rate-controlled CPTs have been carried out in permafrost, at rates from 1 mm/s to as low as 10^{-3} mm/s, to determine both stratigraphic detail and creep properties [A.9-9]. Examples of the application of the CPT and pressuremeter to pile predictions are provided in References [A.9-8], [A.9-10] and [A.9-11]. Seismic wave velocities (compression and shear) can also be successfully measured in permafrost[A.9-12] to determine the elastic properties.

Ground temperatures should be measured if permafrost is expected. The most reliable approach is to install a thermistor string in the borehole and to read the instruments once the temperature has stabilized. A less accurate method is to measure the temperature of each soil sample in the field as soon as it is retrieved. Temperature measurements using the CPT have also been reported[A.9-12].

Special laboratory testing procedures are required for permafrost[A.9-7].

A.9.3 Characteristic material properties

Selection of characteristic material properties for design of arctic offshore structures requires careful consideration of all of the available experience and a carefully designed site characterization programme including *in situ* and laboratory tests. This is combined with an appreciation of the uncertainties in measurements and analytical models to select characteristic values that are compatible with the required structural reliability for each limit state in this International Standard.

The greatest uncertainty in the measurement of engineering parameters is generally that due to sample disturbance, especially for samples taken offshore in permafrost regions. These samples are susceptible not only to mechanical disturbance, but also to thermal disturbance (thawing or freezing) while gas dissolution (either from pore water or frozen hydrates) also occurs. Similar uncertainty exists in the interpretation of *in situ* tests.

A.9.4 Design considerations

A.9.4.1 General

Permafrost and gas hydrates are of particular concern in some arctic offshore regions.

Permafrost sediments experience local melting and possible thaw subsidence with the prolonged extraction of warm hydrocarbons during production. This can result in settlement of topsides production systems, displacement-controlled loading on production casings, and reduced foundation resistance. Design consideration for permafrost and gas hydrates include the following.

a) Specific considerations include

- total and differential settlements associated with thawing,
- reduction in foundation soil shear strength associated with thawing,
- creep-related settlements for heavy structures founded above ice-rich permafrost.

b) The design process normally involves

- thermal analyses to evaluate the extent of thawing or freezing,
- deformation analyses to evaluate the extent and time dependence of foundation settlements,
- stability analyses to consider possible ramifications of a reduction in the foundation shear strength.

The limitations of analytical methods should be considered in all such analyses.

a) Factors to consider in thermal analyses are

- thickness and temperature profile of the permafrost,
- pressure-temperature condition of hydrates[A.9-13],
- thermal properties of the soils, accounting for freezing point depression and pore water salinity[A.9-14], [A.9-15],
- thermal boundary conditions associated with the overlying water, structures, wells and the geothermal gradient,
- range of well operating conditions.

b) Factors to consider in deformation analyses are

- extent and rate of thawing,
- immediate and time-dependent volumes that change on thawing,
- changing boundary conditions that affect redistribution of pore fluids and consolidation, particularly the moving, thawed soil-permafrost boundary,
- changes in the mechanical properties of foundation soils during and after thawing[A.9-16],
- creep characteristics of the permafrost.

c) Factors to consider in stability analyses related to permafrost or hydrate degradation are

- changes in soil strength as a result of thawing,
- time-dependent changes in the strength of the thawed soil associated with the dissipation or generation of excess pore pressures,
- the effects on soil or soil properties of high volumes and pressures of gas that could be released by the decomposition of hydrates.

A.9.4.2 Action factors

No additional guidance is offered.

A.9.4.3 Material and resistance factors

Geotechnical practice worldwide includes two approaches for the calculation of the resistance in limit state design. The first is to apply a material factor to the characteristic undrained strength, s_u, or the tangent of the characteristic friction angle, tan(ϕ'), and to calculate the foundation resistance using this design strength. The second is to calculate the foundation resistance using the characteristic strength; the foundation resistance is then multiplied by a resistance factor to obtain the design resistance. Hybrid approaches combining a material and a resistance factor have also been proposed.

Both approaches are acceptable within this International Standard. ISO 19901-4 uses a material factor approach, i.e. the characteristic soil strength is reduced by a material factor, before the design foundation capacity is calculated. ISO 19902 for deep-piled foundations uses a resistance factor approach, i.e. the pile capacity is calculated using characteristic strength values and capacity is then reduced by a resistance factor.

For undrained or total stress analyses, the material and resistance factor approaches in most cases give the same result and it is a matter of choice as to which approach is used. For effective stress analyses, there can be significant differences because foundation resistance is a non-linear function of effective friction angle. Material factors in effective stress analysis are, therefore, usually specified in combination with the method of analysis to avoid large variations in reliability when using this method.

Because ice actions on arctic offshore structures tend to result in greater horizontal action components than in more temperate climates, and because the bearing component is a highly non-linear function of action inclination, the resistance factor approach to design is more likely to result in consistent reliability of foundations. This is particularly the case for structures where the action is transmitted to the foundation through more than one path (e.g. piles in friction, end bearing and lateral resistance, and caisson structures through sliding/bearing on the base and passive pressures against infill soils). In many cases, a single method of analysis is also difficult to specify for arctic offshore structure foundations.

A.9.4.4 Dynamic action effect analysis

Examples of foundation design principles for cyclic loading from waves for bearing capacity as well as for foundation stiffness and displacements can be found in References [A.9-17] to [A.9-19].

A.9.4.5 Ultimate limit state

No additional guidance is offered.

A.9.4.6 Serviceability limit state

No additional guidance is offered.

A.9.4.7 Fatigue limit state

No additional guidance is offered.

A.9.4.8 Abnormal limit state

No additional guidance is offered.

A.9.4.9 Stabilized soils

Soil stabilization techniques can be considered in order to increase the strength and stiffness of foundation soils. It is cautioned that some of these methods have been employed to date only for onshore projects and that their application offshore could be impractical. Possible techniques include the following:

- deep mixing, consisting of pressure injection plus mechanical mixing of a cementing agent into the soil to increase strength;
- artificial freezing, which has been used primarily as a temporary construction support for advancing tunnels and shafts, or as a method to maintain permafrost below foundation components;
- densification.

A.9.4.10 Construction and installation

No additional guidance is offered.

A.9.5 Gravity base structures

Refer to ISO 19901-4 and ISO 19903 for general information and guidance.

A.9.6 Piled structures

Refer to ISO 19902 for general information and guidance.

Guidance on pile design in permafrost can be found in References [A.9-7] and [A.9-20].

A.9.7 Floating structures

A.9.7.1 General

Reference is made to ISO 19901-7 for general foundation design provisions, while Reference [A.9-21] provides specific design guidance.

A.9.7.2 Drag anchors

See Reference [A.9-21] for further details of design considerations for drag anchors.

A.9.7.3 Suction anchors

See References [A.9-21] and [A.9-22] for further details of design considerations for suction anchors.

A.9.7.4 Piled anchors

No additional guidance is offered.

A.9.7.5 Removal

No additional guidance is offered.

A.9.8 Scour

No additional guidance is offered.

A.9.9 Inspection and performance monitoring

Instrumentation systems and monitoring procedures that have been deployed on fixed offshore Canadian exploration structures are described in Reference [A.9-23].

A.9.10 Seismic analysis

A.9.10.1 General

The main thrust of the seismic analysis of shallow-founded structures such as a GBS is the proper treatment of dynamic soil-structure interaction (SSI). SSI analyses can be classified based on the following:

- sequence of analysis, direct or impedance method;
- domain of analysis, frequency or time domain;
- soil behaviour, equivalent linear or non-linear analysis.

Table A.9-1 presents a summary of the common types of SSI analyses, along with the corresponding common domain of analysis and soil modelling. Also included are various issues that require careful consideration for each method.

A.9.10.2 Direct method

SSI analysis by the direct method consists of developing a coupled soil-structure model with a sizable portion of soil, and establishing the input earthquake motion at the lateral and bottom boundaries of the model. The boundary motions should be consistent with the design earthquake time histories, the far-field soil properties, and the presumed type of incident wave train. The extent of the soil mesh should ensure that spurious wave reflection at the boundaries does not affect the response motions of interest.

A.9.10.3 Impedance method

The impedance method, also known as the three-step method, involves

a) determining the foundation input motion, which is the response of a massless foundation to the incident seismic wave train;

b) establishing the dynamic stiffness or impedance of the foundation for a range of frequencies;

c) subjecting a coupled structure-foundation model to the computed foundation input motion.

Table A.9-1 — Summary of the common types of SSI analyses, along with the corresponding common domain of analysis and soil modelling

Type of analysis	Domain of analysis	Soil modelling	Issues
Direct method	Time domain	Equivalent linear or non-linear	Soil component size Modelling hysteretic damping Extent of soil mesh Input boundary motion Permafrost/melting permafrost
Impedance method	Frequency domain	Equivalent linear	Soil component size Secondary soil non-linearity Permafrost/melting permafrost
Impedance method	Steps 1, 2: Frequency domain Step 3: Time domain	Steps 1, 2: Equivalent linear Step 3: Equivalent linear or non-linear	Soil component size Added soil mass Cross-coupling Foundation capacity Modelling hysteretic damping Foundation flexibility Secondary soil non-linearity Permafrost/melting permafrost

A.9.10.4 Analysis domain and soil behaviour

The direct method is commonly executed using FE models in the time domain. They are, hence, suitable for explicit consideration of soil non-linearity, but require thoughtful choice of soil component sizes and properties, and careful determination of location of lateral and bottom boundaries.

The first and second steps of the impedance method are typically executed in the frequency domain, with equivalent linear soil properties. This is due to the existence of consistent transmitting boundaries for various seismic wave patterns that prevent spurious wave reflections at the boundaries, which avoids the need for a large soil model. The third step can be executed in the frequency or time domain. The impedance method involves the following considerations.

- In the frequency domain, the dependence of impedance on frequency is explicitly retained, as well as the cross coupling between various degrees of freedom, especially the coupling of rocking and horizontal impedance functions.
- In the time domain, the dependence of impedance on frequency can only be approximated using linear springs perhaps with added soil mass. Cross coupling requires special considerations.
- Non-linear foundation stiffness can be introduced in the third step of the impedance method using non-linear springs representing global foundation behaviour. The latter should be adequately established using non-linear analysis of the foundation-soil system accounting for embedment and skirts.

Alternative methods, other than the direct and impedance methods, have also been suggested, such as the online response test method which incorporates physical testing and analysis in real time. This method is a lumped-mass analytical method combined with direct shear test on soil specimens taken from the construction site of the offshore structure. Further details of the online response method can be found in References [A.9-24] and [A.9-25].

A.10 Man-made islands

A.10.1 General

No additional guidance is offered.

A.10.2 Island types

No additional guidance is offered.

A.10.3 Design considerations

A.10.3.1 General design considerations

A.10.3.1.1 General

No additional guidance is offered.

A.10.3.1.2 Design requirements

No additional guidance is offered.

A.10.3.1.3 Multi-disciplinary approach

No additional guidance is offered.

A.10.3.1.4 General considerations for man-made islands

A.10.3.1.4.1 General

No additional guidance is offered.

A.10.3.1.4.2 Shape and orientation

No additional guidance is offered.

A.10.3.1.4.3 Facilities

No additional guidance is offered.

A.10.3.1.4.4 Spill containment

Islands are often built of natural porous “fill” material, In the event of a spill, the oil infiltrates the fill and can eventually impact the environment. A potential mitigation option is a fluid-impermeable surface with a certain storage capacity as a first line of defence, in combination with a geomembrane within the fill material with an appropriate drainage system as a second line of defence. The elevation of the geomembrane should be selected based on the range of expected water levels, the location of the freeze-front and ease of removal during decommissioning.

A.10.3.1.4.5 Marine access

No additional guidance is offered.

A.10.3.2 Design against ice

A.10.3.2.1 Ice-structure interaction scenarios

Ice rubble that has formed in front of an island can be considered as additional resistance to ice actions. The occurrence of ice rubble adjacent to an island is more likely for wide structures than for narrow structures. The oncoming ice is pushed through this ice rubble to a certain height. The maximum rubble height is somewhat dependent on the geometry of the structure as well as ice thickness. Maximum rubble heights vary with the respective ice regime.

A.10.3.2.2 Ice actions

No additional guidance is offered.

A.10.3.2.3 Ice encroachment

Ice ride-up occurs as ice is pushed against a structure by an advancing ice sheet and slides up onto the structure. On a continuous slope, unimpeded ice ride-up can extend a large distance, which can be a concern for topsides structures or evacuation routes. Ice ride-down can occur when ice is deflected downward, especially when ice rubble has formed next to the structure.

Ice pile-up generally occurs as broken ice pieces encounter an instability in the ride-up process. Rather than moving up a sloping structure, the ice piles into a mound, often rapidly (in a few minutes). It can be desirable to induce ice pile-up near the waterline in order to limit ice ride-up over a structure. Ice pile-up can also occur against the perimeter structure of an island, such as sheetpile.

A.10.3.3 Geotechnical considerations

A.10.3.3.1 Geotechnical investigations and surveys

No additional guidance is offered.

A.10.3.3.2 Fill characterization

No additional guidance is offered.

A.10.3.3.3 Cyclic actions

No additional guidance is offered.

A.10.3.3.4 Thermal changes

No additional guidance is offered.

A.10.3.3.5 Failure modes

Analysis requirements for failure modes include the following.

- Global sliding: for global sliding, all relevant ice interaction scenarios during a winter season should be considered.
- Decapitation, which should be accounted for in the design of low crested breakwaters and man-made islands. Consisting of widespread failure in a horizontal plane, decapitation can be associated with the layer immediately beneath a frozen crest on the structure, in which case the resistance should be calculated using the weight of the sliding crest and the friction and interlocking along the slide plane. The exact location of the slide plane should be determined using frost penetration analyses combined with

geotechnical analyses. The appropriate ice conditions (thickness, pressure and rate of load application) over the design service life should be considered in determining the potential for decapitation.

- Passive edge failure: the actions for edge failure analysis should be determined, accounting for fill material size, gradient and smoothness of the side slope, ice thickness and ice pressure. In general, the crest of the structure should be at least twice the nominal ice thickness above the mean high water level and the armour layer thickness should exceed the nominal ice thickness. Edge failure is typically a local failure of a few individual rocks caused by large local actions, which in some cases can be much higher than global actions, uneven slopes, ice ride-up or bending.

- Passive wedge failure: for sheetpile-retained islands, the island level should be high enough to prevent passive wedge failure behind the sheetpile under ice action.

- Sheetpile resistance: the sheetpile structure should have sufficient resistance against ice actions by virtue of structural capacity and soil resistance. The sheetpile should be verified for local ice actions, plastic yielding and potential loss of integrity at joints.

A.10.3.3.6 Deformation

No additional guidance is offered.

A.10.3.3.7 Soil improvement

No additional guidance is offered.

A.10.3.4 Coastal engineering

A.10.3.4.1 Meteorological and oceanographic factors

A.10.3.4.1.1 Water levels

The water level at a given island site fluctuates under the influences of astronomical tides, wind-induced storm surge and setdown, changes in the atmospheric pressure and long-term fluctuations in the water body caused by seasonal, climatic or hydrologic effects. The last effect can be particularly important in enclosed seas and lakes. Additionally, islands constructed in or near riverine environments can experience short-term fluctuations in response to hydrologic flow events.

A.10.3.4.1.2 Waves

No additional guidance is offered.

A.10.3.4.1.3 Winds

No additional guidance is offered.

A.10.3.4.1.4 Currents

No additional guidance is offered.

A.10.3.4.1.5 Strudel scours

Strudel scours occur when river outflows inundate the coastal ice and drain through cracks or holes in the sea ice; see 6.6.4. The turbulent vortices that form can erode the seabed and create craters in the sea floor. Because tidal cracks typically form in the ice cover along the slopes of offshore islands, strudel scours have been found to occur adjacent to islands. While slope protection armour units are resistant to damage or displacement by the strudel scour vortices, the unprotected toe of the armoured island slope can be readily eroded by the strudel scour process. Down-slope armour displacement can result from such an event.

A.10.3.4.2 Side slope profile

The major difference in slope protection and beach design in cold ocean regions as compared to other regions is the presence of ice. Ice has both beneficial and detrimental effects. On one hand, the presence of ice limits the wave climate and erosion. On the other hand, ice can damage slope protection, and can ride up and damage surface facilities. Breakwaters designed to withstand wave attack are often able to withstand ice actions. There is a delicate balance between the smoothness required to encourage ice bending (to minimize the ice actions and movement of individual stones) and the roughness required to dissipate wave energy.

The limiting of wave run-up and overtopping to acceptable levels requires understanding of the interaction of wave impacts on the selected island slope. The accommodation of possible ice ride-up and pile-up scenarios requires analyses to quantify the interaction of sea ice with the island slope. The selection of the island slope profile is a significant factor in controlling both wave overtopping and ice encroachment. Island slopes can be planar, incorporating side slope values that are compatible with the armour systems utilized. Compound slopes utilizing a near-water bench have been successfully employed by reducing wave overtopping and accommodating ice ride-up/pile-up accumulations.

To date, man-made islands have been protected by armour stone, pre-cast concrete units, articulated mats of concrete blocks and sand bags. Armour stone can be subjected to normal and shear stresses along the surface. These stresses introduce a rotation, dislodging the individual stones. For this reason, it is desirable that the surface of the armour stone be relatively smooth and the stone layer be well keyed in this respect. Angular stones tend to nest together and interlock. It follows that smoother stone surfaces reduce shear stresses. Another disadvantage of a rough slope with relatively large surfaces of individual rocks is the possibility that rigidly frozen ice can remove the armour stone and float it away from the site.

A.10.3.4.3 Slope protection

A.10.3.4.3.1 General

Local failure modes of slope protection systems include local damage or displacement caused by wave and ice impacts. Such damage should be identified and periodic maintenance and repair should be undertaken. Such damage, if addressed in a timely fashion, does not threaten the structural integrity of the island.

More extreme damage can occur as a result of a particular event or series of discrete events and can threaten the efficient functioning of an island. Significant accumulation of localized damage, left unrepaired, can also lead to impacts on island function. Serious armour loss or displacement, while not extending over large areas, can create significant weakness in a given sector of the island, leading to significant losses in fill material, or locally high rates of wave overtopping or potential ice encroachment.

Widespread and potentially global damage can occur if wave overtopping inundates the island work surface or widespread ice encroachment occurs, thereby creating a threat to life, the environment and the production facilities.

Further details can be found in Reference [A.10-1].

A.10.3.4.3.2 Quarry stone

There is limited experience regarding required rock size to prevent removal by ice, but as a minimum rock size should probably match ice thickness.

A.10.3.4.3.3 Sand- or gravel-filled geotextile bags

Geotextile bags filled with sand or gravel can be used as slope protection in areas where large quarry stone is not available. Such geotextile armour units typically exhibit individual capacities of 1,5 m^3 to 3 m^3, weighing 2 tonnes to 6 tonnes. Different bag placement configurations can be selected to maximize bag coverage (no overlap) or to improve bag stability under wave actions (overlapped placement). Careful selection of bag fabric can provide a service life that is compatible with the design service life, or which anticipates the removal and replacement of damaged bags on a periodic basis. Additional information regarding geotextile bags is provided in Reference [A.10-2].

A.10.3.4.3.4 Linked concrete mats

Concrete mats composed of individual concrete blocks that are linked together have been used successfully in coastal engineering applications. Individual blocks can be physically connected by cables that pass through the blocks or by chain/shackle linkages. The linkage is critical in that the system is composed of individual concrete units that, if not linked, can otherwise be readily displaced by wave and ice actions. Linked mats perform as an integrated unit in the wave and ice impact zone. Concrete mats are more resistant to ice impacts, relative to the softer geotextile armour systems. The smooth, featureless slopes exhibited by concrete mats limit the ability of ice to displace the blocks. Linked-mat systems are underlain by durable filter fabric to contain the island fill material. Wave run-up on these smooth surfaces can be excessive, leading to the incorporation of a composite slope profile with rougher armour units placed on the upper slope. The modular nature of the linked concrete mat system allows for relatively quick installation and localized repair when damage occurs. Failure of linked concrete mats can result from ice impact or wave-induced uplift and these mechanisms should be considered in the design. Additional information regarding linked concrete mats is provided in Reference [A.10-3].

A.10.3.4.3.5 Pre-cast concrete units

Large pre-cast concrete armour units provide island slope protection. A variety of these armour types exist, exhibiting distinct shapes, sizes, weights and degree of interlock. The experience of this type of armour in ice environments is limited.

A.10.3.4.4 Wave run-up and overtopping

No additional guidance is offered.

A.10.3.4.5 Coastal stability

The stability of the coastline is important in the site selection and design of coastal pads and facilities. Shorelines and coastal bluffs can experience long-term change, which can vary considerably over short-term periods. A knowledge of the coastal processes of a project area should be obtained during the early phases of the design process. Given an understanding of the design service life, it is prudent to position the coastal pad or structure a safe distance landward of the shore or bluff to allow coastal changes to occur without affecting the structure or facilities.

A.10.4 Seismic design

Seismic design of man-made islands involves prevention of global and local failure of the island fill materials. It is also necessary that the failure of the retaining system be evaluated. Issues that should be addressed are summarized in the following.

- Global design: this involves lateral failure of the island at the mudline, below the mudline or through the island due to seismic lateral actions. Available methods include 2D or 3D linear or non-linear methods.

- Local design: this involves local regions of settlement during the earthquake (especially uneven settlement), due to consolidation or liquefaction. Lateral spread of the island materials during an earthquake requires consideration.

- Retaining system: this involves stability of the island's slopes in earthquakes. Typical methods of slope stability should be used for natural or engineered slopes. Sheetpile retaining systems should use methods applicable for pier and wharf design. Caisson retaining systems should consider methods suitable for retaining walls. In some cases, the caissons can act as small GBSs with a shallow foundation and the methods contained in Clause 9 should be used.

A.10.5 Construction

No additional guidance is offered.

A.10.6 Monitoring and maintenance

No additional guidance is offered.

A.10.7 Decommissioning and reclamation

A case history describing the abandonment of Mukluk Island in the Alaskan Beaufort Sea is provided in Reference [A.10-4].

A.11 Fixed steel structures

A.11.1 General

In addition to the provisions of ISO 19902, the design of structural elements that behave as beams, columns or beam-columns can be performed in accordance with national or regional standards; see, for example, References [A.11-1] to [A.11-5].

A.11.2 General design requirements

No additional guidance is offered.

A.11.3 Structural modelling and analysis

No additional guidance is offered.

A.11.4 Strength of tubular members and joints

No additional guidance is offered.

A.11.5 Strength of stiffened-plate panels

Examples of design standards for stiffened-plate panel configurations are References [A.11-6] and [A.11-7].

Reference to membrane action applies only to the plate panel and not to the stiffeners or primary structure supporting the panel.

The use of membrane action should be avoided without careful consideration of the p-delta effects related to primary load paths and maximum deflection under load with and without permanent deflection. Classification societies have rules for bulkhead deflection under hydrostatic actions that can be in conflict with the local ice action design provisions of this International Standard.

A.11.6 Strength of steel-concrete composite walls

No additional guidance is offered.

A.11.7 Seismic design

A.11.7.1 Steel framed structures

No additional guidance is offered.

A.11.7.2 Steel stiffened-plate structures

While there is limited guidance in ISO 19902 for seismic design of GBS-type steel stiffened-plate structures, the general principles of steel structure seismic design, as applied to steel tubular framed structures, still apply. The following provides some general guidelines.

- Ductile performance in cold temperatures: a cold temperature steel should be used for the design of the portions of the structure that are exposed to ambient temperatures and expected to undergo plastic deformations in earthquakes. Such material should have a demonstrated ability to undergo plastic deformations at the design minimum EL temperature.
- Global plastic mechanism: the formation of plastic mechanisms together with the location and nature of plastic hinges in the structure should be clearly identified and reviewed to ensure that they do not lead to global collapse.
- Global deformations: due to lack of large-scale experimental data, designers rely on FE models of the steel structure to obtain global deformations in areas of plasticity.
- Local strain demand: the global deformations should be translated into local strains using detailed FE models. The limits on total strain should be established based on project material data.
- Seismic detailing: in order to ensure that the local components are capable of sustaining plastic deformations, compact section detailing should be maintained, as defined by the provisions of ISO 19902.
- Controlled buckling: in some cases, it is possible to obtain satisfactory ductile performance even with the buckling of some components. In such cases, the satisfactory performance should be demonstrated using established engineering principles.
- Capacity design: the components of a ductile GBS should be clearly identified as force-controlled and displacement-controlled, for the purposes of further design and assessment.
- Skirts: if it is desirable to design the steel mud skirts in such a way as to cause a sliding failure prior to the development of GBS plastic mechanism, the upper bound properties of the mud skirts should be considered prior to the design of the adjacent base structure. The allowable stresses in the steel skirts should be decided on the basis of the function of the GBS. When the GBS is, for example, of the re-floatable barge type, the skirt stresses should remain in the elastic range under all load conditions since deformed skirts hamper the re-installation of the structure.

A.11.8 Fatigue

For fatigue analysis associated with ice actions, reference should be made to A.8.2.6.3. High cycle, low amplitude cyclic stresses can be caused by frequent, low intensity ice action events, while low cycle, high amplitude cyclic stresses can be caused by abnormal, high intensity ice action events.

Attention should be given to the validity of S-N curves with respect to low temperature application.

A.11.9 Materials, testing and NDT

Special attention should be given to piles driven into frozen ground under low temperature conditions.

Materials testing temperatures in ISO 19902 are consistent with the definition of LAST in this International Standard. If local regulatory requirements provide an alternative temperature specification, consideration should be given to complying with the more onerous provisions between those of ISO 19902 and those of the alternative. In doing so, the choice of test temperatures should be consistent with the minimum local temperature specification.

A.11.10 Corrosion and abrasion protection

A.11.10.1 Cathodic protection

No additional guidance is offered.

A.11.10.2 Ice abrasion

No additional guidance is offered.

A.11.10.3 Knife-line corrosion

Experience to date has shown that it is possible to minimize the metallurgical and electrical differences between the weld areas and the parent plates to such a degree that knife-line corrosion is avoided. Various electrical methods have been used to demonstrate that certain levels of potential voltage differences between the different metals correlate well with deterioration rates. Additionally, accelerated corrosion tests can be carried out on welded test specimens to demonstrate that the degree of metallurgical difference in the weld zone (resulting from the welding process) does not subsequently result in high rates of deterioration.

A.11.11 Welding

No additional guidance is offered.

A.12 Fixed concrete structures

A.12.1 General requirements

No additional guidance is offered.

A.12.2 Actions and action effects

No additional guidance is offered.

A.12.3 Structural analysis

A.12.3.1 Dynamic analysis

No additional guidance is offered.

A.12.3.2 Loss of intended internal pressure

No additional guidance is offered.

A.12.3.3 Physical representation

A.12.3.3.1 Soil-structure interaction

No additional guidance is offered.

A.12.3.3.2 Other support conditions

Additional transverse shear reinforcement can be provided to transfer the action to the opposite face in order to prevent pull out and punching type failures where only part of the thickness of the structural component is activated.

A.12.3.3.3 Thermal effects

Deformation-induced actions such as the effects of temperature differences and thermal gradients can, in general, be determined on the basis of linear analyses. The non-linear elastic behaviour of reinforced concrete due to cracking under the imposed strains can also be taken into account by applying reduction coefficients on the linear elastically determined action effects. For SLS action effects (for ULS and FLS limit states, thermal effects other than for shear are normally neglected), a coefficient of reduction less than 1,0 is generally accepted, provided that the selected value is supported by relevant documentation. For verification of the required tightness and calculation of crack-widths for SLS, the temperature-induced strains can be considered by taking into account the differences in axial stiffness for the tension and compression sides of the cross-section.

A.12.3.4 Types of analysis

A.12.3.4.1 Linear elastic static analysis

The assessment of the stiffness of a structural member used for structural analysis is computed either from the concrete cross-section alone or by also taking account of the effect of the reinforcing steel. Young's modulus for the concrete should be appropriate for the nature of the action (static or dynamic), and for the age of the concrete.

The effects of deformation actions, such as thermal effects or differential foundation settlements, should be included in the form of strains rather than stresses, and on the basis of elastic behaviour. For instance, in computing crack width, thermal strains should be added to strains from other action effects. For long-term sustained temperature differences, the beneficial effect of strain due to creep can also be considered.

A.12.3.4.2 Non-linear analysis

No additional guidance is offered.

A.12.3.5 Analysis requirements

A.12.3.5.1 Analysis of construction stages

Depending on the size and dimensions, a concrete structure can be erected partially in a dry-dock and partially afloat. The structure should be erected afloat (wet dock) in a predefined sequence to optimize the construction schedule by limiting the stoppages in the different form and concrete lifts. The different concreting steps afloat result in an accumulation of forces and stresses in the lower parts of the structure (the so-called “locked-in” or “built-in” forces and stresses) that can, at the end, depart significantly from the force and stress distributions that can result from an idealized single-step construction sequence. A review of the different construction steps should be carried out using appropriate FE models representative of the construction sequence. Alternatively, the global refined FE model used for the detailed design of the concrete structure can be applied to the different stages by using, for instance, the super-elements technique.

A.12.3.5.2 In-service serviceability analysis

Ice pressure within cracks is not normally included in crack width calculations.

A.12.3.5.3 Fatigue analysis

No additional guidance is offered.

A.12.3.5.4 Accidental and abnormal analyses

No additional guidance is offered.

A.12.3.6 Seismic

No additional guidance is offered.

A.12.4 Concrete works

A.12.4.1 Design

A.12.4.1.1 Design principles for shell members

No additional guidance is offered.

A.12.4.1.2 Design principles for fatigue

No additional guidance is offered.

A.12.4.1.3 Design principles for durability

No additional guidance is offered.

A.12.4.1.4 Freeze-thaw cycles

A.12.4.1.4.1 General

The changes in the strength and strain properties of concrete during freeze-thaw cycles are not well known because, generally, compressive and tensile strength have been assessed only at normal temperatures. In particular, the bond strength between aggregate stones and the cement stone and the relation between the bond strength and freeze-thaw cycles are uncertain.

The most important factors influencing the freezing resistance of concrete are the space between air pores, the volume of air pores, the water-cement ratio, the type of binder and the location of the concrete in the structure. The most essential factor is the critical degree of saturation. When this is exceeded, the concrete can be damaged during freezing.

A.12.4.1.4.2 Abrasion

Overview of abrasion process

Ice actions can be applied to concrete aggregate stones protruding from the surface once the finer concrete substances have worn off. Ice frozen onto the concrete can, in addition, result in external mechanical actions to the aggregate. The magnitudes of the actions depend both on the ice properties and on the size of aggregate stones. Repeated actions can occur because of the ice failure process.

Reference should be made to relevant field data for the type of concrete used and the ice conditions expected.

Abrasion mechanisms

Ice actions can cause different types of stress at the concrete surface. When the surface is smooth after a normal casting and concrete aggregate stones are covered by cement, moving ice causes compression normal to the surface as well as a tangential friction action. The magnitude of the friction action depends on the quality of the surface in question, i.e. the friction coefficient between the ice and the concrete. The value of the dynamic friction coefficient between sea ice and smooth concrete surfaces has been established through tests as 0,24.

Ice frozen onto the concrete can cause tensile actions normal to the surface. The stresses induced have been shown to be rather small. The average bond strength of concrete when frozen onto ice is approximately 0,3 MPa. Abrasion of the concrete surface due to this process is generally slight and occurs only for new concrete.

The real abrasion of the concrete surface starts when ice acts on the concrete aggregate stones protruding from the concrete surface, partly due to abrasion caused by ice friction and partly due to disintegration of cement stone caused by salt-frost effects. Ice impacting the structure can produce local pressures on the protruding aggregate stones that are significantly greater than the average global contact pressure. Reference should be made to 8.2 and A.8.2 in this regard.

Ice processes

Friction effects between concrete and ice have been measured. The factors found to have the most dominant effect on abrasion are the temperature of the ice, the local pressures applied by the ice to the concrete surface, and the strength of the concrete, especially changes in the strength as a result of freeze-thaw cycles. The abrasion rate is greater for lower ice temperatures and for higher stress intensities.

With respect to ice actions, the main parameters that influence the abrasion rate of a surface material[A.12-1] to [A.12-7] are

— normal and shear actions;

— ice temperature;

— relative velocity;

— sliding distance.

The magnitudes of the normal pressures can be evaluated by considering first a smooth contact surface. In these conditions, the highest pressures arise due to brittle ice crushing. The magnitudes of the local pressures are obtained by assuming that the width of the contact area is very small. The method described in A.8.2.5.2 for local ice actions can be applied by assuming that the contact area is very narrow, $w_{\mathrm{L}} \approx 0$, and it follows that the pressure distribution coefficient $\chi_{\mathrm{LB}} = 8{,}0$ (see A.8.2.5.2).

Ice pressures on very small local areas can increase to a level around 25 MPa to 40 MPa. Higher pressures up to 80 MPa have been measured in the Canadian Arctic on a local area of 10 mm[A.12-8]. These high local pressures can not only abrade the concrete but also lead to accelerated corrosion in steel structures.

While the abrasion rate is not sensitive to the ice temperature if the temperature is higher than −10 °C, the acceleration rate increases significantly in temperatures lower than −10 °C. The effects of ice velocity have been studied because the friction coefficient increases at low ice velocities. Tests have shown that the sliding velocity has only a minor influence on the rate of ice abrasion[A.12-3] through [A.12-5]. On the other hand, field measurements on a lighthouse in the Baltic Sea indicate that shearing actions can cause more damage to concrete than compressive pressures[A.12-9] through [A.12-11].

The extent of ice movements of an ice field around a structure can be used to determine the sliding distance between the structure's surface and an ice sheet. The abrasion rate of concrete generally decreases with the sliding distance.

Abrasion tests

The abrasion problem of offshore concrete structures for arctic and cold regions is a complex combination of the effects produced by cyclic freezing and thawing in seawater, temperature changes and ice actions, as follows.

— The abrasion depth and resistance of concrete can be determined by means of either abrasion diagrams or laboratory tests. The best results are achieved when using both. With abrasion diagrams, the abrasion depth can be estimated as a function of the compressive strength of concrete and ice sheet movement.

The abrasion resistance can also be measured with a 10 min laboratory abrasion test, prior to which the concrete plate should undergo a cyclic thaw test in seawater for 50 cycles at temperatures ranging from −50 °C to +20 °C.

- The most important mechanical factor pertaining to measurement of the resistance to abrasion of concrete is the strength of the concrete. The bond strength of aggregate stones and cement stone and its resistance to repeated freeze-thaw cycles is especially crucial. In order to ensure good resistance to abrasion, the compressive strength of concrete should be at least 70 MPa. Naturally, the concrete should also be frost-resistant; see 12.4.1.4.1. The strength of concrete during repeated freeze-thaw tests is generally highest when the water-cement ratio is not more than 0,30 to 0,35.
- During repeated freeze-thaw tests of ordinary cement concretes, the bond strength of aggregate stones at the concrete surface diminishes more rapidly than either the compressive or tensile strengths. Apparently, changes in temperature exceeding 40 °C deteriorate the bond of stones at the surface and increase surface cracking.
- The best results in both the strength and abrasion tests are achieved with concretes containing silica and blast furnace slag, and the poorest results with lightweight aggregate concretes.
- The resistance to abrasion of concrete can be improved by preventing frost damage, by keeping the entire wall either sufficiently warm or frozen so that it is not exposed to freeze-thaw cycles.
- If the bond strength of concrete aggregate stones is at least 8 MPa, the resistance to ice abrasion of concrete is considered to be very good.
- If the abrasion depth in the laboratory conditions after a freeze-thaw test of 50 cycles is no more than 10 mm, the resistance to ice abrasion of the concrete can be considered good.
- Increasing the maximum size of the aggregate reduces the abrasion of concrete. Large stones protruding from the concrete surface break the ice before the finer concrete particles are damaged.
- The use of hard, homogeneous concrete in the ice abrasion zone reduces abrasion, because the surface is subjected to even abrasion and there are no stones subjected to ice action.

Mitigation measures

In certain circumstances, steel armour can be fitted to the outside of the concrete elements subject to ice abrasion. However, it is necessary to take particular care in designing and installing such devices, because the migration of water between the protected concrete surface and the inside of the armour with the associated risk of freezing can result in local damage. Furthermore, steel plating requires adequate cathodic protection that either is not exposed to, or is designed for, ice actions.

A.12.4.1.4.3 Concrete cover

Caution should be taken when increasing the concrete cover for resisting abrasion and wear because, beyond certain limits, an excessively large concrete cover (in the range of 60 mm to 70 mm) can be a source of spalling even under moderate actions. In that case, skin reinforcement should be provided. Alternatively, steel armour can be provided for abrasion and wear protection without increasing concrete cover, with the subsequent drawback of corrosion and the requirement for corrosion protection.

Where it is proposed to improve abrasion resistance by the use of external steel plates on the external face, care should be taken to avoid delamination resulting from the migration and freezing of water vapour beneath the plate.

A.12.4.1.5 Design principles for buckling

No additional guidance is offered.

A.12.4.1.6 Design principles for imposed deformations

No additional guidance is offered.

A.12.4.1.7 Design for fire resistance

No additional guidance is offered.

A.12.4.1.8 Partial factors for materials

No additional guidance is offered.

A.12.4.1.9 System ductility

No additional guidance is offered.

A.12.4.1.10 Minimum reinforcement

No additional guidance is offered.

A.12.4.2 Materials

An appropriate testing standard for adequate freeze-thaw resistance in concrete is Reference [A.12-12], or equivalent.

For further information on lightweight aggregate for concrete, reference should be made to, for example, Reference [A.12-13].

Reinforcement in permanently submerged concrete does not require special corrosion protection, particularly if the structure is fitted with cathodic protection. In parts of the structure with the potential for corrosion of the reinforcement, requirements for concrete quality (resistance to chloride penetration and oxygen diffusion, use of silica fume and fly ash, additives, etc.), coatings and cover are feasible measures, as well as use of galvanized rebar. If improved reinforcement is necessary, stainless steel is preferred over epoxy-covered reinforcement because the latter requires careful handling to avoid damage. Fibre-reinforced polymer reinforcement can be considered since it has already been accepted by some national codes, such as ACI and CSA, but it is necessary to demonstrate its suitability at low temperatures.

Appropriate testing methods for concrete air-voids are found in References [A.12-14] through [A.12-16].

A.12.4.3 Execution

A.12.4.3.1 Falsework and formwork

No additional guidance is offered.

A.12.4.3.2 Pre- and post-tensioning

No additional guidance is offered.

A.12.4.3.3 Protective measures

No additional guidance is offered.

A.12.4.3.4 Concreting

No additional guidance is offered.

A.12.4.3.5 Embedded components

See Reference [A.12-17] for embedded items.

A.12.4.3.6 Hydrotesting

No additional guidance is offered.

A.12.4.3.7 Hot and cold weather works

A.12.4.3.7.1 Concreting in cold weather

Guidelines for concreting in cold weather can be found, for example, in CSA A23.1:94[A.12-18] and ACI 306R[A.12-19]. Cold weather concreting, curing and protection of concrete should meet the following requirements.

a) Special attention should be given to the curing of concrete to ensure maximum durability and minimal cracking.

b) Seawater should not be used for the initial curing of reinforced or pre-stressed concrete. After three days, concrete can be submerged in seawater to effect the final curing.

c) Seawater should not be used for cleaning formwork.

d) For thick, massive concrete sections, heat generation caused by hydration of the cementitious material should be evaluated, and measures should be taken to control cracking and restraint stresses under various conditions of volume change and restraint.

   NOTE Measures to protect concrete from severe temperature differentials are described in Reference [A.12-18] or an equivalent standard.

e) The concrete should be maintained in a moist condition at a temperature above 10 °C for at least the first three days after placing, or for the time necessary to reach 35 % of the specified 28 day compressive strength. When it is necessary to expose concrete to severe exposure and/or abrasion immediately following the basic curing period (although it is recommended that such situations be avoided), the concrete should be cured either for an additional four consecutive days at a minimum temperature of 10 °C, or for the time necessary to reach 70 % of the specified 28 day compressive strength.

Special requirements for the type and duration of the curing process, together with the details of any special conditions that it is necessary to maintain, should be specified.

During freezing weather, water curing of concrete should be terminated 12 h before the end of the protection period.

Curing compounds should not contain chlorides. Curing compounds should not be used on surfaces where succeeding layers of concrete will be placed and bonded, unless one of the following conditions is met.

- They are entirely removed at the end of the curing period by sandblasting or use of an approved solvent.
- Conclusive tests show that the residue of the membrane does not reduce the bond to below design limits.
- Suitable mechanical means for full bond development are provided.

Curing compounds should not be used on a surface where coatings or paint will be applied unless prior compatibility with the coating has been confirmed by tests.

When the air temperature either is at or below 5 °C, or is forecast to fall below 5 °C within 24 h of placing, all materials and equipment required for adequate protection and curing should be on hand and ready for use before concrete placement is started.

When referring to concrete construction, cold weather is defined as a period when for three consecutive days the mean daily temperature drops below +5 °C.

When temperatures above +10 °C occur during more than half of any 24 h period, the concrete should no longer be considered cold weather concrete.

During cold weather, means should be provided for maintaining the temperature of newly placed concrete above the minimum values contained in codes[A.12-18] referring to concrete placement and workmanship, for a minimum period of three days or until sufficient hydration has occurred to protect the concrete from frost damage.

Aggregate should be free from snow and ice at the time of use.

All snow and ice should be removed before concrete is deposited on any surface. Calcium chloride or other de-icing salts should not be used as de-icing agent in the forms. Concrete should not be placed on, or against, any surface that lowers the temperature of the concrete in place below the minimum values shown in Table A.12-1.

The required minimum temperature of the concrete immediately after placing can be achieved by heating the water or the aggregate, or both (e.g. see recommendations for cold weather concreting as given in Reference [A.12-19].

Once mixed, the concrete should be maintained at a temperature of not more than 6 °C above the minimum temperatures specified in Table A.12-1.

Table A.12-1 — Minimum concrete temperature after placing

Air temperature °C	**Minimum concrete temperature after placing** °C		
	Minimum dimension of the concrete section		
	<1 m	1 m to 2 m	>2 m
>–1	13	10	7
–18 to –1	16	13	10
< –18	18	16	13

These concrete temperatures should be maintained for a duration that depends on the ingredients used, their position in the mixture and the required strength. The *in situ* strength development during cold weather construction should be monitored to ensure adequate safety associated with the removal of shoring and formwork.

A.12.4.3.7.2 Grouting of pre-stressing duct during cold weather

No additional guidance is offered.

A.12.4.3.7.3 Placing and bending reinforcement during cold weather

No additional guidance is offered.

A.12.5 Mechanical systems

A.12.5.1 Introduction

No additional guidance is offered.

A.12.5.2 Permanent mechanical systems

A.12.5.2.1 Crude oil storage system

GRP (glass-fibre reinforced plastic) pipes can be used as long as brittleness criteria are met. Steel qualities for such use are found, for instance, in Reference [A.12-20] or other relevant standards.

A.12.5.2.2 Other storage systems

GRP pipe should be used with caution in ballast and seawater systems because of the potential damage from differential displacements of the supporting structure.

A.12.5.2.3 Risers and J-tubes

No additional guidance is offered.

A.12.5.3 Mechanical systems — Temporary ballasting/deballasting water systems

No additional guidance is offered.

A.12.5.4 Attachments and penetrations

No additional guidance is offered.

A.12.5.5 Mechanical systems — Design of piping supports

No additional guidance is offered.

A.12.6 Marine operations and construction afloat

No additional guidance is offered.

A.12.7 Corrosion control

No additional guidance is offered.

A.12.8 Inspection and condition monitoring

No additional guidance is offered.

A.13 Floating structures

A.13.1 General

Many design solutions, both global and local, are available to the designer of a floating structure for use in ice-covered waters. There can, therefore, be cases where such a structure cannot be logically placed within this International Standard, or where specific requirements are found not to be relevant. In such cases, the design should be based upon the principles documented in this International Standard and should achieve a level of safety equivalent or superior to the safety level implicit in this International Standard. The principles documented in this clause are applicable both to steel-hulled floating structures and to structures fabricated from other materials.

This International Standard does not provide detailed instructions for producing reliable estimates of the environmental parameters to consider for all floating structure designs. In this regard, it is important to incorporate past experience for data gathering and analysis procedures, statistical techniques, and defining the key environmental influences and factors for a particular system, including those associated with ice management. Because long-term data are often lacking in arctic and cold regions, operating plans and procedures should recognize specifics of the environment and associated uncertainties. The involvement of ice and metocean experts, as well as experienced mariners in such conditions, is imperative for safe and effective operations.

It is also important that the design engineer who uses the environmental information be aware of the uncertainties in the parameters provided and the effects of any uncertainties on the overall system being designed. Assumptions made and operating limits defined for floating structure designs should also be carried forward as the basis for operating procedures once the system is put into service, and refined as operating experience is gained.

See Reference [A.13-1] for provisions relating to tension leg platforms. While tension-leg platforms and jack-up structures are beyond the scope of this International Standard, the ice environment and action provisions contained in 13.3 and 13.4 can be applied.

A.13.2 General design methodology

A.13.2.1 Design philosophy

The range of ice considerations for most floating installations is generally broader than that for fixed structures. This is due to

- the interrelationships that exist between the design and operational aspects of a floating installation;
- the ice detection, avoidance and management systems used to protect it;
- their likely levels of effectiveness;
- the different means by which system reliability can be achieved.

There are many unique features associated with floaters operating in ice. For floaters operating as vessels, there are specific requirements for ice clearing from water intakes, turrets and thrusters. Ice rubble, small floes or small pieces of glacial ice can accumulate between legs of a structure and influence the effective dimensions of the structure for certain scenarios.

A.13.2.2 Design and operational approaches

A variety of design and operating approaches can be selected for floating installations in ice-prone waters as follows.

a) Passive: at one end of the spectrum, a floating installation can be designed to withstand all of the expected ice and other environmental actions, both normal and extreme, in a passive stationkeeping mode (where the floating structure is free to weathervane without thruster intervention), without any type of ice management support and without the capability to disconnect and move off location. This is similar to the design approach normally adopted for fixed offshore structures, and for many floating installations in open water environments.

b) Semi-active: this scenario still does not make use of any ice management techniques. In order to prevent interactions with ice that can exceed the resistance capabilities of the installation, the floating structure can be moved off location in the context of well defined ice alert procedures. One such example is a seasonal installation operating during the so-called shoulder seasons when ice conditions are relatively light.

c) Active: at the other end of the spectrum, a floating structure can be operated to avoid particular ice conditions, for example, by managing the ice encountered by the installation in the context of well defined ice alert procedures. If conditions become too severe, the structure can stop operations and move off location.

A wide range of design and operating approaches can be taken, with varying levels of ice tolerance (in the platform's structural and stationkeeping capabilities), different disconnect and move-off systems (and time frames for this response) and various levels of ice management support.

The range of options that can be considered for floating installations in ice-covered waters is illustrated in Figure A.13-1.

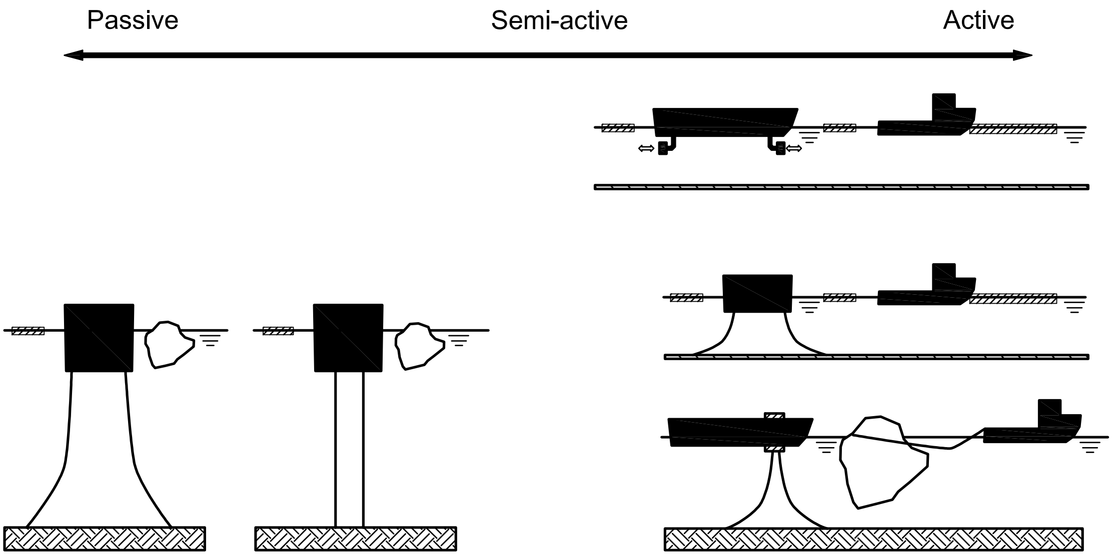


Figure A.13-1 — Range of options for floating structures in arctic and cold regions

For any floating installations that operate actively, the importance of reliably detecting adverse ice conditions (e.g. icebergs, multi-year ice floes, large first-year ridges, rubble fields, ice pressure events) prior to their interaction with the structure and the capacity and reliability of an ice management system to contend with adverse ice situations should be clearly recognized. A logic diagram that shows the relationship between the various factors is provided in Figure A.13-2.

Some floating installations can be appropriately designed for specific ice interaction scenarios, according to vessel classifications, rather than according to the event-based strategy implicit in this International Standard.

The consequences of ice actions on the various components of a floating production installation can be influenced by operational considerations, such as flushing of flowlines and disconnection of subsea equipment. Such considerations are used for the designation of exposure levels, as specified in Clause 7. Exposure levels can be applied for the entire or portions of floating structures, examples of which are provided in Table A.13-1. The owner can specify higher consequences according to the value of the asset and lost production time.

A.13.2.3 Design considerations

A comprehensive and methodical approach is advised to ensure that all project-specific factors and combinations are addressed. A multi-disciplinary review and/or formal HAZID type approach is recommended.

Table A.13-1 — Exposure levels for major components of floating structures

Component	Exposure level	Notes
Entire installation	L1	Actions can be reduced in the context of ice management and disconnection capabilities
Hydrocarbon storage	L1	—
Hull	L1/L2	Where actions pose high/low risk to life or the environment
Stationkeeping system	L3	—
Wellhead	As given in ISO 19904-1	—
Flow lines and risers	As given in ISO 19904-1	—
Flow lines and risers	L3	If flushed, within the context of an ice management system satisfying the provisions of this International Standard
Other components	L1	Where actions pose high risk to life or the environment
Other components	L2	Where actions pose moderate risk to life or the environment
Other components	L3	Where actions pose low risk to life and the environment

A.13.3 Environment

No additional guidance is offered.

A.13.4 Actions

A.13.4.1 Applicability

No additional guidance is offered.

A.13.4.2 Ice scenarios

No additional guidance is offered.

A.13.4.3 Interaction factors

Impressed current, low friction coatings, other coatings suitable for use in ice or stainless steel belts can be considered for reducing loss of shell plate thickness through abrasion and corrosion.

A.13.4.4 Determination of ice actions

No additional guidance is offered.

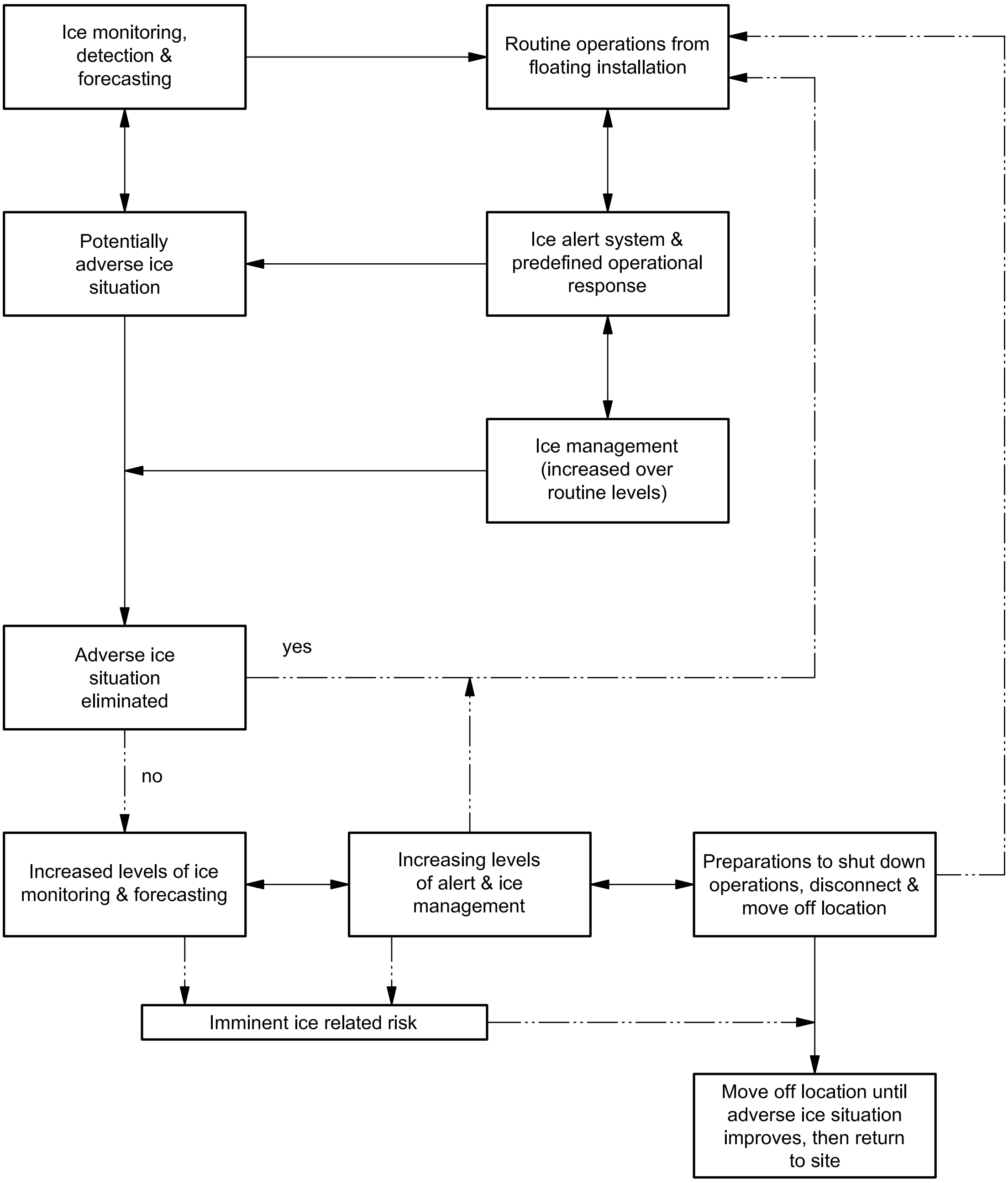


Figure A.13-2 — Relationship between the various factors for floater operations in ice environments

A.13.4.5 Other ice action considerations

No additional guidance is offered.

A.13.4.6 Action variations

No additional guidance is offered.

A.13.5 Hull integrity

A.13.5.1 Structural design philosophy

Some rules for ice-strengthened vessels apply icebreaking mechanisms and load equations that are more appropriate for moving ships than stationary ship-shaped structures. Stationary floating structures cannot selectively avoid extreme features and can have limited manoeuvrability, and should be designed accordingly.

Vessels intended for seasonal production can experience different or more onerous ice actions during the field deployment and departure voyages, to which additional consideration should be given.

A.13.5.2 Hull ductility

Any area exposed to low air temperatures should be constructed with ductile materials suitable for operation in this environment. It can be necessary to upgrade structural steel class and grades for weather-exposed plating and for inboard framing members attached to this plating if the design service temperature is below the calculated design temperature for the material at the specific location.

A.13.5.3 Structural analysis and design

For local ice actions, the maximum area over which local pressures are applied can be limited by the nominal contact area associated with the global ice action.

Discrete impacts from glacial ice, ridges and other ice features can result in crushing of the ice and damage to the hull of the vessel. In cases where there is significant damage to the hull, a full dynamic analysis can be required.

A.13.5.4 Structural considerations

No additional guidance is offered.

A.13.5.5 Condition monitoring

No additional guidance is offered.

A.13.6 Hull stability

A.13.6.1 Subdivision

See Reference [A.13-2] for guidelines for ships operating in ice covered waters in general and, in particular, for longitudinal subdivision requirements.

Double-hulled vessels include double-side, double-bottom and double-side, and single-bottom designs. In certain situations such as for floating concrete structures, a double bottom is not necessarily required to provide the necessary damage protection. Adequacy with respect to ice actions should be demonstrated.

A.13.6.2 Intact stability

Reference [A.13-2] provides specific guidelines for the intact stability of arctic ships. While focused on ship hull forms, many of the provisions can be applied to other floating structures.

A.13.6.3 Damaged stability

Specific guidelines for damaged stability of ship hull forms are provided in Reference [A.13-2].

A.13.7 Stationkeeping

A.13.7.1 General

A.13.7.1.1 Types of systems

For stationkeeping systems in arctic and cold regions, 13.7.1 stipulates that annual probabilities of exceedance for actions be calculated according to Clause 7. EL actions are specified in 7.2 at an annual probability of exceedance of 10^{-2}, which corresponds to a return period of 100 years. This International Standard imposes the additional requirements of AL design for ice actions and requires that Clause 7 apply for all stationkeeping design, whether mobile or permanent. In 13.7.1, return periods shorter than 100 years are also permitted if the return period is determined through a risk assessment, taking into account the possible consequences of stationkeeping system failure.

A floating structure with suitable means of keeping its position at the specific site of intended operation usually consists of a stationkeeping system connecting the installation physically to the seabed, or a DP system whereby the floating structure is kept in position by means of thrusters, or a combination of both.

The type of stationkeeping system involved depends on the type of floating structure and the chosen system solution. Table A.13-2 gives an overview of the relevant stationkeeping systems.

Table A.13-2 — Overview of stationkeeping systems

Structure type	Normal stationkeeping system	Alternatives
Monohull (fixed direction)	Spread moored	Slack or taut lines fixed or quick disconnect
Monohull (rotatable)	Single-point moored turret	Slack or taut lines fixed or quick disconnect DP or thruster assisted
Semi-submersible	Spread moored	Slack or taut lines fixed or quick disconnect DP or thruster assisted
Spar	Spread moored	Semi-taut, taut or catenary lines
TLP	Vertically, tensioned, tethers	Fixed system, no possibility for disconnection

A.13.7.1.2 Monohull floating structures

The following positioning systems can be used for monohull floating structures.

a) Spread mooring: a system consisting of mooring lines terminated at different locations on the installation and pointing outwards, providing an almost constant installation heading.

b) Turret mooring: a system consisting of mooring lines attached to a turret with bearings, allowing the installation to vary its heading. The turret can be of a disconnectable/reconnectable type, allowing the disconnection of both mooring lines and risers from the vessel to avoid direct contact from icebergs or sea ice above a certain action level. Positioning systems include

   - a passive or active mooring system allowing the installation to freely weathervane;
   - a combination of a passive or active mooring system and thrusters for heading control;

  - a combination of an active or passive mooring system and thrusters for both heading control and reduction in mooring loads;
  - those kept in position by thrusters only.

c) Single-point mooring: a system consisting of a fixed tower or a single-point mooring system (SALM, SPM, STP, etc.).

A.13.7.1.3 Semi-submersibles and buoy type floating structures

The following positioning systems can be used for semi-submersibles as well as buoy type installations (spars, buoys and SALMs):

- passive or active spread mooring system;
- combination of a passive or active spread mooring system and thrusters for reduction in mooring loads;
- those kept in position by thrusters only.

A.13.7.1.4 Tension leg platforms

The TLP concept is kept in position by vertical, tensioned mooring components. While the components are normally made of steel, designs using composite materials are also applicable.

Reference [A.13-1] contains provisions relating to TLPs.

A.13.7.1.5 Other performance enhancing systems

Supplementary to the above systems, various performance enhancing or ice action and action effect reduction means can be utilized. Examples include air bubbler systems and water sprays, special hull paints and added thrusters.

Additionally, each of the above-mentioned mooring systems can be equipped with remote and quick-disconnect mooring systems to facilitate the quick release of all mooring lines.

A.13.7.2 Design of the stationkeeping system

No additional guidance is offered.

A.13.7.3 Disconnection and reconnection

Disconnection of the mooring lines and other connected lines can be done individually, or partly or fully coupled. An FPSO is an example of an installation that can be equipped with the latter option where all lines are physically connected to a connecting component (disconnectable turret).

A TLP, by nature, does not have a disconnection/reconnection capability included in the design.

A potential design approach for disconnectable turret systems is to allow the turret to drop to a safe depth with respect to the draught of iceberg or sea ice ridge keels.

A.13.7.4 Planned and emergency disconnect

No additional guidance is offered.

A.13.7.5 Stationkeeping system failures

No additional guidance is offered.

A.13.8 Mechanical systems

A.13.8.1 General considerations

No additional guidance is offered.

A.13.8.1.1 Applicability

No additional guidance is offered.

A.13.8.1.2 General considerations for all systems in arctic and cold regions

Low air temperatures increase the risk of failure in load-bearing parts as well as in mechanical equipment (for mooring, life-saving, lifting appliances, processing, etc.) due to changes in steel properties.

A.13.8.1.3 Icing and snow

Special ice-phobic coatings can be effective in reducing ice accretion. These coatings have a short useful life. Selective application (e.g. on forward areas of superstructure) of such coatings should be considered, particularly for small vessels operating in areas where icing is known to be a problem. Such coatings should not be used on walking areas due to their inherent slickness.

A.13.8.2 Hull systems

A.13.8.2.1 Sea inlets and cooling water systems

The volume of sea chests should be approximately 1 m^3 per 750 kW engine output of the floating structure, including the output of the auxiliary engines necessary for the floater's service.

Other arrangements for sea chests and sea bays can be considered.

A.13.8.2.2 Ballast system

When a tank is situated partly above the ballast waterline (BWL), an air-bubbling arrangement, vertical heating coil or other ice growth reduction system, capable of maintaining an open hole in the ice layer, is normally acceptable. Other ice growth systems are ballast or cooling water recirculation systems. Before the pumping of ballast water is commenced, the proper functioning of level gauging arrangements should be verified and air pipes checked for possible blockage by ice.

A.13.8.2.3 Marine systems instrumentation

Issues for consideration include the following.

- A branch pipe with a small diameter to a sensor can cause many problems with respect to viscosity, freezing, hydrate formation, condensation, etc.
- Icing from the outside of valves can cause problems with regard to the position indication of the valve.
- Handles and wheels of manual manoeuvring units can be exposed to icing.
- Certain types of fire and gas detectors and recording methods can be dependent on their own temperature, the temperature of the environment, riming of lenses, etc.
- Relays can operate slowly at low temperatures.

For pneumatically operated valves, dry air should be used to avoid hydrate formation and blockage of supply lines. For hydraulically operated valves, particular attention should be given to the viscosity characteristics of the fluid at low temperatures to ensure that the valve operates within the required time frame.

A.13.8.2.4 Lighting

No additional guidance is offered.

A.13.8.2.5 HVAC and air systems

No additional guidance is offered.

A.13.8.2.6 Starting arrangements

Self-propelled floaters with engines that are started by compressed air should be provided with not fewer than two air receivers and the total capacity of the air receivers should be sufficient to provide, without replenishment, air for

a) 12 starts in the case of a floater with reversible engines;

b) 6 starts in the case of a floater with non-reversible engines.

The compressed air should be provided by more than one independently driven air compressor and the air compressors should have sufficient capacity to charge the air receivers from empty to maximum pressure in not more than 30 min.

The capacity of the smallest air compressor should not be less than two-thirds of the capacity of the largest air compressor.

A.13.8.2.7 Propulsion, thrusters and steering for self-propelled floaters

No additional guidance is offered.

A.13.8.3 Offloading systems

The following aspects should be taken into account for the proper design and operation of this equipment:

- protection;
- local heaters;
- hydraulic and/or pneumatic proper for cold environment operation;
- load-bearing units that are checked and validated and the proper selection of materials;
- accessibility and proper operation of all equipment;
- offloading hoses and associated gear;
- rapid disconnect valves and shut-down systems;
- planned and emergency disconnect operations;
- direct and indirect ice actions.

A.13.9 Operations

A.13.9.1 General

Special operational issues for floaters in arctic and cold regions include low ambient light, ice and snow accumulation on the deck and exposed equipment, hypothermia and freezing of exposed skin, and vessel motions in heavy ice conditions.

A.13.9.2 Operations and emergency procedures manuals

Depending on the type of system employed, operational procedures can include, but are not limited to,

- communications;
- prevention and pollution, garbage and refuse;
- mooring procedures;
- cargo transfer operations;
- crew transfer procedures;
- bunker transfers;
- crane operations;
- deck operations;
- engine room operations;
- vessel stability;
- ice alert.

Depending on the type of system employed, emergency procedures can include, but are not limited to,

a) severe weather and ice conditions;

b) damaged vessel;

c) power failure;

d) abandon vessel;

e) mooring system failure;

f) ballast emergency;

g) fire or explosion;

h) blowout;

i) detection and leakage of gas;

j) medical emergency;

k) helicopter emergencies;

l) man overboard and search and rescue.

A.13.9.3 Deck surfaces

No additional guidance is offered.

A.13.9.4 Damage control

No additional guidance is offered.

A.13.9.5 Equipment and doors

Prior to conducting any activity, operating personnel are expected to take due precautions for safe operation as specified in the operations manual. Conditions include, but are not limited to,

- checking of actual wind chill conditions;
- checking of proper lighting in all work areas;
- provision of proper heating;
- proper functioning of all equipment;
- proper protective clothing;
- proper and fully operable communication equipment;
- use of a buddy system;
- removal of snow and ice.

A.13.9.6 Inspection and maintenance

Some systems might not be accessible for part of the year. Properly engineered solutions lead to safer operation until access is possible. For more information on the design of floaters with respect to provisions for inspection and maintenance, see Reference [A.13-3].

Systems that are immediately accessible, like a fire system, can be readily monitored and inspected. Normal inspection frequencies ensure proper operation. Cold temperatures, ice growth or changed characteristics can prevent their efficient operation. Increased inspection frequencies can be required in such circumstances.

Some equipment like the mooring system and subsea components connected to the floater are not immediately accessible. Consideration of the following alleviating methods can ensure the proper functioning of such systems at all times:

- overdesign of the critical components;
- installation of a full back-up;
- installation and use of remote control inspection methods and systems.

A.13.9.7 Planning and operations

No additional guidance is offered.

A.13.9.8 Requirement for an ice management plan

No additional guidance is offered.

A.14 Subsea production systems

A.14.1 General

A.14.1.1 System components

This International Standard deals with ice actions for the flowlines and umbilicals referenced in ISO 13628 (all parts)[A.14-1]; it does not deal with the pipeline transportation systems referenced in ISO 13623[A.14-2].

A.14.1.2 Exposure level for system components

No additional guidance is offered.

A.14.1.3 General provisions for ice actions

No additional guidance is offered.

A.14.1.4 Repair

No additional guidance is offered.

A.14.2 Ice and seabed considerations

A.14.2.1 Interactions above the sea floor

No additional guidance is offered.

A.14.2.2 Interaction with gouging ice features

A.14.2.2.1 Sub-gouge soil deformations

A gouging ice feature can produce large sub-gouge horizontal and vertical deformations in the surrounding soil. The state-of-the-art for defining sub-gouge displacements, and for understanding them in general, is rudimentary. The most extensive information in the public domain is derived from centrifuge tests conducted as part of the PRISE (Pressure Ridge Ice Scour Experiment) programme[A.14-3]. A comprehensive treatment of actions from gouging ice features is provided in Reference [A.14-4].

Three zones of ice-soil-pipe interaction have been identified; see Figure A.14-1:

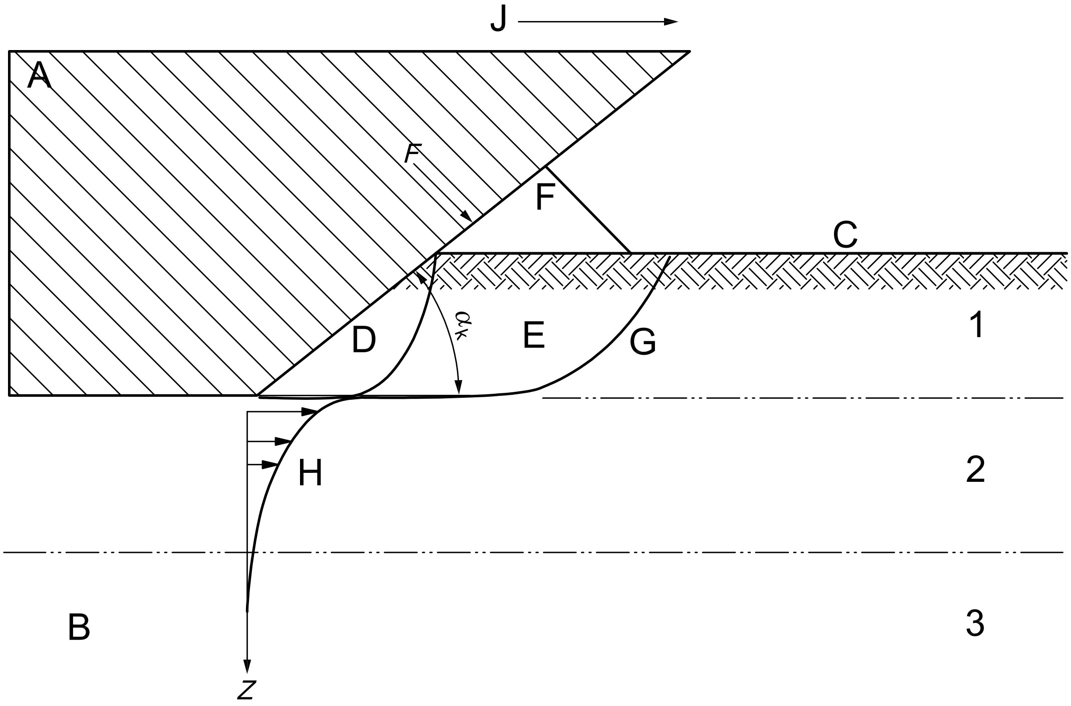
- Zone 1 – soil layer displaced by the ice feature;
- Zone 2 – soil layer subjected to permanent deformations;
- Zone 3 – soil layer subjected to elastic deformations.

A.14.2.2.2 Ice gouging parameters

Ice gouge parameters relevant to the design of subsea installations include

- gouge dimensions (length, depth, width, shape of track, cross-section shape, identification of single or multi-keeled features);
- pit dimensions (depth, plan dimensions);
- gouge frequency (year-to-year and seasonal variability, areal frequency, linear frequency, proportion of seabed disturbed, geographical distribution, water depth dependence, etc.);

- change in seabed elevation over the gouge length, sometimes termed rise-up;
- ice-soil interaction parameters (slope of contact face, i.e. attack angle or rake angle, ice pressure applied to the soil, soil displacements beneath gouge).



Key

A	ice keel	J	ice movement direction
B	soil	1	soil zone 1
C	sea floor	2	soil zone 2
D	dead soil wedge	3	soil zone 3
E	passive soil wedge	z	depth below ice keel
F	passive soil frontal mound	F	ice bearing action
G	soil rupture surface	α_k	keel attack angle
H	sub-gouge displacement profile		

Figure A.14-1 — Soil displacements during the gouging process[A.14-5], [A.14-6]

Many applications require more than just average or extreme values of these parameters, and full probability distributions or joint probability distributions are often necessary. With multi-beam sonar technology, data on variations in the width and depth of gouge features, which can be useful in certain applications, are now available. For example, the shape of the cross-section can influence the magnitude of sub-gouge soil deformations.

While it is preferable to measure the above parameters directly from gouge surveys, this is not always possible. Inference through mathematical or physical models is sometimes made and guidance is provided in A.14.2.2.4 and A.14.2.2.5.

A.14.2.2.3 Ice gouge measurements

Traditionally, gouge surveys were based on linear tracks but many now involve overlapping tracks from which the full three-dimensional topography of the sea floor can be determined.

Surveys are used typically to characterize

- gouge dimensions (imaging techniques);
- gouge frequency (repeated surveys, identification of new features, infilling or erosion of gouge features);
- specific mechanisms associated with the gouge process.

Repetitive surveys along the same line or over the same area are considered as the most reliable means of determining the frequency of new gouges. Since gouge characteristics and severity can vary from year to year, surveys over several years can be required. Wherever possible, representative gouge statistics from the immediate vicinity of the subsea installation should be used.

Surveys should be designed specifically to estimate gouge parameters. Surveys designed for bathymetric and other purposes have typically proved to be inadequate. Instruments used for gouge surveys include

a) multi-beam sonar (imaging);

b) sidescan sonar (imaging);

c) profiling sonar (sea floor depth);

d) sub-bottom profiler (soil characteristics, gouge geometry).

These remote techniques can be supplemented, where necessary, with seabed sampling or direct observations.

Because of wave erosion and infill in particular environments, gouge surveys should be scheduled in the spring or early summer as soon as the area is clear of ice. Immediate infill can potentially take place for deep narrow gouges in certain soils and its effect on design burial depth should be assessed (potentially through sensitivity analysis).

Potential issues for the interpretation of seabed surveys include

- correct gouge identification (including discrimination from other, non-gouge features, particularly when eroded or infilled);
- identification of recent, older and relict features;
- resolution, bias and accuracy of measurement devices;
- accuracy of survey methods;
- characterization of parameters according to established protocols;
- avoidance of bias when compiling parameter values and distributions from measurements;
- truncation of gouges at edge of images;
- natural infilling effects on ice gouges;
- water depth ranges and seabed soil types.

Expert interpretation is recommended to ensure consistent data quality.

A discussion of iceberg gouge survey techniques and protocols for interpretation is given in References [A.14-7] and [A.14-8]. Protocols for sea ice gouge surveys are discussed in Reference [A.14-9].

A.14.2.2.4 Mathematical models of the ice gouging processes

Models of the ice gouging process can be broken down according to function:

- characterization of parameter distributions (often used);
- estimation of gouge frequency (sometimes used);
- estimation of gouge dimensions (used occasionally);
- characterization of gouge processes (used occasionally);
- characterization of sub-gouge soil deformations (used occasionally).

Some common types of models include the following.

a) Gouge depth distribution models: the most common method for predicting the gouge depth distribution is to use measurements made during field surveys. Many analyses have used all depths above the resolution of the measurement system, rather than only the tail of the distribution. It should be recognized that this implicitly assumes that extreme and abnormal gouges follow the same depth distribution as the whole population. Most commonly, an exponential distribution has been used to describe gouge depths, but the most appropriate probability distribution should be investigated on a case-by-case basis for the available data of interest. When data are scarce, the exponential distribution can be used with an appropriate provision for uncertainty. Particular consideration should be given to the use of truncated distributions when the data are limited by the system resolution. When extrapolating gouge depth distributions from limited data, consideration should be given to the physical limits discussed in A.14.2.2.6.

b) Gouge frequency models: phenomenological modelling has been done using information regarding bathymetry, geotechnical and metocean conditions for the Okhotsk Sea[A.14-10] and for other areas[A.14-11] through [A.14-13], and also for shoreline locations where tidal-induced ice drift is significant[A.14-14]. The required inputs for this type of modelling include

   - speed and direction of ice drift, and/or currents and winds,
   - bathymetry,
   - size of drifting ice feature (including mass),
   - sail height and/or keel depth of the ice feature,
   - knowledge about the local geometry, e.g. spacing between adjacent keels, and any protection offered by factors such as
     - several keels being present within the same ice floe for which only certain ones are allowed to ground,
     - effects of the local bathymetry and shoreline, which can preclude, for example, keels exceeding a given draught, and/or drifting from certain directions.

c) Kinetic energy and driving action models: these models are typically used to address circumstances where gouging is limited by the kinetic energy of the feature or by the available driving actions. Models developed to analyse kinetic energy-limited gouging equate the kinetic energy of the moving ice feature with the work done. Early modelling and assessment efforts include References [A.14-15] and [A.14-16], in which an assessment of these models was conducted using iceberg gouge data compiled from observations off Canada's east coast. Other numerical modelling efforts include References [A.14-6], [A.14-17] and [A.14-10], among others. The available models differ in various ways such as

   - the energy sinks included,

- the methods used to compute soil resistance,
- the slope of the interaction face between ice and seabed,
- whether vertical displacements and rotations of the ice feature are considered.

The most appropriate model depends on the specific case of interest.

Models other than those listed above can be used to assist with the interpretation or extrapolation of gouge data. Examples include those dealing with infill and those providing physical limits to gouge parameters.

Due account should be taken of uncertainties in all models and their parameters.

A.14.2.2.5 Physical models of the ice gouging processes

A number of physical models have been developed to assist with the understanding of ice gouge processes. These include the following.

a) Small-scale testing in a centrifuge: the most extensive centrifuge tests were done as part of the PRISE (see A.14.2.2.1), although some others have been performed[A.14-18].

b) Testing in hydraulic basins: small-scale tests have been reported in References [A.14-19] through [A.14-25], among others.

c) Large-scale test results (see, for example, reference [A.14-26]) are all proprietary.

d) Field tests: large-scale tests have been done near Spitsbergen[A.14-27] through [A.14-29].

A.14.2.2.6 Limits to ice gouging parameter distributions

Many factors and processes can limit the gouge dimensions that are created on the seabed. Potential limits include the following.

a) Driving actions: the available environmental driving actions and the ability of the ice cover to transmit them can limit gouge length and depth. These are most applicable to the case where a gouging ice keel (typically contained in an ice floe or as part of a hummock field) is being driven by pack ice. In this case, the available kinetic energy is large; effectively infinite. There are several potential limits to the driving action, including the following.
    - The sheet ice containing the gouging ice keel can fail.
    - The sheet ice floe or hummock field can rotate.
    - Ridging and rafting can start to form elsewhere in the pack ice.

b) Kinetic energy: the kinetic energy of the drifting ice mass can also limit gouge length and depth. This limit is most applicable to cases where an isolated ice feature (e.g. a ridge within an ice floe or an iceberg) drifts freely into the seabed. Analyses of this type of interaction should include the most significant site-specific energy sinks, which can involve
    - work done on the soil over the length of the gouge track, which includes several aspects as work is done in deforming the soil
        i) in front of the keel,
        ii) by clearing the soil away from the advancing keel,
        iii) by soil acting on the bottom of the ice keel;

- uplift and/or pitch motions of the ice feature;
- work expended through failure of the gouging ice feature (e.g. a multi-year or first-year ridge in sheet ice).

c) Ice keel processes: abrasion or mechanical failure of the ice keel can limit gouge depth. Observations on Canada's east coast of iceberg gouging have shown that ice blocks were broken off from the keel during gouging[A.14-30]. Although no specific observations are available for gouges produced by first-year or multi-year ridges, it is generally assumed that some ablation takes place for a variety of ice keel types.

d) Strong soils: when the strength of the gouging ice keel is less than that of the seabed soil, this can impose important limits on gouge depth, most generally for the case where first-year ridges encounter relatively stiff seabed material[A.14-31].

e) Geography: the local geometry of the shoreline or bay (e.g. for a loading line), or bathymetry (e.g. if a sill were present), can impose limits with respect to the size, number and drift directions of ice features that can enter an area. Gouging ice features can become grounded, thereby preventing further ice movements.

A.14.2.3 Strudel scouring

Soil conditions exert considerable influence on the development of strudel scours. Stiff plastic clay and gravel are resistant to scouring, while silt, sand, and soft clay are easily displaced. These soil characteristics should be considered in the analysis.

Field surveys of scours in the actual area combined with knowledge of these interrelated factors provide an estimate of the number of free spans and the probability distribution for their length.

A.14.2.4 Permafrost

No additional guidance is offered.

A.14.2.5 Geohazards

No additional guidance is offered.

A.14.3 Actions on subsea production systems

A.14.3.1 General action requirements

No additional guidance is offered.

A.14.3.2 Ice protection structures

Limitations on strength, as well as displacements and rotations of the impacting ice keel, can be used to reduce calculated ice actions on a protection structure. Examples include unconsolidated parts of first-year pressure ridge keels and iceberg pitch motions.

A.14.3.3 Glory holes

Glory holes have been used to protect subsea templates from iceberg contact at the Terra Nova and White Rose subsea developments offshore of Newfoundland. The size and geometry of glory holes should consider protection from iceberg interactions, remotely operated vehicle access, flowline connections and stability of side slopes. A key consideration in these designs is the depth of the hole and, therefore, the clearance between the top of the template and the sea floor. The frequency of interactions was determined from the frequency of iceberg keel incursions into the glory hole and the consequent probability of contacting the equipment on the template. The design strategy involved reducing annual interaction frequency below 10^{-4}. Some general background on the issues is found in Reference [A.14-32].

A.14.3.4 Risers and loading/unloading systems

No additional guidance is offered.

A.14.3.5 Flowlines and umbilicals

A.14.3.5.1 Protection of flowlines and umbilicals from ice gouging

Where reliable forecasts of potentially gouging ice features are available, production shutdown and flushing of lines can reduce the risk of damage to acceptable levels. Examples include the subsea facilities at Terra Nova and White Rose on the Grand Banks of Newfoundland. Where the probability of ice contact with the seabed is less than the ELIE and ALIE levels, it is not necessary that flowlines and umbilicals be checked for the corresponding action combination.

For cohesive soils and rock, steep-walled trenches can be used, thereby minimizing the quantity of excavated material. For granular materials, only shallower slopes can be achieved. A trench can either be left open or be backfilled; the gouge-induced soil pressures and direct contact should be investigated in this context.

Typically, bending strains resulting from lateral displacements are the most significant design issue for buried lines crossed by gouging ice features. Other processes of concern include ovalization from pressures transmitted through the soil and direct impact from ice keels.

It is generally recognized that a buried pipe can be damaged during the gouging process even though it is not contacted by the ice[A.14-33], [A.14-34]. Generally, the strategy used for the protection of pipelines from ice keels is the avoidance of direct ice contact and the burial at sufficient depth to avoid excessive pipe deformations due to soil movements. In practice, burial is required in ice environments for water depths less than the deepest ice keels that can occur.

The most common method considered for the protection of flowlines and umbilicals from ice gouging is burial in a trench on the sea floor. Strategies such as covering the flowlines and umbilicals with concrete, gravel or rock, bundling more than one line, strengthening the pipe or anchoring the pipe can be used in combination with trenching to reduce the risk of ice damage. Such approaches require special analysis procedures.

Connections to a platform and shore crossings require special consideration in the design due to changes in seabed erosion, ice pile-up and permafrost.

A.14.3.5.2 Field experience

It should be noted that because only a few pipelines have been built in ice-covered regions, relatively little experience is available to guide design efforts. Some of these are listed in Table A.14-1.

Table A.14-1 — Summary of reported operational experience with pipelines in ice-covered regions

Location	Reference	General description
Northstar	[A.14-35]	—
Oooguruk flowline bundle, offshore of Alaska in the Beaufort Sea	[A.14-36] through [A.14-38]	Bundled, 3-phase flowline started operation in 2008.
Nevelskoi Strait, between Sakhalin Island and mainland Russia	[A.14-39]	Although this pipeline has operated without documented damage since 1958, very little quantitative information is available regarding this pipeline.
Melville Island, in the Canadian Arctic	[A.14-40]	The Drake F-76 flowline was installed as a demonstration project offshore of Melville Island in the Canadian Arctic. The pipeline was only operated for a very short time in 1978 and has not been monitored since then. Consequently, no information is publicly available regarding its fate.
Water intake line at Hay River, NWT, Canada	[A.14-41]	This water intake line in Great Slave Lake, NWT, Canada was damaged by ice ridges in 1979. This line was not buried.
Lake Erie, Canada	[A.14-42, A.14-43]	Several gas pipelines are present in Lake Erie. Ice-induced damage has occurred to unburied gas pipelines lying on the lake bed.
NOTE Marine pipelines are currently operating offshore of Sakhalin Island and in the Caspian Sea. Flowlines are also present at Terra Nova and at White Rose on the Grand Banks. Ice gouging is a potential consideration for each of these cases.		

A.14.3.5.3 Burial strategy in ice gouge environments

For flowlines and umbilicals, ice actions should be considered in the context of non-ice actions such as anchor dropping and dragging, other dropped objects, soil displacements due to seismic actions, ship impacts, corrosion and erosion of seabed soils. Since offshore flowlines in arctic and cold regions should typically be trenched to avoid ice actions, the trench depth and backfill requirements to avoid vertical pipe instability due to upheaval buckling should be considered.

An ice gouge design is required if the expected frequency of contacts for an exposed flowline or umbilical system on the sea floor exceeds the frequency associated with ELIE or ALIE ice actions. If operational procedures are used to purge hydrocarbons from flowlines, thereby changing the consequence category, it is necessary that their effectiveness be demonstrated and uncertainties accounted for.

Potential burial strategies to calculate required burial depth include

a) ELIE or ALIE events (in terms of gouge parameters), action factors, pipe response analyses and resistance factors;

b) a fully probabilistic approach, in which the pipe response is calculated based on the joint distributions of environmental parameters, pipe characteristics and soil properties to achieve the target reliability (with reference to A.7.2.4);

c) a variety of intermediate semi-probabilistic approaches.

Option a) involves the selection of, for example, the ELIE or ALIE ice gouge event followed by a deterministic pipe response analysis. Because subgouge deformations depend typically on both gouge depth and width, option c) involves the joint distribution of key gouge parameters and a number of deterministic pipe response analyses for representative ranges of gouge parameters and burial depths[A.14-5], [A.14-44]. This strategy is illustrated in Figure A.14-2.

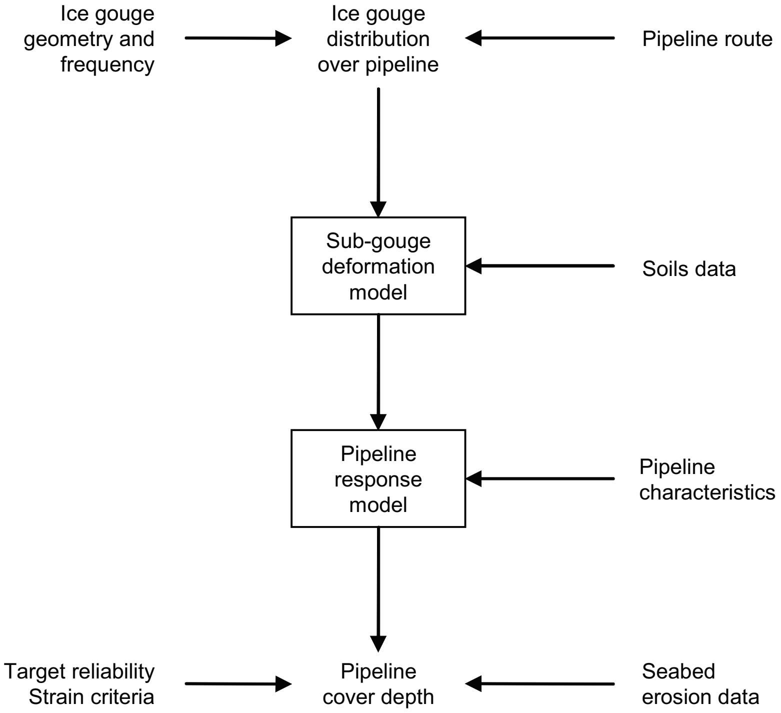


Figure A.14-2 — Strategy for reliability-based design of marine pipelines in ice gouged areas (after Reference [A.14-5])

A key aspect of line burial is the identification of potential mechanisms leading to loss of hydrocarbons. These typically involve direct ice contact, tensile stresses, tensile strains, buckling or wrinkling and ovalization. Experience indicates that pipelines in ice gouge environments generally require a greater wall thickness than those in non-ice environments and that the capability to absorb strains can be more important than high strength in the choice of steel.

The primary issues relating to ice and soil actions that it is necessary to consider include

- the joint distributions of gouge depth and width, the associated pressures applied to soil for various pipe burial depths, and potentially the shape of the gouge cross-section;
- the subgouge soil deformation field, which typically involves the specification of horizontal and vertical displacement fields, both beneath and adjacent to the gouging keel, and their dependence on the parameters specified in the point above;
- the frequency and orientation of pipe crossings by ice gouges.

Another important aspect of pipe burial is the use of an appropriate model of the pipe behaviour based on the specifics of the pipe and trench design, and pipe response to soil movements. Approaches used for pipe/soil interaction include full-scale tests, model tests (including centrifuge) and numerical analyses (analytical, non-linear spring or continuum/FE).

Other factors that should be considered for determining safe burial depths include the state of pipe and trench as a consequence of littoral transport, natural infill, permafrost, upheaval buckling, temperature-induced pipe stresses, coating weights, welds, and operational procedures over the design service life of the project such as trench modification.

See References [A.14-5] and [A.14-44] to [A.14-55] for additional information on design approaches for pipeline burial in ice gouge environments.

A.14.3.5.4 Burial strategy in strudel scour environments

The consequences of strudel scouring can be felt where there is a disturbance of the sea bottom. When the footprint of a strudel scour encroaches on a flowline, an unsupported length of pipe (“free span”) can result if the depth of scour exceeds the design trench depth. An assessment should be considered for pipe behaviour associated with unsupported (or partially supported) span lengths due to EL or AL strudel scour events. The assessment should include the potential for vortex-induced vibrations during scour formation and subsequent hydrodynamic or ice actions.

In the case of circular scours, the critical parameters that determine the risk of pipe failure are the maximum horizontal dimension at the sea bottom, the side slope angle and the depth of the scour. In the case of linear scours, the orientation should be taken into consideration as well as the length, side slope and depth.

A.14.3.6 Resistance to ice actions

No additional guidance is offered.

A.14.4 Seismic design

No additional guidance is offered.

A.14.5 Risk reduction

No additional guidance is offered.

A.15 Topsides

A.15.1 Overall considerations

A.15.1.1 Design considerations for topsides facilities

A.15.1.1.1 General

No additional guidance is offered.

A.15.1.1.2 Ambient temperature

Carbon steel (CS) typically has a lower operating temperature limit of –29 °C, whereas low temperature carbon steel (LTCS) can operate down to –66 °C. Thus, in most arctic and cold regions, CS should be avoided and if the ambient EL temperature does not fall below –66 °C, LTCS can be utilized.

A.15.1.1.3 Sea and glacial ice — Impact on topsides structures

No additional guidance is offered.

A.15.1.1.4 Ice accumulation

No additional guidance is offered.

A.15.1.2 Operational considerations

No additional guidance is offered.

A.15.1.3 Sparing philosophy

No additional guidance is offered.

A.15.2 Design and operational requirements

A.15.2.1 General

No additional guidance is offered.

A.15.2.2 HVAC and utilities

No additional guidance is offered.

A.15.2.3 Architectural

No additional guidance is offered.

A.15.2.4 Electrical

An example of cabling rated for offshore use in marine cold weather climates is the IEEE 45 Type P, fine-stranded, highly flexible cable.

Cold temperature reduces battery output. Battery temperature should be kept at 18 °C or higher to allow recharging in a reasonable amount of time.

A.15.2.5 Isolators

Electrical isolators are used to separate dissimilar metals such as carbon-steel from stainless steel, or aluminium from carbon-steel.

A.15.2.6 Instrumentation and controls

No additional guidance is offered.

A.15.2.7 Mechanical equipment

No additional guidance is offered.

A.15.2.8 Piping

A.15.2.8.1 Pipe testing and inspection

Piping subjected to simultaneous low temperatures and maximum operating pressures should undergo Charpy testing according to ISO 15649[A.15-1].

A.15.2.8.2 Heat tracing and insulation of piping

Electric tracing components and installation methods classified areas should comply with Reference [A.15-2] or [A.15-3], or with another equivalent standard.

A.15.2.8.3 Circulation of fluids

No additional guidance is offered.

A.15.2.8.4 System draining and blow down

No additional guidance is offered.

A.15.2.8.5 Deck drains

Typically, insulation to within 750 mm of the module is provided.

A.15.2.9 Safety

A.15.2.9.1 General

No additional guidance is offered.

A.15.2.9.2 Blast protection

Sealed compartments are generally bounded by architecturally insulated cladding and serviced by large volume HVAC ducting. Even following good layout practice and with the use of blow-out panels, it can be expected that sealed compartments can lead to confinement problems not normally encountered in open, naturally ventilated modules. This, in turn, can lead to predicted blast pressures greater than normally encountered in non-arctic regions. The risk of icing effects on blow-out panels should be considered.

A.15.2.9.3 Fire protection

No additional guidance is offered.

A.15.2.9.4 Human factors/ergonomics

No additional guidance is offered.

A.15.2.9.5 Safety showers and eyewash stations

No additional guidance is offered.

A.15.2.9.6 Changing rooms and storage

No additional guidance is offered.

A.15.2.9.7 Safety equipment

No additional guidance is offered.

A.15.2.10 Relief and flare system

Some fluids become quite viscous when cooled appreciably and pressure safety valves (PSVs) should be sized accordingly. As the viscosity of the fluid increases, the required PSV size and inlet/outlet piping pressure drops increase for a given flow rate.

Balance below PSV has been known to freeze (i.e. rain or snow gets inside and subsequently freezes), causing failure. These PSVs have an open vent in the bonnet, which always remains open for the PSV to work properly. A possible intermediate precaution can be to install a small “street” elbow in the vent and point the outlet downward to minimize the potential for rain/snow to enter. The street elbow should be installed in such a manner that venting gas and/or liquids from the PSV cannot result in a safety hazard to personnel.

The opening pressure of rupture disks, particularly stainless steel, can be strongly influenced by temperature. The opening pressure of the rupture disk should be selected to account for ambient temperature swings (day/night and summer/winter). It can be necessary to select a lower rupture disk opening pressure to take into account the cold temperatures. Using lower rupture disk opening pressures can lead to premature failures in the summer if operating close to the opening pressure. In some cases, it can be necessary to insulate and heat trace the rupture disk holder.

The flare header knock-out drum should be insulated and heat traced. Consideration should be given to installing heating in the flare header knock-out drums/water seal drums. If weep holes are used, hydrocarbon leakage can potentially be avoided by using a system sloping towards the header and knock out drum.

A.15.2.11 Storage

Water within the channel of a closed ball valve on a production storage tank expands when freezing occurs. This can lead to piping and/or valve failures due to the large forces generated. The resulting failure can cause an environmental spill of produced fluids.

The storage tank relief system should be designed to avoid potential freezing of water accumulation. Relief valves for atmospheric storage tank overpressure and vacuum protection should be designed to avoid any water accumulation that can lead to the seat sticking from freezing.

A.15.2.12 Actions on structure

No additional guidance is offered.

A.15.2.13 Provisions supply and mechanical handling

No additional guidance is offered.

A.15.2.14 Working environment

No additional guidance is offered.

A.15.3 Seismic design

A.15.3.1 General

Because of potential effects of ice-induced vibrations, arctic and cold region structures tend to be stiffer than corresponding open water structures. It is often necessary to make specific seismic considerations for such structures.

A.15.3.2 Seismic design of the topside structure

Seismic actions on the topsides structure should be calculated using either

a) coupled analysis, in which the topsides structure actions can be calculated directly by analysing the topsides structure modelled together with the substructure (more accurate than the uncoupled analysis); or

b) uncoupled analysis, in which the topsides structure can be modelled separately from the substructure, using appropriate boundary conditions to model the substructure, the seismic action acting on the topsides being based on the substructure analysis.

Dynamic coupling between the topsides and substructure can be assessed by using a screening method such as contained in Reference [A.15-4].

Seismic actions from either coupled or uncoupled analysis are applied to the structure using either of the following methods.

- Dynamic analysis: topsides actions from a coupled or uncoupled analysis can be calculated using response spectrum analysis or linear or non-linear time history analysis. This method is more accurate than the equivalent static analysis.
- Equivalent static analysis: the topsides can be analysed using a static analysis by applying appropriate seismic accelerations to the topsides mass. The seismic accelerations should be taken from results of the substructure analysis and the potential for dynamic amplification should be considered.

Structural connections should be designed in accordance with the seismic provisions of Reference [A.15-5] or a code having similar provisions.

A.15.3.3 Seismic design of topsides equipment and supports

These provisions apply to the design of all structural components and connections required for transferring lateral and vertical actions from the centre of mass of the equipment to their anchorage.

For the purposes of this section, the following definitions apply.

- Structural damage is defined as a failure of any load-bearing component of the equipment, anchorage failure, or any connection failure. Typical examples of structural damage are bent or buckled support frames, failed anchorage welds or failed fastening hardware.
- Mechanical damage is defined as any dislocation or separation of components. Examples of mechanical damage include disengaged circuit cards and modules and opened doors, drawers and covers.

Actions on equipment, appurtenances and distributed systems should be calculated using either of the following methods.

a) Equivalent static analysis: actions are calculated by applying the appropriate acceleration to the tributary mass in a static analysis.

b) Dynamic analysis: actions are calculated directly in a dynamic analysis of a subsystem, using response spectrum or time history methods. The dynamic analysis is considered more appropriate for flexible equipments.

Critical systems, including related equipment and components, are those that are required to function immediately following an earthquake for life-safety, environmental or financial purposes, as defined by the owner or regulator. Examples include fire protection, blowdown, emergency power, certain HVAC, ESD, smoke and fire detection, etc. They are also typically required to perform an active function following the ALE to achieve system functionality. Critical systems should be defined by a systematic risk assessment.

In lieu of explicit structural analysis, critical equipment can be demonstrated to have adequate seismic resistance by analysis, by shake table tests or by the use of historical earthquake performance data.

Certain support details have been demonstrated to perform poorly in shaking loads in past earthquakes. These include C-clamps and vertically oriented friction connections. These supports should not be used for multiple, adjacent supports or any situation where failure of an individual support can cause an unzipping of the system.

Prior to commissioning, field inspections of the topsides should be performed by experienced engineers to ensure adequate seismic design. These inspections should focus on areas of concern that are not obvious in drawings. A primary emphasis should be on differential displacement issues and design details. Potential seismic interactions should be investigated. The inspection should also include a review of field-routed items, such as small-bore piping or instrument air lines that can be damaged in an earthquake.

Some equipment consists of complex assemblies of mechanical and electrical parts that typically are manufactured in an industrial process that produces similar or identical items. Such equipment can be designed by empirical methods for functional and transportation loads, and can be ruggedly constructed such that it has the ability to survive strong motions without significant loss of function. For such equipment, seismic design is generally not required other than for anchorage and attachments.

It is not intended that all components or parts of equipment, such as shafts, bearings, switches, gears, or similar items, not related to critical systems be designed for seismic actions.

A.15.3.4 Seismic design of component interfaces

An interface check is required since structures and systems can have different structural dynamic properties and can respond differently to earthquakes.

Pipelines and flowlines in arctic and cold regions can be trenched into the soils at the structural interface in order to prevent damage from ice gouging. Differential motion between trenched lines and the structure should be considered in the seismic design.

A.15.3.5 Passive protection systems for seismic design

A seismic passive protection system is defined as a special structural subsystem incorporated into a structure with the aim of reducing the response of the structure to seismic shaking. The passive protection system typically consists of a specific structural configuration coupled with the use of special isolation and/or energy dissipation devices. The term “passive” means that no active control is used to modify the response.

The performance objective of passive protection systems is to decrease the response of a structure to seismic shaking. Typically, a passive protection system is employed in situations where a conventional structural framing solution cannot cost-effectively meet the ALE requirements.

A seismic isolation system introduces an isolation interface between two parts of a structure, effectively decoupling the two parts and, thus, reducing the transmission of seismic shaking from the lower part to the upper part. The isolation system can also include a wind-restraint system, energy dissipation devices and/or displacement restraint system.

A seismic damping system increases the ability of a structure to convert seismically induced kinetic energy to other energy forms, mainly heat, during seismic shaking. This is achieved through the introduction of special damping devices into the structure, which dissipate the energy due to the relative motion between each end of the device.

In rare cases, a passive protection system is also aimed at the reduction of ELE response or at the protection of equipment and systems critical to the post-disaster performance of a structure.

The following should be considered for passive protection systems in arctic offshore structures.

a) Low temperatures: the application of passive protection systems in arctic offshore structures should consider the effects of the design low temperatures (EL and AL) on their performance. For example, some components, such as viscous dampers, or friction pendulum bearings, have a proven record of reliable performance in freezing conditions while others, such as rubber bearings, should be protected from freezing.

b) Wind load: isolated structures should resist design wind loads at all levels above the isolation interface. If necessary, a wind restraint system should be provided to limit lateral displacement in the isolation system.

c) Wave and ice load: the dynamic response of the isolated structure to wave and ice loads should be considered. The isolation system should not introduce adverse effects into the structure's response to these loads.

d) Restoring force: the isolation system should be configured to produce a restoring force such that the lateral force at the total design displacement is greater than the lateral force at 50 % of the total design displacement by at least 2,5 % of the weight of the isolated structure.

e) Displacement restraint: the isolation system can be configured to include a displacement restraint that limits lateral displacement to a value that is less than the design displacement due to ALE. If such a restraint requirement is used, it should be explicitly considered in the analysis and the design of both the isolation system and the structures below and above the isolation interface.

f) Vertical load stability: each component of the isolation system should be designed to be stable under the maximum vertical action effect and the minimum vertical action effect when subjected to the design displacement.

g) Global overturning of isolation system: the resistance to global structural overturning at the isolation interface should meet the ALS requirements for the required action effect combinations. All gravity and seismic design situations should be investigated.

h) Uplift of isolator units: local uplift of individual components is permitted if the resulting deflections do not cause overstress or instability of the isolator units or other components of the structure.

i) Structure separations: minimum separations between the isolated structure and surrounding fixed obstructions should not be less than the design displacement, unless it can be demonstrated that the system meets the performance criteria with pounding.

j) Components crossing the isolation interface: components of seismically isolated structures and non-structural components that cross the isolation interface should be designed to withstand the total maximum displacement at the interface. The components should not interfere with the performance of the isolation system. Particular attention should be paid to staircases, wells, risers and piping.

k) Seismic force-resisting system: structures that contain a damping system should have a basic seismic force-resisting system designed for the reduced seismic action but conforming to recognized seismic structural systems.

A.16 Other ice engineering topics

A.16.1 Ice roads and supplies over ice

A.16.1.1 General

Crossings of lakes and rivers have been achieved using the naturally formed ice cover in winter for centuries. The main requirement to cross safely is to have continuous ice of sufficient thickness to support the intended loadings.

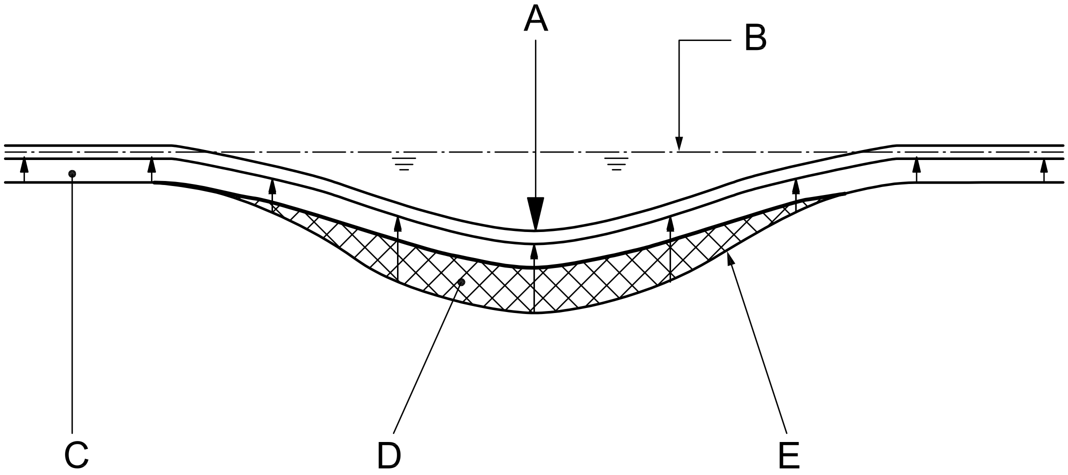
There are numerous examples of the use of floating ice to form roadways over rivers, lakes and oceans for the transportation of heavy loads. There are several good examples of the successful use of floating ice for the support of large-scale loadings, both moving and stationary, including the seasonal deployment of drilling rigs. To support these actions, the natural ice was thickened by flooding or spraying seawater onto the ice surface until the total ice thickness reached a value of approximately 6 m, where the original ice thickness had been as little as 1 m. Long-term loading can induce creep or time-dependent deformation in the ice.

A.16.1.2 Floating ice design criteria

A.16.1.2.1 Background

Ice has a density about 10 % less than that of water and floats on the water surface unless it is held down by external actions. Because of this difference in density, 90 % of the ice is below water and 10 % is above water. The height of the ice above water is referred to as the freeboard. When an external action is applied to the ice surface, the ice behaves as a plate on an elastic foundation, whereby the ice directly under the action is deflected downward. This deformation results in an increase in water pressure on the bottom of the ice as shown in Figure A.16-1, and the integral of the increased water pressure over the area of the deflected shape equals the value of the applied action. It should be taken into account that the vertical deflections illustrated in Figure A.16-1 have been exaggerated and do not imply that the freeboard is negative.

The bending of the ice under the action imposes a flexural stress on the ice cross section. If the applied flexural stress does not exceed the maximum flexural stress that can be supported by the ice sheet (i.e. the flexural strength of the ice), the load can be supported. Ice is a material weak in tension and relatively strong in compression. Thus the critical stress is the maximum tensile stress at the bottom of the ice directly under the load. Obviously, it is necessary that the freeboard of the ice remain positive during this process. If the ice is forced under water and the surface is allowed to flood, the bearing capacity of the ice rapidly diminishes, with potentially dire consequences. In summary, it is necessary to meet two criteria for the static loading of an ice plate, i.e. that the maximum flexural stress does not exceed the flexural strength of the ice and that the freeboard remains positive.



Key

A applied vertical action

B waterline

C pressure to support ice sheet

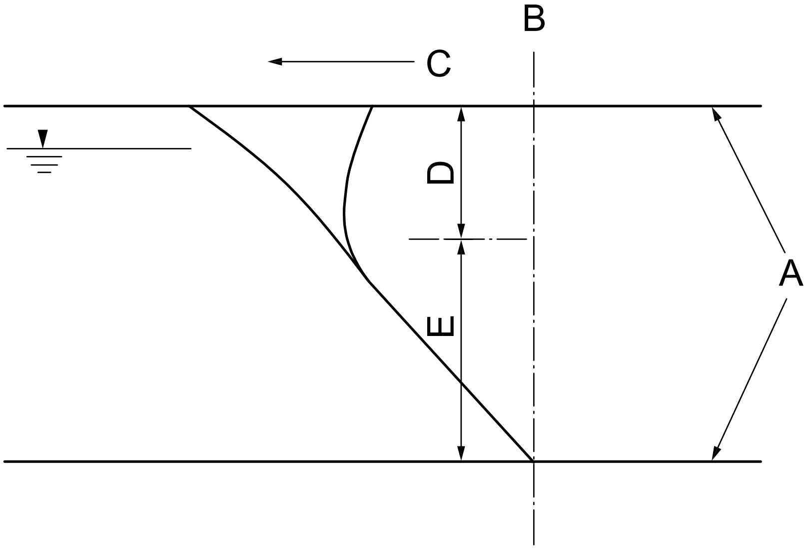
D additional pressure due to ice deflection

E total pressure

Figure A.16-1 — Floating ice in bending under lateral load

Ice is a material found in nature at a temperature near its melting point. Thus, its mechanical properties are sensitive to temperature changes. At temperatures near the melting point (0 °C for freshwater ice and −1,8 °C for sea ice in 30 ‰ salinity seawater), it becomes very ductile and prone to creep. At temperatures well below the freezing temperature, it becomes stronger but also very brittle. Brittle materials fail suddenly without warning and a reasonable level of ductility is desirable in ice. Too much ductility, especially during warm spring days when the entire ice sheet reaches the melting temperature, can result in large creep deformation and subsequent submergence of the load without any visual damage to the ice. It is necessary that submergence be avoided, whether through flexural failure or by excessive creep deformations.

A typical natural temperature profile of ice is shown in Figure A.16-2. The cold ice at the surface, where the ice is in compression, experiences large changes in temperature and, thus, can be strong and brittle or weaker and very ductile. Where snow cover is present, the swings in ice temperature at the surface are dampened due to the insulating properties of snow. As stated previously, ice is relatively strong in compression and, thus, the swings in strength near the upper surface have little effect on the bearing capacity. By contrast, the temperature of the ice at the bottom surface is relatively invariant and, thus, the strength and ductility remain constant[A.16-1]. Since this is the location of the critical stress, one can rely on the basic load-bearing capacity of the ice remaining constant through the main winter season. It is only in the latter part of spring when the ice is isothermal at the melting temperature and it begins to lose latent heat that deformations can become large.



Key

A upper and lower ice surfaces

B freezing temperature

C increasing negative temperature

D zone of fluctuating temperature

E zone of constant temperature gradient over time

Figure A.16-2 — Typical ice cover temperature profile

Any heat source, such as a warm spring or water discharge from a plant or municipality, deteriorates and melts ice, with a consequent loss of strength. It is not necessary to set complex criteria for the flexural strength and bearing capacity of ice. Using the stress method, an allowable stress can suffice, based on proven experience with loads on ice. It is of paramount importance to ensure that the ice thickness is adequate at all locations on a road or bearing surface and that the actions themselves, and their distribution, are well known. In addition, the ice integrity and a lack of major flaws and cracks is important. Even though ice displays surface cracking, this does not mean it is unsuitable for the intended actions. Surface cracks resulting from changes in ambient temperature are common in ice covers. As long as these cracks engage only the upper third or so of the ice thickness, they do not result in diminished strength. Cracks that penetrate the ice and are “wet” are a concern and can result in diminished strength.

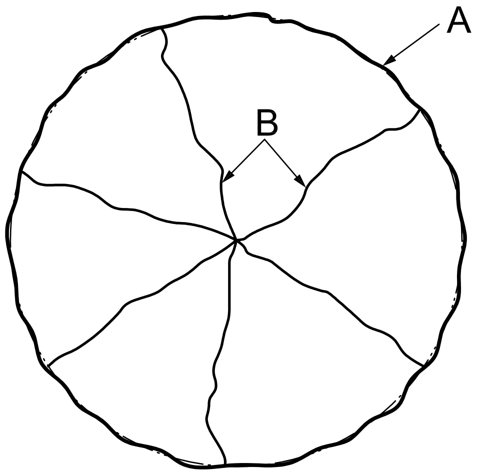
The two design steps for completing a structural analysis of a loaded ice sheet are as follows.

- Ensure that the maximum tensile extreme fibre stress of the ice sheet is less than the allowable flexural stress for ice.

- Ensure that the ice sheet's short-term and long-term deflections are less than the available freeboard.

The flexural strength of a floating ice plate is defined as the allowable maximum tensile extreme fibre stress induced by the action or action combination. This is almost invariably the stress at the bottom of the ice beneath the heaviest action.

A typical failure scenario for a uniformly loaded area on top of an infinite ice sheet is illustrated in Figure A.16-3. As the action is applied, the sheet deflects until the first crack or yielding develops in the underside of the sheet beneath the centre of the action. Further action results in the propagation of radial cracks through the thickness of the ice to some distance outside the loaded area. Further application of the action results in the development of a circumferential crack pattern. Once this has become fully developed, a complete breakthrough can immediately occur.



Key

A circumferential crack pattern

B radial crack pattern

Figure A.16-3 — Typical ice cover failure pattern

When ice fails in bearing, “shear” plugs can form around the loaded area. These are closely related to flexural failure. Flexural failure does not necessarily require the long wedge illustrated above. For yield line type failures, the wedge length is approximately twice the ice thickness, thus supporting the observed shear plug type of failure.

A.16.1.2.2 Theoretical models

These models assume that the ice structure acts as an elastic, homogeneous, isotropic plate on an elastic foundation, to simulate buoyancy. Reference [A.16-2] presents a design procedure that can be employed to predict the extreme fibre stress in an ice sheet due to a uniformly distributed load. The extreme fibre stress in the ice sheet, σ_{max}, expressed in either kilopascals or megapascals, is predicted by the Westergaard equation as given in Equation (A.16-1):

$$\sigma_{\text{max}} = 0{,}275(1+\nu)\frac{P}{h^2}\log_{10}\left(\frac{E\,h^3}{k\,b^4}\right) \tag{A.16-1}$$

where

ν is the Poisson ratio;

P is the magnitude of action, expressed in either kilonewtons or meganewtons;

E is the elastic modulus, expressed in either kilopascals or megapascals;

h is the ice thickness, expressed in metres;

k is the sub-grade reaction, expressed in either kilopascals per metre or megapascals per metre, equal to 9,81 kPa/m for freshwater;

r_c is the radius of loaded area, expressed in metres;

b is the effective beam length, expressed in metres, equal to $\sqrt{1{,}6r_\mathrm{c}^2 + h^2} - 0{,}675h$ for $r_\mathrm{c} < 1{,}724h$ and equal to r_c for $r_\mathrm{c} \geqslant 1{,}724h$;

The Westergaard equation (A.16-1) is an approximate solution to the plate equations and can lead to errors for loadings with a radius large compared with the characteristic length, L_c [defined in Equation (A.16-2)]. When Equation (A.16-1) is used to limit the ice sheet stresses to a value that is less than the flexural strength of the ice, cracking in the ice sheet cannot occur. The industry standard is to not allow the occurrence of a “first crack”. Once the “first crack” condition occurs, flooding of the ice surface is possible. The flooded water adds to the imposed action, P, accelerating the deflection, and causes difficulty in clearing equipment from the loaded area. Breakthrough usually does not occur until the formation of the circumferential cracks illustrated in Figure A.16-3. In general, the thinner the ice road, the faster the transition from “first crack” to breakthrough. It is believed that thicker ice sheets allow stress and load transfer on mechanical levels that are not available to thinner ice sheets. Local crushing of the ice of the thicker ice sheet pieces allows this mechanical load transfer[A.16-3].

In summary, the “first crack” or first yield condition governs the practical design of ice roads. For applications such as landing a helicopter on ice, a gravity action higher than that causing the first crack can be acceptable, as discussed in A.16.1.7.

When it is necessary to calculate the extreme fibre flexural stress, σ_x, expressed in kilopascals or megapascals, corresponding to units of P, at distance, x, from the centre of the load, Equation (A.16-2) is employed[A.16-4]:

$$\sigma_x = 0{,}249\left(\frac{P}{h^2/6}\right)\exp\left(\frac{-x}{0{,}691L_\mathrm{c}}\right) \qquad \text{(A.16-2)}$$

where

x is the distance from the centre of the load, expressed in metres;

L_c is the characteristic length, expressed in metres, equal to $\left[\dfrac{Eh^3}{12k\left(1-\nu^2\right)}\right]^{1/4}$.

The characteristic length, L_c, can in practical cases take on the value $16h^{3/4}$, expressed in metres. Loads placed on a floating ice cover or plate introduce flexural stress into the ice at other locations within relatively close proximity. The net total stress at a point is determined using the principle of stress superposition. The stress analysis performed is elastic and, thus, lends itself to this procedure. If long-term loading and creep occurs, with attendant plastic strain and deformation, then the principle of superposition cannot be used.

A.16.1.2.3 Industry experience

For a number of years, industry and government agencies have predicted the load-carrying capacity of ice sheets using P, the ice sheet strength, expressed in tonnes, as given in Equation (A.16-3):

$$P = C_\mathrm{ir}h^2 \qquad \text{(A.16-3)}$$

where

C_{ir} is the coefficient for ice road operation, expressed in tonnes per square metre, in the range of 35 t/m^2 $\leqslant C_{ir} \leqslant$ 70 t/m^2;

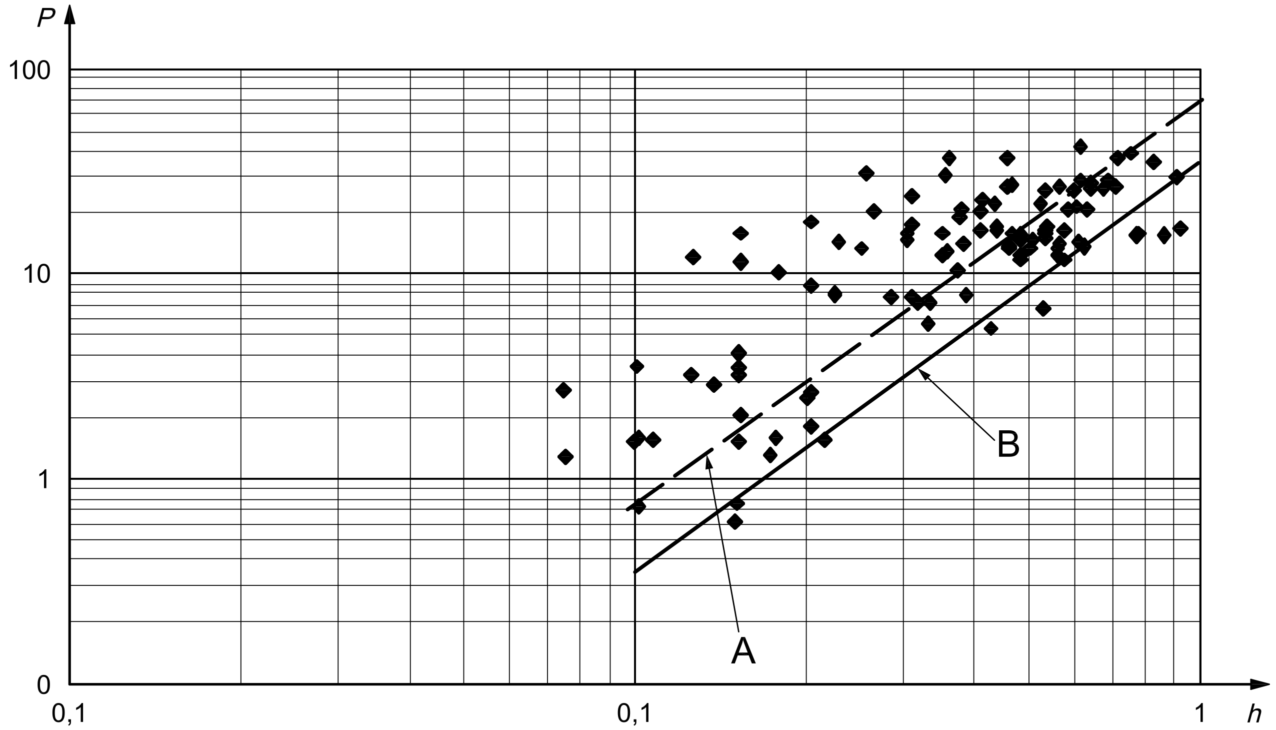
h is the ice thickness, expressed in metres.

On the basis of ice failures reported by industry, a curve-fit was made[A.16-5], [A.16-6] as shown in Figure A.16-4.

An important observation from Figure A.16-4 is the location and number of failures with respect to the $P = 35h^2$ and the $P = 70h^2$ lines. Of the 106 failures, 49, or 46 %, occurred when the thickness was greater than the thickness required by the $P = 70h^2$ line. Even when the thickness was greater than the thickness required by the $P = 35h^2$ line, failures still occurred. Nine percent of failures recorded in Figure A.16-4 occurred for ice thicknesses equal to or greater than the thickness required by the $P = 35h^2$ line.

Empirical evidence also demonstrates that the colour of an ice sheet, whether white or blue, is not a good determinant of flexural strength. The surface ice can often be quite granular since it is formed from sintered snow or surface flooding mixed with snow. However, this material can have quite a high strength in compression, being at the upper surface of the ice. There is no good reason to discount the strength of this material unless it is obviously weak or, especially, if it is not bonded to the underlying ice. It is more productive to look for continuous, well bonded ice.

Sea ice, while it might or might not have as high a strength as freshwater ice, is a ductile material and is, thus, more forgiving and less prone to sudden failure. There is no reason to degrade the ice bearing capacity because it is sea ice.



Key

A $P = 70h^2$

B $P = 35h^2$

P vertical load, expressed in tonnes

h ice thickness, expressed in metres

♦ data points

Figure A.16-4 — Ice bearing failure data — Individual failed and safe ice loads[A.16-6]

Ensuring that the actual ice thickness is greater than the ice thickness required, i.e. using the $P = 35h^2$ line, is not a guarantee that ice sheet bearing capacity failure does not occur. While the probability of failure decreases as the value of P decreases, failures at thickness greater than determined from the $P = 35h^2$ line are still statistically significant. In Figure A.16-4, failures at an ice thickness between the $P = 35h^2$ line and the $P = 70h^2$ line are likely to be the result of an operational problem or due to an ice sheet defect. This fact highlights the requirement for proper inspection and safety control measures on an ice road project to ensure that site operation factors such as speed and edge loading are controlled.

A.16.1.2.4 Design recommendations

Industry practice throughout most of Canada has been to employ a load value between $35h^2$ and $50h^2$ for early season operation, especially on ice road opening, and between $60h^2$ and $70h^2$ for later season operation. Ice road openings at a value of $60h^2$ to $70h^2$ are carried out on occasion with diligent monitoring and inspection effort.

Comparing Equations (A.16-1) and (A.16-3), the flexural stress level associated with a P value of $35h^2$ to $50h^2$ corresponds to a flexural stress level of 500 kPa to 550 kPa at the bottom surface of the ice sheet. It is emphasized that the bearing capacity of ice is calculated in Equation (A.16-1) assuming that the strain and stress vary linearly through the ice thickness and that the ratio of stress to strain is a constant and equal to the modulus of elasticity. Both stress and strain are maximum at the extreme fibres or at the top and bottom and are zero at half the ice thickness, or at the neutral axis. None of this is strictly true. The ice stress-strain relationship is non-linear, especially under creep or time-dependent loading. Also, finite element analysis has shown that the compressive stress immediately under the load at the ice upper surface is much higher than predicted by simple linear beam theory and that the tensile stress is lower than predicted by simple beam theory. This behaviour is in conformance with concentrated loads placed on steel and concrete beams and is dealt with accordingly in the respective codes where shear is considered to govern the design. Web stiffeners are added in rolled steel sections and shear reinforcement is used in concrete design to account for this concentrated load effect.

Linear elastic theory has traditionally been used to calculate the load-bearing capacity of ice sheets and provides reliable, readily calculated stresses and loads. Experience has shown that the recommended allowable stresses accurately predict the ice capacity and that exceeding these stresses results in significantly increased rate of failure. When Equations (A.16-4) for edge loading and (A.16-1) are applied, flexural stress levels based on the above correspondence should be used. Because of the above reasons, the range of values, 500 kPa to 550 kPa, used to estimate safe loads using these equations cannot be compared directly with those used for ice actions applied to sloping structures (see A.8.2.4.4 and A.8.2.8.3).

Equation (A.16-3) is a simple empirical equation meant for application in simple load situations. When ice roads are opened early in a winter season, generally the loads are concentrated and of simple foot-print. Long trailer loads should not be used in the early season. The ploughs employed to open the ice roads typically have two axles and the width of the load is approximately equal to its length. These concentrated actions during early season operation require a relatively safe value of A in the range of $35h^2$ to $50h^2$.

Later in the ice road season during rig hauls and trailer moves, when the road is well established, the loads are long and coupled. Heavier total loads are possible on roads with less ice thickness since the trailer axles are further removed from the vehicle drive axle. Stresses superimposed at the point of maximum flexural stress, usually at the drive axle, are relatively small from the secondary trailer loads. The lower flexural stresses from trailer operations and the fact that the ice thickness and other ice road parameters are better monitored on a completed ice road enables the use of $60h^2$ to $70h^2$ in Equation (A.16-5). For these long and coupled loading situations, the methods outlined in Equations (A.16-1) and (A.16-2) are recommended.

Standard safe operating procedures for equipment involved in an ice road operation should clearly state the limitations assigned in order to allow the use of a particular P value. When limiting conditions such as wet cracks or a sudden change in air temperature are encountered, compensation should be made to ensure safe operation. Safe operating procedures should also state requirements for inspection and monitoring to ensure that defects such as wet cracks are found in a timely fashion.

A.16.1.2.5 Cracked ice sheets

For an action at the edge of an ice sheet, the maximum extreme fibre flexural stress, σ_{edge}, expressed in kilopascals or megapascals, corresponding to P, is given in Equation (A.16-1)[A.16-7]:

$$\sigma_{\text{edge}} = 0{,}529(1 + 0{,}54\,\nu)\frac{P}{h^2}\left[\log_{10}\left(\frac{Eh^3}{kb^4}\right) - 0{,}71\right] \tag{A.16-4}$$

where

ν is the Poisson ratio;

E is Young's modulus, expressed in kilopascals;

h is a unit ice thickness, expressed in metres;

k is the foundation modulus;

b is the coefficient defined in Equation (A.16-1).

An example calculation comparing the stress, $\sigma_{(\text{A.16-4})}$, from Equation (A.16-4) to the stress, $\sigma_{(\text{A.16-1})}$, from Equation (A.16-1) for a continuous ice sheet is outlined for the given ice sheet parameters as follows:

$$\begin{aligned}\frac{\sigma_{(\text{A.16-4})}}{\sigma_{(\text{A.16-1})}} &= \frac{0{,}529(1+0{,}54\,\nu)}{0{,}275(1+\nu)}\left(\frac{4{,}5-0{,}71}{4{,}5}\right)\\ &= 1{,}43\end{aligned}$$

where

ν is assumed to be 0,33;

E is assumed as 5 000 000 kPa;

h is assumed to be 1,0 m;

k is assumed to be 9,81 kPa/m for freshwater;

b is assumed to be 2,0 m.

The edge load stresses predicted by Equation (A.16-4) are generally 50 % higher than the values predicted for the centre of the same continuous ice sheet from Equation (A.16-1). As the log term in Equation (A.16-1) and Equation (A.16-4) becomes very large (i.e. the action becomes concentrated), the ratio of stresses becomes

$$\begin{aligned}\frac{\sigma_{(\text{A.16-4})}}{\sigma_{(\text{A.16-1})}} &= \frac{0{,}529(1+0{,}54\,\nu)}{0{,}275(1+\nu)}\\ &= 1{,}70\end{aligned}$$

In the worst case scenario, the stresses increase by 70 % when a wet crack is approached or crossed on an ice road by a very concentrated load. When intersecting wet cracks occur, additional reductions in the capacity of the ice sheet occur[A.16-2].

The deflection of infinite ice sheets due to short-term loading can be determined using the methods given in Reference [A.16-8]. When the load is stationary for a period longer than about one day, allowance should be made for creep deflections. Methods using either field measurements from floating platforms or a reduced elastic modulus can be employed. These methods are discussed in A.16.2.2.3.

When a load is located close to a free edge, other methods are available, including that in Reference [A.16-9] for rectangular load patches.

A.16.1.3 Ice flexural strength for design

No additional guidance is offered.

A.16.1.4 Dynamic behaviour and dynamic amplification factor

Moving loads create a pressure wave in the water under the ice that can amplify the deflections and stresses[A.16-10]. Theoretically, the amplification is infinite at resonance but, in practice, measurements indicate the dynamic amplification is about 1,5[A.16-11]. Moving loads can be problematic when approaching a shoreline from the floating ice. The pressure wave created by the moving load reflects off the shallow bottom or off the shoreline and the result can be a rupture of the ice. This phenomenon results in the formation of a hole in the ice, which, while it does not affect the vehicle creating it, can affect vehicles following that are required to cross the same ice and cannot because of the hole created. Also, vehicles travelling a narrow passage or inlet covered by ice set up a wave that can reflect from the nearby shorelines, causing ruptures in the ice. These situations are unique and require careful observation and a consequent limitation on speed. In general, it is desirable to limit the speed of moving loads on ice to avoid dynamic effects. This is particularly important if the loads are close to the maximum allowed for the particular ice plate.

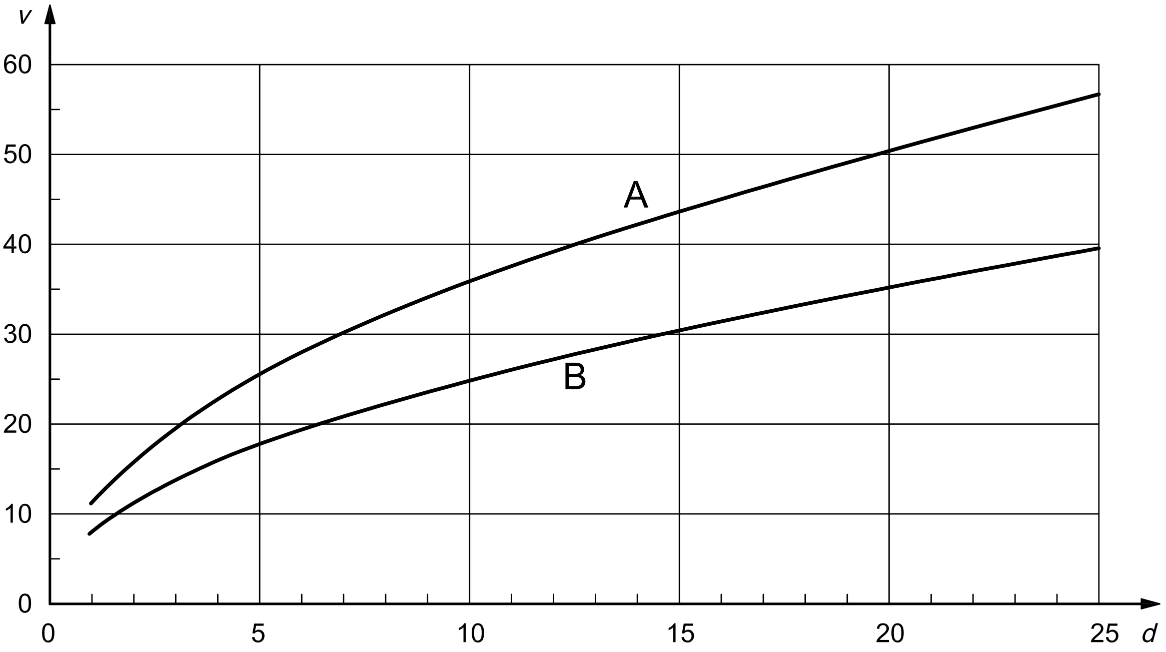
The speed of the water wave is dependent primarily on the depth of the water, the thickness of the ice cover and the elasticity of the ice. In deep water, the greatest deflection and the most severe stresses occur when the vehicle on top of the ice and the wave below it are travelling at the same speed. If the ice sheet is highly stressed because the ice is too thin or cracked, the stress from the wave plus the stress from the action can be enough to cause a sudden failure.

The critical vehicle velocity, v_c, expressed in kilometres per hour, for maximum dynamic magnification is determined principally by the water depth and can be expressed as given in Equation (A.16-5):

$$v_\mathrm{c} = 11{,}3 d^{1/2} \tag{A.16-5}$$

where d is the water depth, expressed in metres.

At or near to the critical speed, the ice deflection and the ice stress/strain can be 1,5 times the values when the vehicle is travelling slowly. Field measurements have indicated that the dynamic magnification factor is not significant at a speed of less than 70 % of the critical velocity. These aspects are summarized in Figure A.16-5. From Figure A.16-5, a water depth of greater than 14 m is required for travel at 30 km/h where dynamic effects are completely avoided. Travelling at or close to the critical speed should be avoided.



Key

A significant dynamic effect above this speed; to be avoided

B minimal dynamic effect below this speed; recommended

v vehicle travel speed, expressed in metres per second

d water depth, expressed in metres

Figure A.16-5 — Critical speed for dynamic effects

When a vehicle is travelling parallel to a shoreline, resonant waves reflect back through the ice. The wave pattern is critical when the vehicle weight is close to the load-bearing limit of the ice. Reflected waves are greatest when a vehicle approaches a shoreline at a right angle. If possible, roads and vehicles should meet the shoreline at a 45° angle. It is important that drivers obey the posted speed limit when a road meets the shoreline and when a vehicle's weight is close to the maximum limit for the ice.

A.16.1.5 Safe use of ice roads and standard procedures

Preparation of the ice surface for flooding, if it is used to thicken the ice, and for traffic, varies according to local practice and experience. If flooding is carried out, then the heavier snow is removed using a mechanical means, such as a blade or snow blower before flooding commences. A thickness of 5 cm to 10 cm of snow can be left on the surface before flooding begins. Some projects do not have the means available to remove the snow and the deeper snow cover on the ice is soaked with water and allowed to freeze. It is important to ensure that the water-soaked snow has completely frozen before continuing with the application of water. To prepare an ice cover for vehicular traffic, especially for wheeled traffic, the snow can either be removed by blade or blower, or it can be packed down to a relatively high density to ensure the wheeled vehicles do not become stuck. The snow, where possible, should be well removed from the road with the snow banks along the side being sloped or “feathered” back. This avoids stress concentrations at the road edge and excessive cracking of the ice, plus it discourages the accumulation of further drifting snow.

Thickening of the ice is usually accomplished using low head, high volume pumps that lift water from beneath the ice onto the surface. The water is applied in layers about 3 cm thick and allowed to freeze before another layer is applied. In this way, the accumulation of ice thickness averages about 3 cm per day for most roads as a job average. During very cold periods when the winds are low, the rate can be higher but the average considering the ability to cover existing ice and delays due to weather and equipment is as quoted. It is best practice not to dyke or confine the water but to allow it to flow freely and achieve a tapered cross section of the road or pad. This avoids sharp transitions and the formation of cracks at the edge of the flooded area. It is sometimes necessary to use snow dykes to prevent water from escaping and to achieve the required ice accumulation over a reasonable length of time. Judgment is required at all times.

The equipment used for thickening the ice varies and locally available equipment is often the most convenient and effective. The pumps should be capable of operating in very cold temperatures. They should be submersible or Archimedes screw-type (augers) that have no hoses to freeze. These types of pumps are self-contained and drain readily when shut down. On road construction, the pumps are moved from hole to hole, which have been previously drilled, as the road is flooded. The crews operating the pumps require means of transportation and of moving the pumps, and they also require a drill or auger to make a hole of the required diameter. Spraying techniques can also be used to construct roads as this accelerates the accumulation of ice thickness. The principles of spraying are described in A.16.2.1.2.

A.16.1.6 Grounded ice roads

Grounded ice roads are usually roads established in very shallow water whereby the ice is thickened and pushed onto the underlying soil. They are also roads established on shore where an ice and snow cover is provided to protect the native soil or tundra from damage by wheeled and tracked traffic. Since soil provides a stiffer support or sub-grade for the ice, flexural stress in the ice is very often not a consideration in the design. It is necessary that the ice have sufficient thickness to spread the wheel loads and avoid overstressing of the tundra. In the case of offshore grounded roads, values of the sub-grade modulus, expressed in units of kilopascals per metre or kilonewtons per cubic metre or equivalent, should be high enough to ensure that the ice is not overstressed. Some weak soils have a sub-grade modulus that is little better than that of water (1 tonne/m^3) while others such as dense sand have a modulus that is orders of magnitude greater than that of water. It is important to know the sub-grade modulus when assessing the load-bearing capacity of grounded ice. The methods outlined in Equations (A.16-1) and (A.16-2) can be employed to assess the effect of sub-grade modulus on the required ice thickness. Obviously, the consequences of failure are not as severe as they are in deep water where life can be endangered and equipment lost, but still a failure does render the road unusable until it is repaired.

A.16.1.7 Helicopter landings on ice

For helicopters landing on the ice, the following additional points should be taken into consideration.

a) A helicopter can keep its rotors running, resulting in an upward lift that can reduce the concentrated vertical action on the ice.

b) By applying the procedure described in a), the ice thickness can be measured prior to personnel and equipment drop off, thereby ensuring adequate bearing capacity.

c) Since the helicopter is stationary and not moving across the ice, breakthrough does not occur even if the first crack appears [with reference to Equation (A.16-1)]. Breakthrough results only from an action that requires the formation of the full pattern of circumferential cracks (see Figure A.16-3). This action is approximately 1,5 to 2 times the action associated with the first crack.

Based on the above considerations and past experience during ice expeditions, the recommended value for C_{ir} in Equation (A.16-3) is 50.

A.16.2 Artificial ice islands

A.16.2.1 Grounded ice islands

A.16.2.1.1 General

For decades, grounded ice islands have been used for oil and gas exploratory drilling in the Canadian Beaufort and US Alaskan Beaufort Sea. As with floating ice platforms, they provide a relatively inexpensive and environmentally sustainable means of supporting drilling operations. Up to 2005, three wells had been drilled in Canada and five had been drilled in Alaska using this technology.

For years, grounded ice rubble formations have been observed in shallower water in polar and sub-polar regions. Grounded rubble masses are stabilized and often remain stationary for the remainder of the winter season. Grounded rubble also serves to stabilize the surrounding pack ice, pushing the active shear zone further offshore. Stable rubble masses, with further artificial stabilizing, can provide a solid base for operations such as exploration drilling, and then melt leaving minimal trace during the summer.

Ice islands should be firmly grounded, with sufficient freeboard to ensure adequate contact with the seabed to resist the design lateral ice actions. The spray ice formed during construction should have adequate density and volume to provide the required weight, which ensures the correct bottom contact at the seabed. The spray ice should also have the required minimum shear strength to ensure that the lateral ice loads cannot produce a shear displacement through a plane of weakness in the island.

A.16.2.1.2 Construction

The water used for the construction of a grounded ice island should be placed and frozen above the water level. Spray operations readily achieve this placement of material due to the fact that the water is nearly frozen and immobile when it falls on the surface. Free flooding does not readily achieve this placement goal. When free-flooded water is placed on thickened ice, the water tends to flow to low points, which can be the source of the pumped water.

Grounded ice islands have been constructed in the past within the landfast ice zone of the Beaufort Sea. Access has been via a floating ice road from shore to the island. The ice road is established in late November or early December and construction of the island begins shortly thereafter. In addition, the surrounding ice is used as a platform from which to construct the island. It is necessary that the thickness of the road and the ice around the island be approximately 1 m to support the construction equipment. The road is thickened by flooding during the island construction to support the transport of the drilling rig and supplies. For the transport of very heavy loads, such as was required for the Pioneer ice islands in 2003[A.16-12], a grounded ice road was used. Currently, grounding of the ice can be accomplished economically only in water depths of up to about 3 m. Grounding can be accomplished by spraying and/or the use of ice chips.

Construction of spray ice-grounded islands occurs during December and January to allow the completion of drilling operations before the spring break-up. The exact duration of construction depends on the location and year, but usually the latter part of December and most of January constitute the bulk of the construction period. Pumps with a rated capacity of 12 m^3/min to 30 m^3/min are used. These pumps should have a pressure at the discharge nozzle of 1,5 MPa. Lower pressures are insufficient to achieve the requisite atomization of the water for efficient ice making. Depending on the water depth and diameter required for lateral stability and operations, an ice island can have a volume of 500 000 m^3 to 1 500 000 m^3. A pump normally operates for about 20 h/day or 10 h/shift, and its efficiency is 80 % to 90 %. Thus, to build an island with a volume of 1 000 000 m^3 of ice, two pumps with a rated output of 20 m^3/min can take 25 days to spray the water and construct the island. This calculation assumes no downtime for weather. With downtime for weather included, normally four pumps of this capacity are required to complete an island of this volume in a 30 day to 40 day period. It is not uncommon to have continuous periods of warm, windy weather in which little progress is made. Once the weather turns cold, to take advantage of this period, it is essential to have the equipment and capacity available.

Ambient temperature has the most direct effect on the ability to freeze the sprayed water. If normal seawater is being pumped, experience shows that at temperatures above −18 °C little progress is made in ice building. This happens to be near the eutectic point for salt water freezing and it can be shown this is a transition for spraying results[A.16-13]. Wind, on the other hand, is a detriment to efficient spraying. A moderate wind of 5 m/s to 7 m/s is desirable for removing heat released from the sprayed water and the avoidance of forming a thermal envelope at the island site, but strong winds hinder spraying. They result in the water droplets being blown downwind from the island and thus lost. Efficiency drops when the winds are strong and winds in excess of about 12 m/s can bring the spray operation to a halt. In strong winds, there is only the opportunity to spray downwind, whereas in moderate winds one can spray crosswind as well, increasing the coverage and flexibility of any pump. An ideal situation for ice making is a day with a temperature of −30 °C to −35 °C and winds of 5 m/s. Pumps with a capacity of 20 m^3/min can produce 1 m/day of ice over an island with a diameter of 250 m to 300 m.

If freshwater is used, then there is no transition at –18°C and spraying can continue to the freezing temperature of 0 °C. Of course, the rate of freezing decreases with an increase in temperature, and the best results are obtained at low temperatures.

Spraying water into the air using high pressure pumps (1,5 MPa pressure at the nozzle) causes it to be lofted tens of metres into the air and also causes it to be atomized. The air travel results in rapid cooling of the water droplets and, if the spray nozzle is properly sized and aimed, the water droplets are about 80 % frozen when they fall to the existing ice surface. It is desirable not to have the water droplets 100 % frozen at contact with the surface as this leads to the formation of corn ice or snow, which has very little cohesion; this is not a good bearing surface as it lacks shear strength. Also, it is not desirable that the spray be too wet or the resulting slush that lands on the ice requires a long time to freeze. If the spraying is planned and managed properly, optimum build-up or ice accumulation rates are achieved with maximum density and shear strength. The density of spray ice is usually about 0,6 tonnes/m^3 and the shear strength is on the order of 35 kPa to 150 kPa[A.16-14], [A.16-15]. This density and shear strength are very suitable for resisting lateral ice loads from the surrounding moving pack ice and for supporting heavy loads such as a drilling rig on the island.

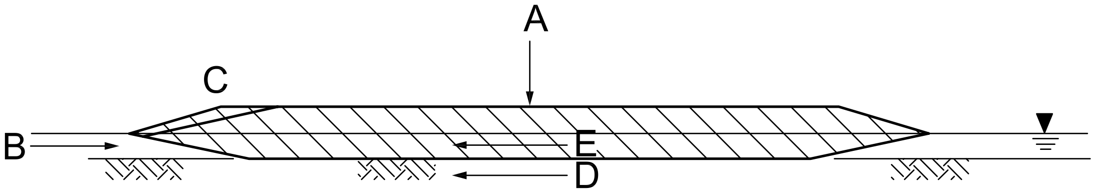
Spray ice is a very workable material and can be shaped, excavated and moved readily with bulldozers and front-end loaders. The surface of the island at the end of the construction period is usually rolling and never flat. Thus, it is important to be able to level the ice to produce a usable working surface.

Grounded spray ice islands have been built since 1985 without the benefit of underlying ice rubble, mainly because none was available at the sites where construction took place. Ice was sprayed on top of the level first-year ice and, thus, the bulk of the island was formed of spray ice. If grounded or floating rubble is available over the site, then it can be used and the construction time reduced. The rubble forms a good solid base for the island. With larger pumps, more water can be pumped and more ice can be formed in a given time. This applies not only because there is more water pumped, but also because the increased pumping rate results in a higher momentum for the water stream, causing it to be propelled higher and farther. This, in turn, increases the time of exposure to the cold ambient air and results in more freezing, which is required for the increased water supply. Larger pumps produce a volume of ice in a day that is proportionally more than for a smaller pump. Thus a pump with a capacity of 20 m^3/min produces more than 20/12 or 1,7 times the ice per day than a pump with a capacity of 12 m^3/min, all other factors being equal. It is, therefore, desirable to use the largest pumps practical when building a spray ice island.

At present, the maximum water depth for which grounded spray ice islands can be used realistically is 12 m to 15 m. The maximum depth depends on the mobility of the ice pack and on the timing of the start of construction. If the local geography results in the ice becoming landfast early, then it is possible to access the site early and to complete the construction in time for the intended operation. Water depth itself is not so much the issue as the fact that with increasing water depth the ice pack remains mobile for longer periods during the winter. Generally, it is necessary for the ice to become landfast and stable by about 1 January for a project to be successful. This, of course, applies to operations where the construction is supported from the ice. If a ship is used to support the construction, then there is more tolerance for ice movement later in the year. While spraying can be used to help ground the ice locally to stabilize the pack, most practical applications involve construction using the existing ice as a support.

Once constructed, the grounded portion of the island forms the core of the island beyond which there is the sacrificial edge which, in the event of a major ice movement, can be subjected to shear-type failure. All critical, non-relocatable facilities, such as the drilling rig and any camp, should be located within the core radius.

The shape of the ice island edge is very different from that of gravel or other earth. Since, unlike soil or gravel, the ice is buoyant and since the natural ice sheet is bent and submerged during spraying of the island, the underwater part of the edge naturally takes on the reverse taper shown in Figure A.16-6. Profiles taken after the completion of construction have generally confirmed this as the shape of the island edge. The taper can run further than shown in Figure A.16-6 due mainly to overspray. This overspray can be removed during construction and placed on the island proper.



Key

A weight of ice

B ice action

C edge failure plane

D shear resistance at ice/seabed interface

E internal shear resistance

Figure A.16-6 — Ice action and resistance of an ice island

A.16.2.1.3 Material properties of the ice

A.16.2.1.3.1 General

The material properties of the grounded ice island determine the ability of the ice island to resist lateral load and to support the surface load in bearing. A.16.2.1.3 focuses on spray ice since it is the primary material employed in the construction of grounded ice islands.

A.16.2.1.3.2 Material properties of spray ice below waterline

In determining the sliding resistance of spray ice islands, the shear strength of the spray ice underwater should also be considered since, depending on the bottom soil conditions, a shear failure can develop on a plane through the island itself.

While there are limited data on the shear strength of spray ice below the waterline, available data suggest that the spray ice below the waterline is a low friction material (when considered as a granular material) and one can assume that the shear strength of the ice below the waterline equals the cohesion of the submerged ice material. Table A.16-1 lists upper and lower bounds on the submerged ice material or shear strength of saturated spray ice indicated by various test methods.

Table A.16-1 — Underwater spray ice strength

Test method	**Shear strength** kPa
Pressure meter	$99 < \tau_{\mathrm{ice,bw}} < 145$
Borehole jack	$147 < \tau_{\mathrm{ice,bw}} < 217$
Flat jack	$55 < \tau_{\mathrm{ice,bw}} < 77$
Cone penetrometer	$40 < \tau_{\mathrm{ice,bw}} < 50$

The shear strength of spray ice below the waterline was assumed to be the lowest recorded strength and a shear strength of 40 kPa was chosen for designs in the 1980s.

An extensive series of cone penetrometer tests was conducted at the Karluk Spray Ice Island during the verification programme[A.16-14]. The average bearing pressure below the waterline was 3,8 MPa. The following range of bearing pressure was noted:

1,6 MPa < bearing capacity < 6,3 MPa

Assuming, as is standard practice, that the shear strength is 1/6 of the bearing capacity[A.16-16], then the Karluk Spray Ice Island had the following bounds on shear strength below the waterline.

$$267\ \text{kPa} < \tau_{\text{ice,bw}} < 1\ 050\ \text{kPa}$$

The lack of voids and general continuity of the ice at Karluk, plus the high cone test results, indicate high shear strength. A weighted mean shear strength using all of the above data is 56 kPa.

The spray ice has considerably higher shear strength than the sand of the seabed. For a shear strength of 56 kPa, an ice island with a core radius of 100 m has an internal shear resistance of 439 MN. Generally, shear failure through the sea bottom material governs in any sliding stability calculation.

A.16.2.1.3.3 Spray ice properties above waterline

Data from spray ice platforms and islands suggest that spray ice above water behaves as a Mohr-Coulomb material such that the shear strength, $\tau_{\text{ice,aw}}$, is given by Equation (A.16-6):

$$\tau_{\text{ice,aw}} = c_{\text{ice,aw}} + \sigma \tan \phi_{\text{ice,aw}} \qquad \text{(A.16-6)}$$

where

$c_{\text{ice,aw}}$	is cohesion for the spray ice above water, assumed to be equal to 283 kPa;
$\tan\phi_{\text{ice,aw}}$	is the tangent of the friction angle for spray ice above water, assumed to be equal to 0,85;
σ	is normal pressure, expressed in kilopascals.

The normal pressure, σ, is the vertical stress component in the ice at the point where $\tau_{\text{ice,aw}}$ occurs. The above water spray ice material has a cohesion of 283 kPa as compared with 56 kPa for the underwater material.

A.16.2.1.3.4 Ice and soil interface

By grounding the ice island through the surcharging of the existing ice surface with successive layers of spray ice, the bottom of the ice island comes into contact with the seabed. This interface between the ice and the seabed soils is an important consideration in assessing the stability of the grounded island against lateral ice actions. If the seabed is a granular material, then the shear resistance of the interface is given by Equation (A.16-7).

$$\tau_{\text{is}} = \sigma_{\text{is}} \tan\phi_{\text{is}} \qquad \text{(A.16-7)}$$

where

τ_{is}	is the shear strength of the ice/soil interface, expressed in kilopascals;
σ_{is}	is the normal stress due to the weight of ice, expressed in kilopascals;
ϕ_{is}	is the friction angle at the ice/soil interface, expressed in degrees.

For a frictional material, the shear strength of the interface increases with increasing weight of ice on the bottom. Since the ice below water is slightly buoyant, all of the weight on bottom results from the freeboard of ice above the waterline.

The on-bottom weight, W_{ii}, of an ice island with a circular plan shape is determined by Equation (A.16-8).

$$W_{\text{ii}} = \frac{\pi D_{\text{c}}^{2}}{4} \left\{ \left[\gamma_{\text{i}} \, h_{\text{fb}} + \left(\gamma_{\text{is}} - \gamma_{\text{w}} \right) d \right] \right\} \tag{A.16-8}$$

where

D_{c} is the core diameter, expressed in metres;

γ_{i} is the above water spray ice density, expressed in kilonewtons per cubic metre;

γ_{is} is the below water spray ice density, expressed in kilonewtons per cubic metre;

γ_{w} is the seawater density, expressed in kilonewtons per cubic metre;

h_{fb} is the island freeboard, expressed in metres;

d is the water depth, expressed in metres.

The on-bottom weight calculated from Equation (A.16-8) is a force, expressed in kilonewtons, with the parameter units stated. The density of the spray ice above water and below water is approximately 0,6 tonnes/m^3.

If the seabed is cohesive, then the shear strength at the interface is determined by Equation (A.16-9).

$$\tau_{\text{is}} = c_{\text{soil}} \tag{A.16-9}$$

where c_{soil} is the cohesion of the soil, expressed in kilopascals.

In this case, the shear strength at the interface is not dependent on the weight on bottom, or at least it does not appear to be. Once the island is set on bottom, any loose seabed material can be consolidated by the weight of the ice; this, in turn, increases its shear strength. The degree to which the shear strength is enhanced depends on the initial density of the soil, its permeability and the physical structure of the soil.

The seabed can also be a Mohr-Coulomb material, in which case both cohesion and friction are considered in the resistance calculation.

A.16.2.1.4 Lateral stability against ice action

The lateral stability of a grounded ice island should consider the actions shown in Figure A.16-6. Lateral ice actions are resisted by the shear resistance of the island.

The island is first considered as a rigid body and its resistance, R_{ii}, to the ice actions is determined by Equation (A.16-10).

$$R_{\text{ii}} = \frac{\pi D_{\text{c}}^{2}}{4} \left\{ c + \left[\gamma_{\text{i}} h_{\text{fb}} + \left(\gamma_{\text{is}} - \gamma_{\text{w}} \right) d \right] \tan\phi \right\} \tag{A.16-10}$$

where

D_{c} is the core diameter, expressed in metres;

ϕ is the bottom friction angle, expressed in degrees;

c is the bottom cohesion, expressed in kilopascals;

γ_i is the above water spray ice density, expressed in kilonewtons per cubic metre;

γ_is is the below water spray ice density, expressed in kilonewtons per cubic metre;

γ_w is the seawater density, expressed in kilonewtons per cubic metre;

h_fb is the island freeboard, expressed in metres;

d is the water depth, expressed in metres.

The resistance calculated from Equation (A.16-10) is expressed in units of kilonewtons with the parameter units stated.

As shown in Figure A.16-6, edge failures can occur that can alter the actions applied to the island. Generally though, edge failures require about the same level of action as is required to crush the oncoming ice.

Lateral actions on the island due to movement of the surrounding pack ice are calculated in the same manner as those on other offshore structures. Activities on the ice island only take place during the winter and, thus, are during a time when the surrounding ice is relatively stationary. Usually the thickness of first-year ice is used to determine the action effect, with the contact width being the waterline diameter of the structure. The ice action imposed on the ice island due to the pack ice, F_ii, is determined from Equation (A.16-11).

$$F_\text{ii} = p\,w\,h \tag{A.16-11}$$

where

p is the effective ice crushing pressure, expressed in kilopascals;

w is the contact width of the grounded structure, expressed in metres;

h is the average ice thickness, expressed in metres.

When multi-year ice is in contact with the island, it is necessary to calculate the action considering the thickness of the multi-year ice and its width of contact with the surrounding pack ice. In cases when the multi-year ice, because of its thickness, can be grounded, it can become a stabilizing agent against ice motion in the area. Each situation should be evaluated prior to the time of construction and use of the particular island.

A.16.2.1.5 Load-bearing capacity

A.16.2.1.5.1 Assurance of load-bearing capacity

Spray ice has proven to be a material very capable of supporting its own weight when set down on the seabed and of supporting heavy surface loads such as drilling rigs. This is accomplished by the construction method whereby the sprayed seawater droplets are not totally frozen and the freezing process is completed on the island surface. By doing this, the development of good cohesion in the spray ice is assured. This is in contrast to materials, such as artificial snow, that have low cohesion and provide a weak bearing surface.

The combination of the rig load plus the weight of the spray ice can cause vertical creep settlement during drilling of the well. Creep settlements on the order of 200 mm are common.

A.16.2.1.5.2 Below-water capacity

Tests and observed behaviour indicate spray ice to generally be a cohesive material. From foundation theory for a circular plate[A.16-16], the bearing capacity, q, expressed in kilopascals, is determined from Equation (A.16-12):

$$q = 1{,}2\tau_{\text{ice,bw}} N_{\text{c}} \tag{A.16-12}$$

where

$\tau_{\text{ice,bw}}$ is the shear strength of spray ice below water level, expressed in kilopascals;

N_{c} is equal to 5,14.

A.16.2.1.5.3 Above-water capacity

For Equation (A.16-6), the shear strength of the above water ice is at least 283 kPa. Using the previous formulations for bearing capacity from Timoshenko, given as Equation (A.16-12), the bearing capacity for the above water ice is at least 1 747 kPa. Since the shear strength is dominated by the cohesion term, the total shear strength can be estimated as 283 kPa.

A.16.2.1.6 Thermal considerations at the well

For drilling a well, it is necessary to analyse carefully the heat transfer to the ice during drilling. Failure to do this in the past has resulted in significant melting of the ice under the main rig loads and near collapse of the rig. Insulation, either passive or active, should be used for any drilling programme lasting more than a week. Passive systems use insulation and active systems use a saline solution continuously pumped through the annulus between the conductor pipe and the surface casing (see Figure A.16-7)[A.16-15]. The insulation system chosen should be capable of maintaining the ice adjacent to the conductor pipe below the thaw temperature.

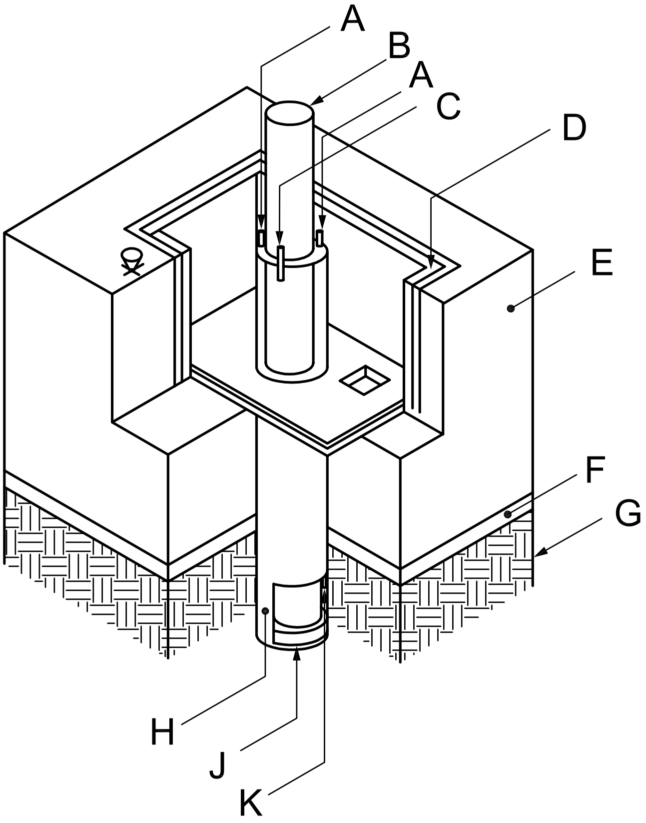
A.16.2.1.7 Verifications and monitoring during construction and drilling

No additional guidance is offered.

A.16.2.1.8 Safety considerations

Safety measures covering a wide range of activities on floating ice and on the island are of prime importance during construction and drilling. Issues to be considered include the following.

- Will there be significant ice movement during construction?
- What will be the effect of ice movement, both on the access road and the island?
- What measurements can be taken and what data obtained to predict movement?
- What response is required to movement?
- What movement of ice is likely during drilling or operations on the island?
- Is the safety of the well compromised?
- Will critical access to the island be denied?
- Will emergency planning for the well be compromised?
- What mitigative measures are available?



Key

A	brine injector tube	F	sea ice
B	conductor	G	seabed
C	brine return tube	H	outer casing
D	well cellar	J	cement plug
E	spray ice	K	brine outlet

Figure A.16-7 — Cut-away of a refrigerated conductor

A.16.2.1.9 Construction QC and monitoring

Monitoring of the surrounding ice cover during construction is vital to the success of an offshore programme. This monitoring should include

- daily visual observations by the personnel on site;
- satellite imagery;
- continuous monitoring of ice motion;

Reasonable alert procedures should be in place and carefully planned to provide critical information without undue alarms.

During the construction phase of the island, the quality control (QC) tasks verify material quantity and material quality as required by the design and consist of ice volume, ice temperature and ice density measured from samples *in situ* (see A.8.2.8.10) plus the recording of key pump operating parameters. A key activity during the construction consists of visual inspection of the spraying process and of the island itself.

The ice thickness and the related constructed volume can be measured at predetermined locations using marked tubing installed in the ice at the start of construction. The tubing should be extended during spraying to ensure access for measurement. Ice temperature can be measured using “strings” of thermistors.

A.16.2.1.10 Post construction verification

At the completion of the island construction, a programme is generally conducted to verify that the design conditions for the island have been met or exceeded. The activities associated with this phase are as follows:

- review information on geometry, density (see A.8.2.8.10) and temperature obtained during construction;
- perform spot checks on the island's total thickness at select thickness monitoring stations (approximately 10 % of the thickness stations should be checked in this manner);
- conduct cone penetrometer tests (CPTs).

A.16.2.1.11 Monitoring during drilling

The principal activities are the measurement of settlement of the ice surface, measurement of ice temperature near the cellar and conductor, and ice movement monitoring.

The position of the island, measured at a pre-determined location, should be established at least daily. Also, any movement of the surrounding ice relative to the island should be determined.

A.16.2.2 Floating ice islands

A.16.2.2.1 General

Both the mining and the oil and gas industries have employed floating ice platforms to carry out drilling programmes over bodies of water. In the oil industry, loads up to 1 500 tonnes have been placed on these platforms for periods of 100 days or longer. A typical thickness of such a platform is 6 m and the diameter is on the order of 150 m. Mining exploration programmes tend to employ lighter weight core sampling drills on thinner ice platforms. The references and points noted on ice roads in A.16.1.1 apply to ice platforms.

A.16.2.2.2 Construction

When spraying is employed to construct a floating ice island, the same procedures and safety precautions given in A.16.2.1.2 for spraying on a grounded ice island apply.

A major difference for constructing a floating ice platform relative to a grounded platform is that it is necessary to ensure that the ice in the platform flexural tension zone is of sufficient strength to safely carry the design (typically 550 kPa) flexural stress. Free-flooded ice platforms have consistently strong ice top to bottom. Sprayed floating ice platforms are typically formed by spraying onto a layer of natural ice to commence the flooding operation. For this reason, the bottom tension zone is in the stronger natural ice area. This is a convenient occurrence that adds to the structural integrity of sprayed platforms.

Free-flooding operations on an ice platform can be carried out with electric submersible pumps when thicknesses of over approximately 3 m are required. This is especially useful in very cold climates where the operation of smaller gas or diesel powered pumps can be a problem. Smaller gas or diesel powered pumps are employed typically to free-flood, especially for smaller ice platform programmes. Often the gas powered pumps are moved about by hand. Mobile pumps, especially when employing diesel power, are often mounted on a wheeled or tracked chassis.

A.16.2.2.3 Design for short-term and long-term load-bearing capacity

When designing an ice platform, both the short-term stress and long-term deflection, or creep, should be considered[A.16-17] to [A.16-19].

The same principles of stress analysis given in A.16.1.2 for floating ice road design apply for the stress analysis of stationary loads on an ice platform. Creep of the ice in the platform results in relaxation of stress over time.

Safe ice platform design requires that deflection for ice loading does not exceed the available freeboard. The available freeboard with both freshwater and seawater ice equates to approximately 10 % of the platform ice thickness. The design case deflection, δ, expressed in units consistent with δ_0, can be calculated as given in Equation (A.16-13)[A.16-19].

$$\delta = \delta_0 \left(\frac{h_0}{h} \right)^3 \left(\frac{P}{P_0} \right)^{1,5} \tag{A.16-13}$$

where

δ_0 is the previous case known deflection, in any units of length;

h is the design case ice thickness calculated to satisfy flexural stress limitations, in units consistent with h_0;

h_0 is the previous case known ice thickness, in any units of length;

P is the design case known applied load, in units consistent with P_0;

P_0 is the previous case known applied load, in any units of force.

Equation (A.16-13) can be employed only when the area of distribution for the two load cases and duration of loading are similar. Drill rigs placed on an ice sheet generally have similar equipment layout patterns and similar durations of loading for comparable rig weights.

A.16.2.2.4 Thermal design

The same conditions and recommendations of A.16.2.1.6 apply.

A.16.2.2.5 Monitoring during construction and drilling

The same conditions and recommendations of A.16.2.1.7 apply. Further, monitoring requirements during the drilling phase should ensure that all areas of the ice platform remain above the water level. Water that floods onto the surface acts as a further load on the platform and accelerates deflection. In addition, water on the surface results in an unsafe work area, which makes it difficult to retrieve the rig or other equipment and material.

Ice strength measurements with a borehole jack through the ice profile are a good indicator of the flexural tensile strength. The flexural strength of the ice is approximately 1/9 of the confined borehole compressive strength.

A.16.3 Protection barriers

A.16.3.1 General

Ice rubble fields are accumulations of fragmented ice that form from moving ice sheets around wide offshore structures, islands or sloping beaches in shallow waters. Depending on the water depth, the rubble can be embedded in a moving ice sheet or can be grounded on the sea floor. When moving ice rubble interacts with a structure, the ice actions on the structure can increase compared with interactions with level ice. This should be considered when designing a structure. On the other hand, grounded ice rubble around a structure can reduce the ice actions on the structure due to transfer of actions to the seabed or by change of failure mode.

A.16.3.2 Ice protection structure

A.16.3.2.1 Grounded ice as a protection barrier

Natural ice rubble formation results normally from thin ice interactions in the freeze-up and early winter periods. Also the installation of man-made ice protection structures in shallow waters can initiate the ice rubble formation process in order to protect offshore exploration and production structures.

For a structure sitting on an underwater soil/gravel berm, rubble can become grounded on the underwater berm and move the active failure zone to the outside of the ice rubble[A.16-20]. A berm can also cause thick ice features (floes) to be slowed or stopped by grounding. The reaction created by deformation of the soil berm and uplift of the floe dissipates the floe's kinetic energy and thereby reduces the potential action on the structure[A.16-21].

Ice interaction mechanisms are governed by structure shape and structure geometry, interaction speed and the geometry of the ice feature. Thus, the effect of ice rubble is an important consideration in ice action calculations[A.16-22].

If the grounded ice rubble is significantly larger than the structure it surrounds, the effective structural cross-section to global ice actions is increased. The potential load increase is counterbalanced by the sliding resistance of the grounded rubble and the manner in which actions are transferred through the rubble pile. The ice failure mode changes experienced at the rubble boundaries can result in lower effective ice failure pressures and, consequently, lower global ice actions[A.16-23].

Since it has been observed that most grounded ice rubble remains stable during a winter season, it affords a degree of protection to the offshore structures. Ice rubble can also protect a structure from the potential for ice ride-up and ice overtopping, and it tends to mitigate the effect of dynamic ice actions[A.16-23].

If the structural design relies on ice defence and barriers to reduce actions, the barrier's effectiveness should be qualified by theoretical calculations, full-scale experience or model tests.

A.16.3.2.2 Rubble generation

The mechanism of rubble-pile formation is quite complex and not well understood. In some cases, the rubble forms a ramp for the oncoming ice sheet and fails in bending, particularly for thin ice sheets. In other cases, the moving ice sheet penetrates existing ice rubble and also fails in bending due to the difference of buoyancy and gravitational actions.

When ice rubble forms, the ice sheet is usually thin compared to the width of the island or offshore structure. If the broken ice pieces cannot clear around the structure/island during ice movements, the fractured ice pieces accumulate as a rubble field[A.16-24]. Data on rubble pile heights for the Beaufort, Baltic and Caspian Seas are summarized in Reference [A.16-25].

For wide structures in a sea ice environment, the accumulation of ice rubble can significantly affect the ice failure mode and the resulting ice actions. When the ice becomes too thick to fail in bending or the oncoming ice sheet is constrained, the ice begins to fail in crushing at higher ice stresses. The crushing stress in the active zone is difficult to predict, and it is likely to be lower than can be experienced by narrow, gravity base structures[A.16-26]. Experience from field measurements should be used in such cases.

A.16.3.2.3 Ice barriers

Grounded ice rubble can be used as a protective ice barrier for offshore exploration and production structures. Ice barriers can be constructed using existing grounded ice rubble, or augmented by flooding and spray techniques[A.16-23]. These techniques are well proven in the Beaufort Sea, especially in terms of building protective ice pads (see A.16.2).

One important issue with ice barrier construction is the quality of the ice/seabed contact. If the seabed consists of frictional material (e.g. sand), then the ice barrier should be built with smaller cross-sections and a high freeboard to minimize the lateral ice loading. If the seabed is cohesive, larger barriers with low freeboard become more attractive[A.16-23].

In the case where a barrier is built on a smooth level ice sheet, the ice sheet can impede the drainage and consolidation of the cohesive soil. In addition, the influence of smooth ice on the ice/soil interface shear strength should be considered.

When the ice barrier is built on top of a smooth ice sheet, it can slide a small amount under actions from the surrounding ice sheet, depending on the compressibility of the rubble surcharging it and the nature of the ice surface.

Water depth and water level fluctuations are important factors in assessing ice rubble sliding resistance. Experience in the Beaufort Sea indicates that a grounded ice rubble field usually forms around a structure when the berm is set at 15 m or less, and the rubble extends to about the 18 m to 20 m water depth down the flanks of the berm[A.16-23]. Permanent grounding of ice rubble is more likely for shallower water depths.

In general, the ice rubble formed early in winter from thin ice sheets does not create sails as high as those created from thicker ice sheets later in the season. Its topography (i.e. the relationship between sail height and thickness of grounded ice rubble) is not as well understood as that for sea ice pressure ridges.

Grounded ice protection barriers should be designed to resist lateral ice actions. Such actions tend to cause failure in one of four ways:

a) sliding along a weak plane through the ice;

b) sliding along the bottom at the ice-soil interface;

c) sliding along a weak plane through the soil;

d) passive edge failures.

The sliding resistance of the rubble depends on the strength of the interface between the ice blocks and the sea floor. This is reasonably well defined if the rubble sits on a sand berm. When the ice rubble pile is grounded on the natural sea floor, the interface strength is often uncertain and the designer should perform careful geotechnical investigation and assessment.

A.16.3.2.4 Ice actions and ice/barrier interaction

A knowledge of ice rubble properties is important for characterizing ice action transmission. Ice rubble generally consists of a sail (portion above sea level), a refrozen layer and the keel. In areas of low sail height and minimal snow, the heat flux usually is large and the refrozen layer can attain thicknesses that are double the normal level ice growth for the region. The continuity of the refrozen layer is also important in this respect. Because of difficulties of drilling through high sails, few data have been gathered to date for this condition[A.16-23].

The ice strength and elastic modulus of the refrozen layer are best deduced from *in situ* strength measurements. Measuring salinity and temperature is not a reliable means of determining the strength of rubble ice. The properties of the grounded keels are key to how the ice loads are transmitted to the sea floor or the underwater berm. Based on gross measurements of rubble field behaviour, it is assumed that the keels have sufficient strength and stiffness to effectively transfer most of the ice loads to the sea floor or berm. It is believed that low temperatures during the rubble formation processes and high grounding stresses can initiate the bonding of fragmented ice blocks to form a cohesive mass. There is evidence to indicate that strength increases do occur. Sea floor “pock marks” have been observed where first-year ice rubble fields have been grounded, indicating that significant stress can be applied.

While laboratory measurements of the strength of ice rubble have led to its description as a Mohr-Coulomb material, there is a wide range in the reported values of cohesion and internal friction angle. Angles of internal friction from 11° to 67° have been reported, while reported cohesion values usually range from 0 kPa up to 25 kPa.

The majority of the field measurements and observations in the Beaufort Sea support the finding that once a grounded ice rubble field is established around an offshore structure, the loading transmitted to the structure is often zero and, even when there is transmission, it is usually less than about 30 % of the applied ice loading. There have been cases where greater than 50 % of the applied loading appears to have been transmitted[A.16-23]. It is assumed that in these cases the refrozen layer is probably more continuous than usual.

There are some instances in the spring with warm ice when the loading transmitted is higher than 50 %. This situation matches the model test results, which generally show higher levels of load transmission than in normal winter field situations.

Experiences from the field indicate that grounded ice rubble dissipates or eliminates the transmission of significant dynamic ice actions. The mitigation of ice-induced dynamics can be related to the change in ice failure mode, but the additional mass and damping of ice rubble are also presumed to be a beneficial influence.

Ice rubble deforms with time and under ice actions. The most significant deformations are vertical settlements (creep behaviour) after formation, which can be greater than 1 m. Lateral deformations are often associated with vertical settlement, but also with sustained lateral actions.

Field measurements of ice action transmission through ice rubble fields are difficult. Theoretical calculations of ice rubble field resistance and effectiveness in protecting structures from ice actions can be subject to considerable uncertainty. Consequently, the designer should undertake model testing in appropriate circumstances as an alternative to supplement or to verify such calculations. Due account should be taken of the laboratory simulation of the ice rubble formation processes. Attention should also be given to a suitable scaling of the structure and the ice environment.

A.16.3.3 Methods for mitigating the effects of ice

A.16.3.3.1 Ice control and defence

Passive ice control and defence methods can be used for lowering the risk or safety class associated with a given structure. They can be implemented at the design stage, or operationally during the design service life of the structure.

Ice control and defence methods can also be used to reduce the ice actions on the structure. The following approaches have been attempted.

a) Cutting a trench or moat in the ice around an island or structure. This approach can only be effective if

   - the trench is kept dry or prevented from refreezing,
   - the trench precipitates out-of-plane ice movements.

   This technique suffers from the limitations that

   - it is a one-time solution,
   - the ice can crack, causing the trench to fill and refreeze.

   The trench approach can have a negative effect in that it can induce ice over-ride onto the working surface of the drilling platform it was designed to protect.

b) Placing barriers in front of the structure to initiate the formation of a grounded rubble pile; see A.16.3.2.

c) Using satellite structures to relieve the ice actions on the drilling platform itself. An ice protection system was put in place around Sunkar, a drilling platform in the Caspian Sea, with the dual purposes of

   - adding more sliding resistance

     i) through the formation of grounded ice rubble, if ice movements occur,

     ii) by spraying ice on the satellite structures[A.16-27];

   - helping to provide relatively ice-free access to the Sunkar structure for supply vessels.

   Various concepts have been used or designed for the satellite structures including barges and rock mound breakwaters [A.16-28], [A.16-29].

d) Spray ice, which has been used to augment the sliding resistance of barges deployed at Sunkar, to augment their sliding resistance[A.16-27].

e) Placing piles in front of the structure to augment its sliding resistance and to control ice rubble build-up at the structure. This has also been done at Sunkar [A.16-30] to [A.16-32]. More general model tests of this concept have been performed[A.16-33].

f) Local variations in the structure's perimeter. The GBS at Hibernia was built with local indentations around its perimeter. These were intended to reduce the global load by lengthening the time taken to decelerate an impacting iceberg.

g) Explosives, which have been considered for large ice masses (i.e. icebergs and ice islands) for many years, dating back to about 1926. This approach has never been used operationally for ice defence owing to a number of limitations and concerns.

A.16.3.3.2 Mitigation of ice encroachment

The ice control and defence methods listed in A.16.3.3.1 can also be used to protect the structure against ice encroachment.

Ice ride-up is complex as many factors affect the interaction, and only a rough understanding is currently available. Reference [A.16-34] offers the following guidelines.

- Shallow slopes are more susceptible to ice ride-up.

- Smooth slopes with few irregularities are more susceptible to ice ride-up.

- Ice ride-up is more likely to occur in combination with tidal fluctuations, storm surges or gravity waves, which act to break the ice-shoreline bond and elevate the ice sheet.

Reference [A.16-34] further indicates that “rough, irregular or steeply sloping shores will tend to initiate ice pile-up when onshore ice movement occurs”.

The following ice control methods are available to protect against ice encroachment.

a) Layout of facilities on the island: this includes laying out islands such that they have a perimeter road, and putting the least critical items closest to the island's perimeter. This approach is most applicable to gravel or artificial islands. The perimeter road provides general access around the island as well as protection against ice encroachment onto the island, which can put the facilities at risk.

b) Constructing caisson-type drilling structures with sufficient freeboard that the facilities on them are protected from potential ice encroachments: some structures such as the Molikpaq and the caisson retained island were constructed with steel ice deflectors around the full perimeter at the top of the caisson[A.16-35], [A.16-22].

c) Designing the slopes and faces of drilling islands such that they cause ice pieces in an encroaching ice sheet to become unstable, leading to rubble formation, thereby preventing further encroachment onto the island. The approaches for achieving this include

- using slopes with a variable elevation profile, such as
  - i) a “bump” in the slope which produces an instability in the advancing ice pieces,
  - ii) having a steep section that can bring about a change in ice failure mode;
- placing obstacles along the face, such as steel piles, to inhibit ice ride-up, (the “tank traps” used at Challenge Island[A.16-36] are a variation of this concept, as the tank traps are intended to initiate rubble formation, thus preventing ice ride-up onto the island).

Since encroachment is a local design issue, the exposure level (see 7.1.4) for facilities potentially affected by ice encroachment can be designated individually. For example, it is not necessary that unmanned storage areas of non-hazardous materials be protected from ice ride-up or pile-up. Hydrocarbon storage, production wells and manned areas require design according to the provisions of Clauses 7 and 8.

A.16.4 Measurements of ice pressure and actions

A.16.4.1 General

Ice loading measurements have provided the basis for many important advances in ice engineering with respect to offshore structures, and current design codes state that empirical treatment of full-scale data is often the best approach for determining design ice loads[A.16-21]. Fundamentally, ice loading measurements are undertaken to meet the two general objectives listed in Table A.16-2.

Table A.16-2 — Overview of ice load measurement objectives and requirements

Key requirements of the measuring system	General application and objective	
	Safety assurance of an existing structure[a]	Improved design criteria for future structures
Real-time data	Essential	Not required
Algorithms to interpret the data	Essential, and required in real time	Required, but not in real time
Frequency of data acquisition and alert levels	Real-time data more important than high-frequency data, if a compromise is necessary Alert levels required	Depends on the ice failure mode: high-frequency data (> 10 Hz per channel) required, if ice failure occurs by crushing Alert levels not required
Measurement of global versus local loads	Global loads typically most important	Depends on application; data can be required for either one or both

[a] Many failure modes are possible, such as sliding along various failure planes and overturning. Monitoring systems, taking these into account, should be designed to operate in conjunction with other monitoring systems that are in place, e.g. for foundation response.

A.16.4.2 Measurement techniques

A wide range of approaches for the measurement of ice actions has been used to date. See Reference [A.16-37] for a description of some of them. Comprehensive systems have been used at the following locations:

- measurement system on the SSDC[A.16-38];
- measurement system on the Molikpaq while deployed in the Beaufort Sea[A.16-35];
- measurement system on the Molikpaq while deployed in the Okhotsk Sea[A.16-39];
- monitoring system used at the Confederation Bridge[A.16-40];
- monitoring system at the Hondo Bridge Pier[A.16-41], [A.16-42];
- monitoring system at the Yamachiche Light Pier[A.16-42];
- measurement system at a structure in the Pechora Sea[A.16-43];
- LOLEIF/STRICE[A.16-44].

The most appropriate system should be selected based on the structure, the environmental conditions at the site, and the objectives of the project. Generally, the available field techniques can be classified as either

a) measurements of the stress or strain in the ice; many instruments have been developed to accomplish this[A.16-45], [A.16-46], [A.16-37];

b) measurements of structural response, which, in general, can be accomplished by

  - measuring the strains, deformations, or movements of the structure, including its foundation,
  - placing load-sensing, or pressure-sensing, panels on the structure,
  - measuring the accelerations of the structure in cases of dynamic loading.

A.16.4.3 Limitations and requirements for different techniques

The most appropriate technique for measurement of ice actions depends on factors such as the type of structure, the objectives of the measurement project and the ice-structure interactions of concern. Broadly, these can be classified as either of the following.

a) Structures in relatively static ice; in this case, ice movements that occur while the structure is frozen-in are likely to generate the highest ice loads. The artificial islands used for exploration in shallow water in the Beaufort Sea are an example. *In situ* ice stress meters are typically used to measure and determine ice loadings for this case.

b) Structures in mobile ice; examples include

  - caisson drilling structures in the Beaufort Sea, which were deployed relatively far offshore, compared to the artificial islands. See Reference [A.16-42] for a catalogue of these data;
  - multi-leg and GBS type structures in other locations, such as Cook Inlet[A.16-47], the Bohai Sea[A.16-48] and Okhotsk Sea[A.16-39];

- bridge piers: for most highway bridges, the design loads are produced during break-up, which produces ice runs[A.16-49], [A.16-41] (the recently-built Confederation Bridge is exposed to moving ice over the full winter[A.16-40];
- light piers and lighthouses[A.16-50], [A.16-44];
- ice control booms placed in Lac St Pierre[A.16-51] and Lake Erie[A.16-52];
- research projects, such as those done to
  i) measure multi-year ice impact actions at Hans Island[A.16-53], [A.16-54],
  ii) measure pack ice driving actions (e.g. at Katie's Floeberg, in the Canadian arctic, in Labrador, and near Svalbard[A.16-55],
  iii) measure iceberg impact actions[A.16-56],
  iv) measure indentation pressures at Hokkaido, Japan[A.16-57], [A.16-58], and at various locations in the Canadian arctic[A.16-59], [A.16-60], [A.16-61].

Ice loading data were obtained for almost all of the above cases using measurements of structural response. The methods used to measure structural response for these cases have included panels or load cells on the structure, tiltmeters, accelerometers and strain gauges on the structure.

The use of *in situ* ice stress and strain meters is generally inappropriate for applications involving significant ice movements. Furthermore, in some cases involving moving ice (e.g. caisson-type structures in the Beaufort Sea and some lighthouses), a grounded rubble field has formed around the structure, which affects the actions exerted on the structure itself.

The pack ice driving action measurements are somewhat unique since *in situ* ice stress meters were used to determine the effects within the ice.

The requirements for an ice load measurement system also depend on the type of ice failure that is expected. The type of ice failure can include crushing, flexure, buckling, ride-up, splitting and mixed-mode. Systems with the highest frequency response and data acquisition rates are required for crushing failures where the effect can cycle at frequencies greater than 10 Hz.

Furthermore, for wide structures, ice failure can alternate from being simultaneous across the full structure width to being non-simultaneous, which affects the actions developed[A.16-35].

The requirements for ice load measurement systems also depend on whether they are intended to measure global or local actions. Some systems, such as accelerometers, tiltmeters and large-scale load panels, are capable of measuring only global actions. Others, such as panels and strain gauges (depending on the type of structure), measure local actions and pressures, and these should be integrated to determine the total action effect.

For all systems, there is a requirement for calibration. The most appropriate calibration approach depends on the type of measurement system and the objectives of the measurements.

The time-stability of the instrumentation is another factor that it is necessary to consider. Drift is of most concern in cases where the structure can be in contact with ice for long periods, such as caisson structures in the Beaufort Sea, with the result that true zero levels are difficult to establish and check regularly.

A.16.4.4 Documentation of environmental conditions

Ice load or pressure measurements should be complemented with data gathering efforts to quantify the associated ice and environmental conditions. This is especially important for measurement projects performed to develop improved design criteria for future structures, although these data also help to provide a reality check for monitoring performed to assure the safety of an existing structure.

The key contributing factors, particularly those that are random such as the ice thickness, should be measured. This is especially important for subsequent probabilistic treatment of the data and for calculating ice loads or pressures for a site.

A.16.4.5 Observations of the ice-structure interaction process

A knowledge of what happened is a fundamental requirement for understanding any ice load data that are collected. Because the required environmental data vary from case-to-case, only general suggestions are made here.

It is essential that the collected data should identify and describe the loading scenario that occurred. The key issues include

- the ice feature and type (e.g. first-year or multi-year ice sheets, ice ridges, rafted ice, ice jams, etc.);
- the morphology of the ice feature (e.g. thickness, floe size, feature dimensions, shape);
- the ice failure mode(s) that occur (e.g. crushing, flexure, buckling, splitting, simultaneous versus non-simultaneous failure, ride-up, mixed-mode, etc.);
- the ice movement.

A.16.4.6 Ice load databases and synopses

Ice load databases are useful for estimating the expected actions and pressures on a structure. In addition to the usual requirements for a database (e.g. accuracy, extensiveness, ability to search and output information, ability to add new data, user-friendliness, compatibility of computer software in relation to common operating systems), an ice load database should contain

a) quantitative ice load and/or pressure data, including
    - the measured actions and/or pressures,
    - the areas over which they were measured, or to which they apply,
    - the time histories, and/or the frequency content of the measured data;

b) information describing the structure or site where the data were obtained;

c) description of the loading scenario;

d) information defining the environmental conditions that produced the actions and/or pressures.

Various ice load and pressure databases have been developed to meet the above general requirements. Reference [A.16-62] documents one of the first publicly available databases. It contains information for

- drilling structures and other sites in the Beaufort Sea and the Arctic;
- drilling platforms and structures in other locations (e.g. Cook Inlet, Bohai Bay);
- ship trials in the Beaufort Sea;
- lighthouses in the St Lawrence and the Baltic;
- bridge piers.

Recently, a comprehensive database that contains information for a wide range of structures has been assembled[A.16-42]. A detailed hard-copy report is publicly available describing the information in this database.

In addition to electronic databases, several summary reports have been produced documenting measured ice action and pressure data. While these synopses are not as extensive as an electronic database, they nevertheless provide useful information for subsets of the overall ice load problem. References [A.16-63] and [A.16-64] present summary information for caisson drilling structures used in the Beaufort Sea. Reference [A.16-65] presents an overview of ice actions for some slender structures (i.e. piles, bridge piers and lighthouses). Reference [A.16-66] presents a synopsis of information regarding local ice pressures.

A.16.5 Ice tank modelling

A.16.5.1 General

Ice tank modelling can be used to investigate various ice-structure interactions and offers the advantage that relatively complex problems (that can be difficult to analyse using other methods) can be studied and visualized at a small scale (i.e. smaller than full scale).

Generally, ice model tests have been used to investigate global ice actions resulting from moving ice, such as the expected ice actions and/or the expected ice interaction modes (e.g. ice failure modes, ice ride-up, the build-up of ice rubble around a structure, ice clearing behaviour around a structure, ice blockage, etc.). Ice model tests have not been used to investigate static ice loads, e.g. resulting from thermal effects. Also, ice model tests have generally not been used to investigate local effects, such as local ice pressures.

Ice tank modelling is a flexible tool that has been applied to many ice-structure interaction cases such as

a) various structure types; the types tested include

  - large vertical or multi-faceted caissons,
  - upward breaking and downward breaking cones,
  - narrow versus wide structures,
  - multi-leg structures,
  - berms,
  - moored versus bottom-founded structures,
  - satellite structures placed near a drilling structure to provide ice protection, and access for EER craft or protection for quay areas;

b) Various ice features interacting with a structure, such as

  - sheet ice,
  - first-year ridges,
  - multi-year ridges,
  - broken ice, and floe ice conditions.

Table A.16-3 lists common ice processes treated by means of physical modelling and indicates the important variables influencing them. Model reliability depends on the accuracy with which the model replicates those variables. Note that some modelling situations can involve a combination of processes. Consequently, the variables can be grouped differently as shown in Table A.16-3[A.16-67].

Only a limited number of comparisons have been made between model scale and full-scale results for structures, although several correlation studies have been done for icebreaking ships. Ice model tests have been conducted at different scales for fixed icebreaking conical structures. Comparisons are made for the

Kulluk (a large downward breaking floating conical structure) between model tests conducted at different ice tanks and field data collected while it was on station in the Beaufort Sea.

A problem of major concern in planning a model test programme is the type of ice. Not all ice problems can be investigated reliably using present-day ice tank modelling techniques. An ice model test programme should be targeted to investigate the specific ice interaction problem of interest. Sometimes, it is preferable to test a simplified, basic problem in the ice tank, and then use these results to assess an overall problem that is more complex.

Table A.16-3 — Ice processes and variables that it is important to model

Ice process	Variables of importance
Ice sheet deflection	Ice flexural strength Modulus of elasticity Loading rate Ice thickness
Ice ridging	Velocity of parent ice sheet Ice thickness of parent ice sheet Ice–ice friction Ice sheet strength (flexural, crushing, shear) Keel depth Sail height Consolidated layer
Ice-structure interaction	Structure stiffness Dynamic characteristics of structure/mooring system Velocity of ice sheet Ice thickness Ice sheet strength (crushing, flexural, shear) Ice–ice and ice–structure friction Mode of breaking (crushing, flexure, shear) Ridge properties and dimensions
Icebreaker modelling	Vessel speed Ice–ice and ice–hull friction Ice thickness Ice sheet strength (crushing, flexural, shear) Ice piece size Piece movement around hull and propeller Mode of breaking (crushing, flexure, shear) Ridge properties and dimensions

Previous investigations of ice ride-up and ridge building are examples where this approach has been used. Initially, simple model tests were done to investigate ice ride-up and ridge building processes. These basic data are part of the information set that is used to address more complex issues such as

- designing islands and structures to avoid ice ride-up problems;
- quantifying pack ice driving actions and developing satellite structures designed to form protective rubble around drilling structures in the Beaufort Sea.

Scaling uncertainties and modelling artefacts are another important issue that should be considered in planning an ice model test programme. These can arise from imperfections in the ice modelling material being used. Some model ices are better able to simulate some types of ice interactions than others.

A.16.5.2 Scaling

When model testing is used for ice-structure interactions, appropriate scaling relationships should be selected to represent the mechanisms or processes that dominate the ice actions or response to ice actions. In the physical modelling of ice and structure interactions, Froude similarity (the ratio of inertial to gravitational load) and Cauchy similarity (the ratio of inertial to elastic forces) are maintained between the prototype and the model[A.16-68]. Considerable effort has been expended on the development of model ice with mechanical properties scaled to prototype ice and with analogous failure behaviour. There can also be rigorous modelling of the structure shape, stiffness, and surface characteristics. As long as the failure modes expected in the prototype are correctly simulated, model tests can provide an important input into the design process. Model ice can provide optimum simulation of ice interactions only over a certain range of scale factors, generally within about 10 to 50. Tests done at scale factors that are too high are likely to produce results that are subject to modelling distortions.

Scaling is accomplished by observing the Froude scaling law, as given in Equation (A.16-14), and the Cauchy scaling law, as given in Equation (A.16-15):

$$Fr = \frac{v}{gL} \tag{A.16-14}$$

$$Ca = \frac{v^2 \rho_\mathrm{w}}{E} \tag{A.16-15}$$

where

Fr is the Froude number, the ratio of inertial to gravitational forces;

Ca is the Cauchy number, the ratio of inertial to elastic forces;

v is the speed, expressed in metres per second;

g is the acceleration of gravity, expressed in metres per second squared;

L is the length dimension, expressed in metres;

ρ_w is the density of water, expressed in kilograms per cubic metre;

E is the modulus of elasticity of ice (Young's modulus), expressed in megapascals.

Since inertial and gravitational forces dominate free-surface flow, the Froude number is generally used as the similitude criterion for ice basin modelling. The Cauchy number, then, provides the necessary scaling for material parameters. It is not possible in model tests to simultaneously satisfy the requirements of Reynolds law, which governs viscous effects, with those of Froude/Cauchy scaling. Since viscous effects are relatively small for ice model tests at low speeds, Reynolds law is usually ignored.

In order to satisfy the Froude and Cauchy laws, the various geometrical and physical quantities of the tested objects should be scaled according to Table A.16-4.

Table A.16-4 — Scale relations

Physical values	Model scale	Full scale
Ice thickness	h'	$h = \lambda h'$
Flexural strength of ice	σ_f'	$\sigma_f = \lambda \sigma_f'$
Elastic modulus of ice	E'	$E = \lambda E'$
Density of water	ρ_w'	$\rho_w = \rho_w'$
Density of ice	ρ_i'	$\rho_i = \rho_i'$
Time	t'	$t = \lambda^{1/2} t'$
Velocity	v'	$v = \lambda^{1/2} v'$
Force	F'	$F = \lambda^3 F'$
Friction coefficient	μ'	$\mu = \mu'$
NOTE λ is the geometric scale factor.		

A.16.5.3 Test methods

A.16.5.3.1 Model ice types

Natural sea ice behaves as a brittle or ductile material depending primarily on its temperature, salinity and strain rate. Basic mechanical properties of the natural ice, such as strength and deformation, also depend mainly on the strain rate, ice temperature and salinity content in the ice. Flexural strength is conventionally considered independent from strain rate. Ideally, model ice should behave in the same manner when applying Froude scaling law, i.e. the strengths should be related by a linear scale factor, λ.

In the past decades, significant effort was made in finding the ideal material for model ice. Different approaches used to produce model ice include synthetic ice, hybrid ice and refrigerated ice. Currently, refrigerated ice is the most widely used model ice. To scale the ice properties correctly, the ice is doped by sodium chloride or other chemical dopants, such as ethylene glycol and detergent. A wet seeding technique can be used to produce a fine, crystalline, columnar structured ice. A fine-grained ice can be produced by spraying a saline solution during the entire ice growth process, resulting in a granular structured ice similar to snow ice. Further model ice development includes the injection into the water of air bubbles that are entrained into the growing ice crystals to increase brittleness and decrease ice density.

It is important to note that a standard “model ice” has not yet been established, and judgment is required to ensure that the model ice used is appropriate for the ice-structure interaction of interest, in combination with other factors such as the size and capabilities of the ice tank.

A.16.5.3.2 Testing technique

In general, two testing options are used in ice model tanks. The first method is to push or pull the model through a stationary ice sheet; the second is to have a moving ice sheet pushed against a fixed or moored model. The selected option should be consistent with the test objectives. Parameters measured and the configuration of the measurement systems should be primarily dictated by the test objectives and the characteristics of the structure and its operational conditions.

Differences in the dimensions and layout of the ice tank facility can have some influence on the tests. An important factor is the effect of the basin size (length and width) on the number of tests that can be carried out with one ice sheet. The required actual test length depends on the type of test. As an example, for ice rubble formation tests or ice pile-up tests, the model should be able to proceed until a steady state is reached. The other factor that can restrict the test programme is the proximity of the basin walls. For the case when a model is pulled through ice, the level ice sheet can be considered to have infinite extent if the shortest distance from the point of application of any loads to the nearest tank wall is more than three times the characteristic length of the ice sheet.

The choice of testing technique depends strongly on the type of test. In particular, it should be appreciated that when pushing the ice sheet against a model of a fixed or moored structure, unrealistic cracks can often propagate from the model towards the sidewalls of the tank, In addition, the ice sheet can fail along the pushing plate instead of on the model; this happens especially for thin and brittle ice. As well as for the testing technique option, the most practical way to minimize negative consequences of the boundary condition deviation is to conduct tests with an ice sheet sufficiently wide relative to the model width.

A.16.5.3.3 Ice conditions

Model tests can be performed in ice conditions such as level ice, rafted ice, a newly broken channel, brash ice (old channel), broken ice, rubble ice fields and ridges. The proper documentation of the tests should include the method by which the ice conditions are simulated. It is recommended to document the ice conditions prior to and after the test by still photographs and video records, preferably from some elevation. The number, time and location of ice thickness and property measurements should also be documented. Visible cracks in the ice extending from the broken channel towards the basin walls or towards open water areas should be included in the report.

The thickness of the model ice should be measured after each level ice test and the number of measurements should be sufficient to adequately evaluate variations in ice thickness along the track of the model through the ice. In cases where test runs are performed close to the sidewalls of the ice tank, measurements should be taken on both sides of the broken channel.

In an old channel or rubble field, the thickness should be measured along two or more lines within the model track. Underwater sonar for scanning the lower surface of model ice and laser profiles for evaluation of ice upper surface or similar remote sensing devices is particularly advantageous for tests with ice rubbles/ridges or brash ice. Such measuring systems allow for the non-destructive acquisition of the ice thickness profiles or a 3D picture before running the test.

Ice ridges and rubble can contribute, in many cases, to the design actions on a structure, and conducting model tests for such conditions is of particular importance. Producing model ridges and rubble in compliance with the requirements of similitude theory is one of the most challenging tasks in ice/structure interaction modelling. The conventional method of creating a first-year ice ridge/rubble is to grow level ice with a thickness equal to the thickness of ice blocks constituting a model ridge/rubble, break this ice sheet into irregular pieces and then collect these pieces into a pile. The resulting pile of ice is normally left exposed for some period of time to negative ambient air temperature in order to create a consolidated layer of the ridge/rubble.

In the course of ice ridge/rubble modelling, particular attention should be paid to modelling the effects of the interaction within the non-consolidated part of the ice feature and to the mechanical properties of its refrozen part. The mechanical properties of the consolidated layer can be evaluated in the same way as for level ice, assuming that both sail and keel are carefully removed. For the measurements of the mechanical properties of the non-consolidated part, pull-up, punch and/or shear tests can be employed.

A.16.5.4 Model ice properties

A.16.5.4.1 General

Different model testing facilities use different types of model ice materials. None of the existing model ice materials is absolutely perfect. Thus, ice properties measured for one type of material cannot be directly compared with another material. The geometrical parameters and mechanical properties of the model ice should be determined accurately, regardless of the material composition.

To maintain reliable results, it is recommended to perform property measurements *in situ* in the tank and, whenever possible, without lifting the samples out of the natural environment. The timing and location of the measurements are important. The measurements should be done as close as possible to the actual test area and test time. All measurement procedures should be as simple as possible and measure the desired parameter directly. The test procedures and measurements should be performed by qualified personnel and should be clearly documented. The equipment used in all measurements should be calibrated at the ambient temperatures of the ice tank.

Properties of first-year and multi-year ridges are very difficult to control in ice basins. Samples should be taken from parts of the ridge to document both consolidation and other internal properties. The ice conditions adjacent to the ridge should be documented. For instance, broken level ice surrounding a ridge reduces the actions substantially compared to intact level ice.

A.16.5.4.2 Flexural strength and modulus of elasticity

The flexural strength and the modulus of elasticity are frequently determined by cantilever beam tests. A floating cantilever beam having length L and width B is cut *in situ*. The recommended dimensions of a beam ($L \times B \times h$) are $6h \times 2h \times h$, where h is the ice thickness. The tip of the beam is loaded at a constant speed until the beam fails. It is recommended to use an electrically driven loading device. The applied load as well as the deflection of the beam should be recorded. The determination of the deflection is required only for the determination of the elastic modulus. Strength measurements should be carried out several times during the tempering phase and once after the ice test has been performed. Whenever possible, the strength should be measured at different locations distributed over the tank length. The flexural strength and the modulus of elasticity in bending can be calculated from the failure load and the free-end deflection measurements as given in Equations (A.16-16) and (A.16-17), all in consistent SI units:

$$\sigma_{\mathrm{f}} = \frac{6F_{\mathrm{b}}\,L}{B\,h^2} \tag{A.16-16}$$

$$E_{\mathrm{f}} = \frac{4F\,L^3}{B\,h^3\Delta} \tag{A.16-17}$$

where:

σ_{f} is the flexural strength in bending;

E_{f} is the elastic modulus in bending;

F is the load applied to the cantilever free end;

F_{b} is the failure load;

L is the length of the beam (load point to support);

B is the width of the beam (at the support);

h is the thickness of the ice;

Δ is the deflection of the beam (cantilever free end).

An alternative method to measure the modulus of elasticity in bending is to measure the deflection of an infinite floating ice sheet under a given load. In this case, the elastic modulus is defined as given in Equation (A.16-18):

$$E_{\mathrm{f}} = \frac{3(1-\nu^2)}{16\rho_{\mathrm{w}} g h^3}\left(\frac{F}{\Delta}\right)^2 \tag{A.16-18}$$

where

ν is the Poisson ratio for ice

ρ_{w} is water density;

g is acceleration due to gravity;

Other designations are as for Equation (A.16-17).

A.16.5.4.3 Compressive ice strength

The compressive strength of model ice can be measured using any of the following three methods:

a) uniaxial test is performed in the water;

b) ice block is cut and lifted from the water to perform a uniaxial test;

c) indenter is used to load the ice sheet horizontally.

The compressive strength is the most difficult to measure with high accuracy and the structure of the model ice does not always allow the use of all of the above methods.

A.16.5.4.4 Friction coefficient

The dynamic friction coefficient is determined through measurements of the tangential action when either a piece of model ice is slid along a plate, painted identically to the model structure, or such a plate slides over a piece of model ice. In both cases, the ice and the plate should be pressed together by a given normal action. The friction between two ice pieces can be determined using the same testing arrangements. The contact surfaces of the ice and the plate should be moistened, since wet and dry friction coefficients differ significantly. The friction tests should be performed at a speed corresponding to the ice/structure interaction velocity expected in the tests. The friction coefficient, μ, is calculated according to Coulomb's friction law as given in Equation (A.16-19):

$$\mu = \frac{F_\mathrm{T}}{F_\mathrm{N}} \tag{A.16-19}$$

where

F_T is the mean measured tangential (friction) load during steady motion;

F_N is the normal load on the contact surface.

A.16.6 Offloading in ice

A.16.6.1 General

An offloading system for hydrocarbons generally consists of a tanker and an offloading unit. For decades, tankers have been a reliable method for exporting hydrocarbons from offshore platforms. Shipping is an attractive solution for hydrocarbon transportation in arctic and cold regions, with the loading operation being the most vulnerable marine operation.

A number of offloading concepts have been proposed, including the DeKastri and the Aniva Bay offloading systems, and the Pechora Sea loading tower. The tanker can load directly from the production platform or from a narrower loading tower. These concepts can suffer from a high risk of collision between the tanker and the structure in variable ice drift conditions. The tanker can, alternatively, moor on the loading hose via a single-anchor loading system, but effective ice management using icebreakers is required to protect this system in heavy ice conditions. Another option for arctic and cold regions is to offload from a submerged turret where the hose system is protected by armour from moving ice.

Depending on the design, a full offloading concept in ice is likely to include a moored tanker connected to a moored storage vessel, a moored production storage vessel or another type of floating structure. Alternatively, the moored tanker can be connected to a fixed bottom-supported platform or to a subsea production system.

The loading of a tanker at a production platform, loading tower or subsea buoy (the offloading unit) can include the following phases[A.16-69]:

- initial approach;
- final approach;
- stationkeeping;
- departure.

Operational procedures such as ice management can be used in all these phases to reduce global or local ice design actions, provided it can be shown that the intended level of safety, in combination with structural resistance, is achieved.

A.16.6.2 System reliability

Typically, risk analyses for offloading systems should include

a) a description of ice and associated metocean conditions, and appropriate statistical distributions for key parameters;

b) a description of system components and details of their operation, which should include particulars of the disconnection system, see 13.7;

c) a realistic representation of tanker capabilities and operation, if available, supported by data from actual offloading operations in ice;

d) where appropriate, a description of the ice management capability, including demonstrated effectiveness in the ice conditions to be encountered;

e) a definition of acceptance criteria, consistent with the provisions of this International Standard, for the release of hydrocarbons and loss to life, and potentially for contact frequency between tanker and floating structure, damage to the vessel, damage to the floating structure, and downtime.

Where significant uncertainties exist in the physical environment, the efficiency with which ice management, tanker operations and disconnection can be conducted should be considered in the analysis.

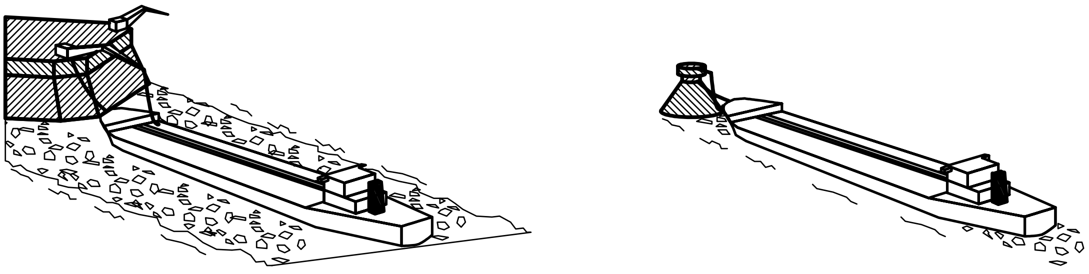
It should be possible to disconnect a tanker connected to an offshore loading terminal even in the case when moving ice becomes stationary. In such circumstances, the ice can start drifting again with any heading and the ice actions and consequent collision risks with a loading structure can rapidly increase. A threshold ice drift speed should, therefore, be defined for disconnection. Disconnection can potentially be avoided in the following situations.

- When the ice-cover has a limited impact on the system (low ice actions and no impediments to manoeuvrability), as can be the case for thin ice or low ice concentrations.
- When reliable ice drift forecasting can be performed at the site, disconnection can be performed only just before the ice starts drifting in a dangerous direction. This type of event can also be assessed as critical only when the drift change is large. In areas where the ice can be landfast, it is important to detect these events so that offshore loading operations can continue. Nevertheless, it is necessary that the ice drift forecasting be extremely reliable so that safety is not compromised.
- When the ice stops drifting, it can start drifting again slowly. For example, when the wind and the current act suddenly in the same direction, the ice cover can move around 200 m in a 15 min period (for a 1 m thick ice cover and wind and water stresses on the order of 0,1 N/m^2). If the tanker is moored on a submerged turret loading buoy in deep water (and requires 15 min to disconnect), and an icebreaker is assisting, the ice management and the flexibility of the mooring normally prevent the development of excessive action effects before a disconnection is required.

A.16.6.3 Requirements for the offloading terminal

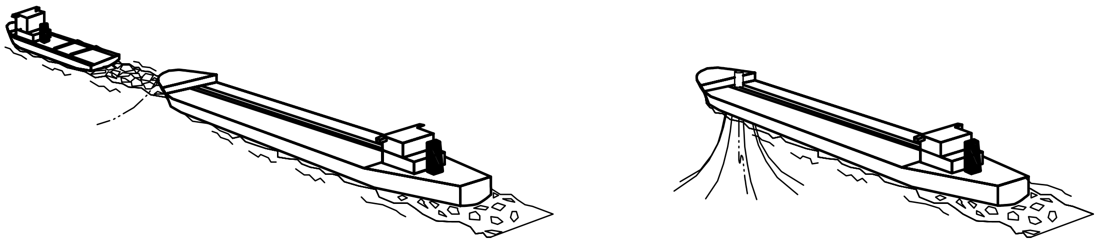
A.16.6.3.1 Types of offloading terminal

The offloading terminal should be designed for the physical environment in which it is planned to operate. This applies especially to moving ice. In principle, there are several potential categories for such offloading terminals (see Figure A.16-8).



a) Platform, a relatively wide, surface-piercing structure

b) Tower, a narrow surface-piercing structure



c) Single anchor loading (SAL) or single point mooring (SPM)

d) Turret loading, for a tanker equipped with a turret

Figure A.16-8 — Potential arctic and cold region offshore loading concepts

A.16.6.3.2 Platform

A platform is generally a relatively wide, surface-piercing structure that should be capable of resisting large global or local loads as well as mooring loads from the loading tanker. This can be the production platform itself, which is normally equipped with one or more loading arms. For a GBS that is square in plan, the loading arms can be located at the corners as shown in Figure A.16-8. Since the tanker is moored to a fixed point on the periphery of the structure, it has a limited capability to remain in the lee of the platform without disconnecting for significant changes in ice drift direction.

The structure should be designed to maintain integrity under impact from the tanker, whether by accident or the result of ice drift.

A.16.6.3.3 Tower

The tower concept is a narrow structure that can be located some distance away from the production platform or storage vessel. The tower is normally equipped with a loading arm. This adaptation of the tower mooring system should be designed to resist ice loads. A rigid mooring system (a wishbone or a yoke) can be stronger than a flexible mooring system and guarantee a minimum distance between the structure and the tanker bow. Model tests show that collision risks due to a sudden change in the ice drift direction are still present with a rigid arm[A.16-70].

A.16.6.3.4 Single anchor loading

A single anchor loading (SAL) or single point mooring (SPM) system is designed so that the tanker moors on a single line coupled with the loading hose and connected to a single anchor on the seabed. In the idle position, the line and the hose can rest on the seabed. The SAL system can be designed so that the hawser for bow loading is protected in a lobster (a segmented, interlocking shield over a hydrocarbon loading line used for protection from ice impact)[A.16-71], [A.16-72]. There are also designs where a non-protected reinforced hawser is used.

Because of limited capacity to resist ice actions, the SAL system can be operated only when effective ice management is available[A.16-73].

A.16.6.3.5 Turret

For turret loading, the tanker is equipped with a turret that can be internal or external to the hull; for offshore loading purposes, a releasable mooring solution with an internal turret such as the submerged turret loading (STL) system can be used. The internal turret loading concept is a fully subsea system. The system should be designed so that it is capable of transferring the load to the mooring system for all conditions including pressure ridges. The riser system should be sufficiently protected to avoid damage caused by floes and broken ice pieces pushed under the hull of the tanker.

A.16.6.4 Requirements for the tanker

Tankers that are loaded in ice should comply with the applicable ice class requirements.

A.17 Ice management

A.17.1 General

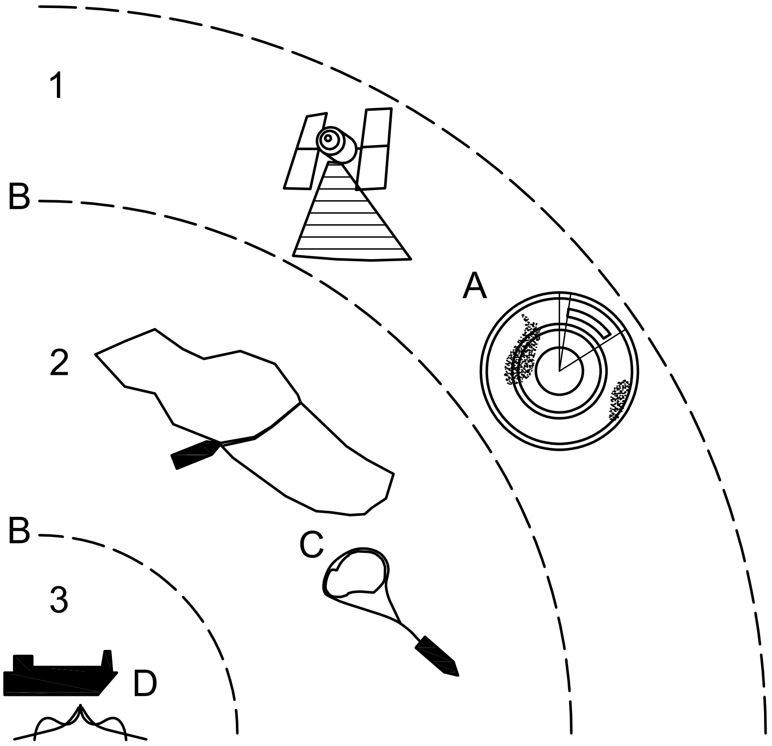
Floating structures that are deployed in ice-covered waters are often supported by highly capable ice management vessels, with the intended role of modifying the local ice environment, reducing ice actions on the structure and enhancing ice clearance around it. The requirement to identify potentially adverse ice features or situations requiring ice management and then to deal with them in a timely manner increases the range of environmental considerations that are normally associated with fixed structures. Fixed structures can also rely on ice management to ensure access to re-supply and offloading facilities and to clear potential escape routes for EER craft.

The type of ice management systems that is employed can have a significant influence on the design approach taken for any particular offshore system. This depends upon expected level of ice management reliability, for example, the ability to consistently detect potentially adverse ice conditions and, in turn, to manage them successfully before they interact with the structure (e.g. by towing icebergs, clearing grounded ice from EER access points, fragmenting severe sea ice features, etc.).

The major components of an ice management system used for floating facilities in ice-prone regions are illustrated in Figure A.17-1. In the outermost region or observation zone, ice features are detected using a variety of techniques, including aerial surveillance (visual or radar) and satellite-based radar or optical systems. Potentially hazardous features such as icebergs, multi-year and thick ice floes, ridges or rubble fields are tracked and their motion forecast according to the requirements of the structure and its operation.

Closer to the structure is the management zone, in which tracking of the features continues, the requirement for physical management is assessed and procedures are implemented. Physical management techniques include deflection by towing icebergs or by applying water cannon to bergy bits and growlers, pushing of large floes, breaking of thicker ice to decrease floe sizes, and breaking up of ridges or rubble fields. This list is by no means exhaustive and all feasible means should be considered. The sizes of the zones vary according to the operational characteristics of the platform and the ice environment. For icebergs off Canada's east coast, the management zone can correspond to drift times on the order of a day, while sea ice management zones seldom extend to drift times of more than a few hours.

Each floating structure has one or more critical zones close in corresponding to times required to shut down production, disconnect risers or release some mooring lines prior to full disconnection. These circumstances typically correspond to a series of alert levels, with associated drift times estimated for the ice feature to reach the platform. Ice management, detection, tracking and forecasting should continue as long as hazardous features remain within the critical zones.



Key

1	observation zone	A	detection
2	management zone	B	threat evaluation
3	critical zone	C	physical management
		D	disconnection

Figure A.17-1 — Typical components of an ice management system

An ice management strategy for icebergs and many sea ice conditions is illustrated in Figure A.17-2. Detection, tracking and forecasting continue throughout the time when potentially hazardous ice features are present. Once a threat is perceived and the feature is within prescribed time and/or distance limits (generally specified in the ice management plan), ice management resources are deployed. If the threat is averted, detection, tracking and forecasting should continue until it is ensured that the feature can no longer approach the structure. Similarly, production should be suspended and the platform disconnected if the threat persists.

Examples of ice management systems that have been used in ice-covered waters include

— the ice management systems that have supported floating drilling operations in the Beaufort Sea[A.17-1];

— the ice management systems that have supported a flowline installation and extended season oil production operations (through a SALM buoy to an FSO) in the Okhotsk Sea off northeast Sakhalin Island[A.17-2];

— the ice management systems that have supported drilling and production operations on the Grand Banks, and floating drilling operations in the Labrador Sea and off West Greenland[A.17-3], [A.17-4];

- the ice management systems that have supported a range of offshore activities in the Caspian Sea, such as the protection of drilling and production structures against adverse ice events, ice clearance to allow marine access to platforms, and icebreaking to enhance various EER approaches.

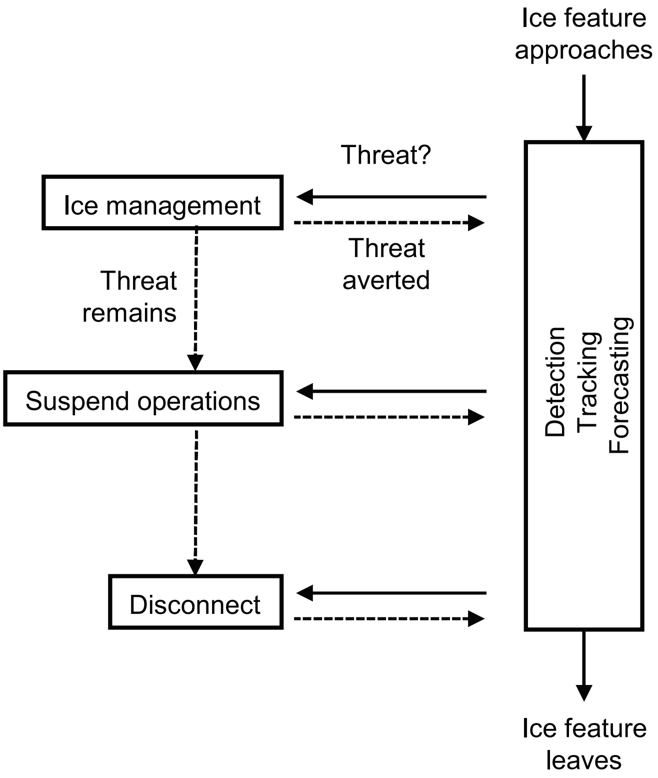


Figure A.17-2 — Typical functions of an ice management system

When these ice management systems were first put into place to support drilling operations on Canada's east coast and in the Beaufort Sea, there was little, if any, related experience in place. As a result, they were configured in a qualitative manner, using judgment, and applied in combination with ice alert and move-off procedures, with the basic objective of reducing downtime levels. At the time, there was insufficient documentation about ice management effectiveness to even attempt to quantitatively assess “system reliability in combination with structural resistance” across a range of ice conditions, ice management techniques and vessel types.

Ice management systems have proven to be quite successful in many situations, with the actual ice related downtime levels providing a feel for their overall reliability. Some representative ice related downtimes are summarized in Table A.17-1.

A.17.2 Ice management system

A.17.2.1 Overall reliability and design service life

No additional guidance is offered.

A.17.2.2 Ice management to reduce ice actions

The use of ice management to reduce the frequency and severity of ice actions on offshore systems is obvious in concept. In the case of iceberg management, it is clear that a successful ice management operation can avoid an impact event, while an unsuccessful management event does not. Sea ice management success is more difficult to characterize since the benefit depends on the level of ice management used (e.g. managed ice piece size, amount of effort spent on ice clearance around a platform).

Table A.17-1 — Downtime and towing effectiveness based on operational experience

Region	Activity	Time period	Ice regime	IM system capability	Approximate downtime	Reference and comments
Beaufort Sea	Kulluk drilling operations	Early break-up through late freeze-up	Thin to thick FY and MY pack ice	High (up to 4 PC2[a] icebreakers)	10 % of the time	[A.17-1]
	Canmar drilling operations	Late break-up through early freeze-up	Thin to thick FY and some MY pack ice	Moderate (1 PC2 and several PC4 icebreakers)	30 % of the time	—
Okhotsk Sea	Flowline installation	Break-up	Thick FY pack ice	Moderate to high (1 PC4 and 2 PC2 icebreakers)	60 % of the time	[A.17-5] (severity of ice underestimated)
	Production via SALM into FSO	Late break-up and early freeze-up	Thick and thin (spring and fall) FY ice	Moderate to high (1 PC4 and 2 PC2 icebreakers)	0 % during freeze-up; 15 % during break-up	[A.17-2]
Canadian east coast	Drilling and production	Spring and summer	Icebergs (no data for pack ice)	Various AHTS[b] vessels	Towing efficiency of ≈ 80 %	[A.17-6]
West Greenland	Drilling	Summer	Icebergs (no data for pack ice)	Various AHTS vessels	Towing efficiency of ≈ 90 %	[A.17-7]

[a] PC refers to Polar class.

[b] AHTS refers to anchor handling tug supply.

Full-scale data[A.17-1] show that ice actions can be reduced by a factor of between 2 and 10 in certain situations, depending on the “amount of ice management” used. However, experience also shows that not every adverse ice situation can be managed with 100 % reliability in a timely manner, even with highly capable ice management systems.

A.17.2.3 Characterization of ice management performance

Various analytic methods have been, and can be, developed to characterize the performance of any ice management system across a range of ice scenarios. However, the actual full-scale field experience that is available to calibrate and verify these methods remains quite limited, particularly for high ice class vessels of novel design in very severe ice conditions.

In this regard, it is important to note that systematic documentation of actual experience is highly recommended to improve future ice management activities. Full-scale demonstration projects can be beneficial, particularly when uncertainties about the effectiveness of ice management systems are both high and very consequential.

Given the current state-of-the-art and a general absence of well documented and quantitative information about ice management effectiveness (particularly for sea ice), it is also recommended that experienced ice management personnel be used to provide judgments on probable ice management effectiveness for the types of quantitative assessments recommended by this International Standard. In this regard, even undocumented input from well experienced operational people is a key factor to recognize, and should be solicited as a key input to any evaluations about ice management approaches and their effectiveness, at least to the extent possible.

A.17.2.4 Ice management system reliability

No additional guidance is offered.

A.17.3 Ice management system capabilities

A.17.3.1 Requirements

No additional guidance is offered.

A.17.3.2 Ice detection

A number of potential ice detection and tracking systems are listed in Table A.17-2. Threat evaluation can follow the procedure outlined in Figure A.17-2.

Table A.17-2 — Summary of potential ice detection and tracking systems

Platform	System	Function	Details
Structure	Visual[a]	Detection and tracking	—
	Marine radar	Detection and tracking	Can include special enhancements such as scan averaging
	Special camera systems	Detection and tracking	—
Shore	Visual[a]	Detection and tracking	—
	Marine radar	Detection and tracking	Can include special enhancements such as scan averaging
	Over the horizon radar	Detection and tracking	—
	Special camera systems	Detection and tracking	—
Aircraft (fixed wing, helicopter, unmanned drones)	Radar	Detection	Search, synthetic aperture, side-looking
	Visual[a]	Detection	—
	Altimeter	Detection	—
Ship	Marine radar	Detection	Can include special enhancements such as scan averaging; some tracking capability
	Visual[a]	Detection and tracking	Some tracking capability
Satellite	Radar	Detection	Some tracking capability
	Microwave	Detection	Some tracking capability, weather limitations
	Visible	Detection	Some tracking capability, weather limitations
	Altimeter, LIDAR	Detection	—
Underwater vehicle	Sonar	Detection	Some tracking capability
Fixed underwater	Upward-looking sonar	Detection	Ice thickness and ridge/rubble detection
	ADCP	Tracking	Speed measurement
	Other sonar systems	Detection	Some tracking capability

[a] Limited in conditions of poor visibility and darkness.

Iceberg detection can involve a wide scope of activities, including long-range observation used for preparedness and vessel allocation, strategic monitoring for prioritization of potential threats, and tactical monitoring for determining drift tracks and speeds. Summaries of iceberg detection systems are provided in References [A.17-6] and [A.17-4]. Key requirements are that all icebergs that pose a threat to the operation be detected and monitored on a continuous or nearly continuous basis. Potential threats can be identified based on estimated travel times relative to the time required for a staged and orderly shutdown followed by disconnection.

Iceberg detection systems always involve some form of radar because of poor visibility, whether due to darkness or fog. Platforms for the radar include the structure (most importantly), support vessels, aircraft (manned or unmanned) and satellites. A good system design involves timely data collection and detection probabilities at various ranges from the structure for the expected sea states, iceberg sizes and environmental conditions that are compatible with the system requirements. False alarm rates should be minimized to ensure efficient use of management vessels.

The reliability of the management system should consider human factors such as experience, training, night-time operations (year-round in some cases), etc. For new operations, reduced performance should be considered with the expectation that performance will improve. Achievement targets should be established and season evaluation of performance should be carried out.

A.17.3.3 Threat evaluation

A.17.3.4 Physical ice management

A.17.3.4.1 Overview

Physical ice management refers to the actual vessel operations that are intended to break up and clear sea ice and/or specific features within an ice cover, and deflect icebergs and small glacial ice masses. At a “high level”, a common perception is that if a vessel can navigate through particular sea ice conditions, it can also offer effective ice management support in like conditions. Another common perception (also at a high level) is that icebergs can simply be “lassoed and towed” by any available support vessel. These ice management perceptions are clearly oversimplifications.

Specific approaches and techniques have been developed for both sea ice and glacial ice management that recognize the capabilities and limitations of the vessels and equipment involved and the ice conditions at hand. Some of the techniques that have been used for sea ice and glacial ice management are described in A.17.3.4.2 and A.17.3.4.3, along with a number of key references where more detailed information can be found.

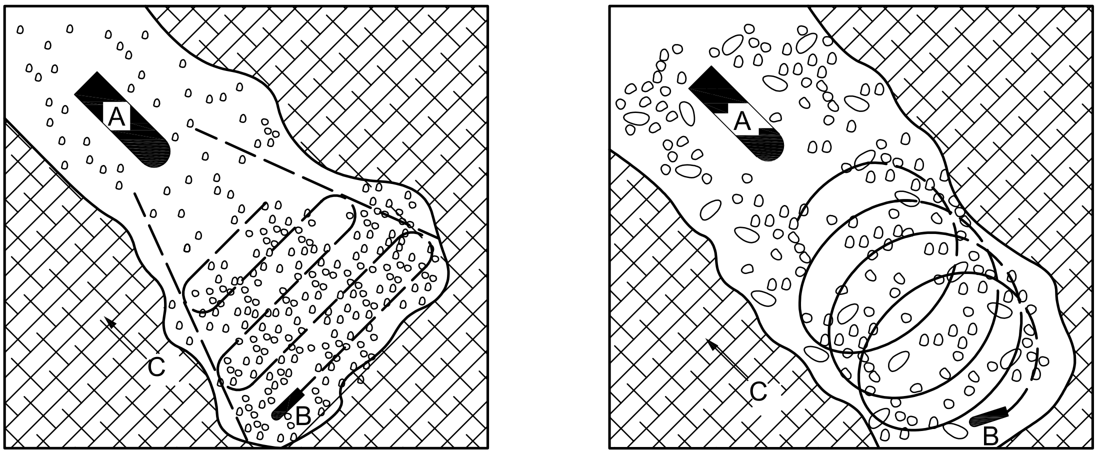
A.17.3.4.2 Sea ice management

The ice management methods illustrated in Figure A.17-3 have been used in various pack ice situations for a stationkeeping vessel (e.g. a tanker on an STL or a DP or moored FPSO) with one ice management support vessel.

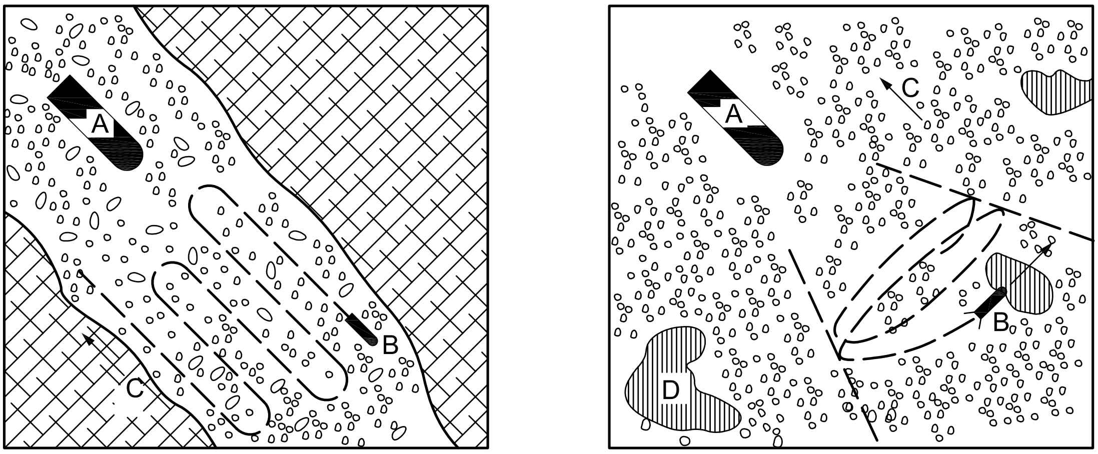
Clearly, the capability of any sea ice management system depends on the number of vessels, their icebreaking performance and tactics, and the particular ice situation at hand. Since it is necessary that ice management vessels aggressively attack the most significant ice features in the sea ice cover, it is necessary that their class be higher than vessels that are intended for normal in-ice navigation during which heavy ice can be avoided. Reference [A.17-8] provides a good discussion of sea ice management.

A.17.3.4.3 Iceberg management

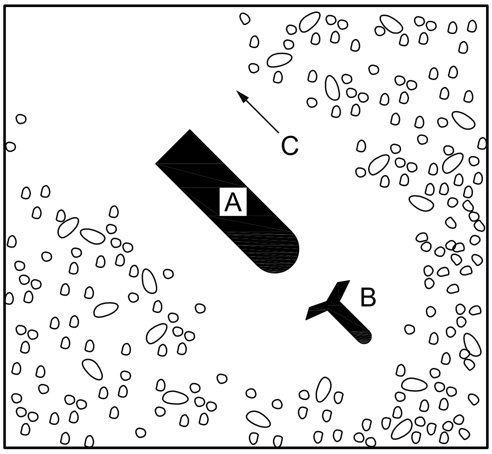
A summary of towing techniques used on the Grand Banks is provided in Reference [A.17-4]. The traditional method for iceberg management is to encircle the feature with a floating rope and tow it with an offshore supply vessel. Towing requires a vessel with minimum 70 tonnes to 140 tonnes bollard pull, a towing winch, a 100 m to 400 m steel towing hawser, and approximately 1 200 m of synthetic floating line or rope. The rope commonly used is braided polypropylene, about 11,5 cm in diameter, and generally deployed in two to three sections each 400 m to 500 m long. The encircling and hook-up procedure as well as the final configuration are shown in Figure A.17-4, and a profile view of the final configuration is shown in Figure A.17-5.



a) Sector technique **b) Circular technique**



c) Linear technique **d) Ice pushing technique**

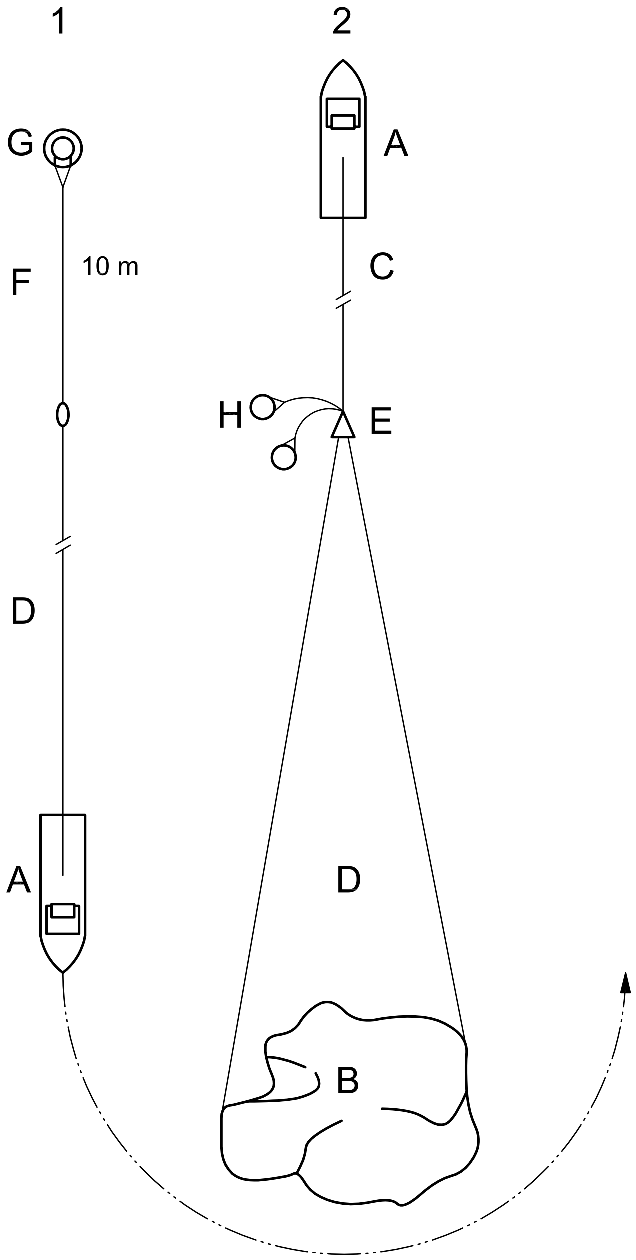


e) Stationary technique

Key

A	tanker or FPSO	C	ice drift direction
B	ice management vessel	D	potentially hazardous ice feature

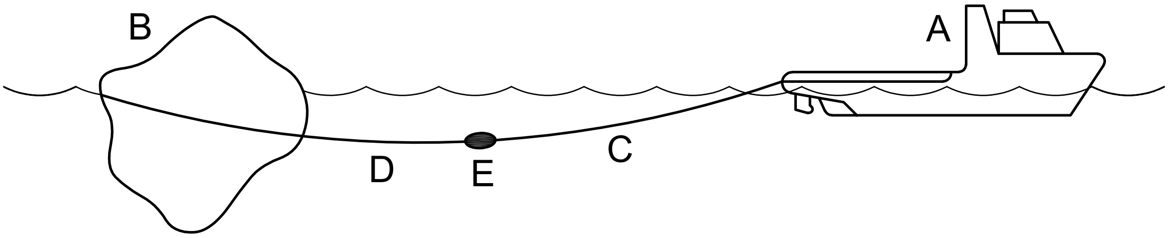
Figure A.17-3 — Schematic of sea ice management techniques[A.17-8]



Key

1	towline connection	D	floating towline
2	towing configuration	E	junction assembly
A	towing vessel	F	tagline
B	iceberg	G	marker buoy or light
C	steel towing hawser	H	marker buoys

Figure A.17-4 — Schematic showing single-line hook-up and towing configuration[A.17-4]



Key

A	towing vessel	D	floating towline
B	iceberg	E	junction assembly
C	steel towing hawser		

Figure A.17-5 — Profile schematic of single towline configuration[A.17-4]

With single-line techniques, smaller icebergs can be towed along a prescribed path. Time and resources permitting, such icebergs can be towed well downstream of the structure but towing beyond the closest point of approach is generally sufficient. For larger icebergs, the objective is to deflect the ice mass by a few degrees from its natural path.

Single-line techniques do not always provide acceptable success rates. For bergy bits and growlers, water cannon and prop-washing techniques are often used. For small icebergs that are difficult to tow, specially designed nets have proved useful. For large and very large icebergs, two or multiple vessel towing configurations have been used in the past and should be available, particularly where there is a risk of very large tabular features.

A.17.4 Ice management planning and operations

A.17.4.1 Scope of ice management plan

To get a more detailed understanding of the scope for an ice management plan, reference can be made to documentation that has been submitted as part of the approval process for various offshore activities, along with various regulatory guidelines. Several examples include

- National Energy Board (NEB) Requirements for Physical Environmental Data Acquisition for Drilling and Production Operations on Canadian Frontier Lands;
- the Kulluk Drilling Program Approval Submission from 1991 (located in the National Energy Board library in Calgary, Canada);
- the Terra Nova Field Development Project material (located in the Canada-Newfoundland & Labrador Offshore Petroleum Board (C-NLOPB) library in St John's, Canada);
- the White Rose Field Development Project material (located in the C-NLOPB library in St John's, Canada).

A.17.4.2 Ice events, threat evaluation and decision-making

The WMO ice terms and classifications[A.17-9] provide definitions for ice features and events that can be used in the ice management plan.

With regard to ice alert systems, the following type of “alert time” calculations should be considered. This example is for drilling operations from a fixed structure, where evacuation can be one of the appropriate response measures. The hazard alert time, t_{HAT}, is the difference between the arrival time, t_{AT}, of the hazardous condition and the time to secure the well, t_{ST}, plus the evacuation time, t_{ET}, plus a margin, t_{MT}, for unforeseen events (up to the discretion of the operator, backed up by a risk assessment). Response measures are initiated for specified values of t_{HAT}, as given by Equation (A.17-1):

$$t_{\mathrm{HAT}} = t_{\mathrm{AT}} - \left(t_{\mathrm{ST}} + t_{\mathrm{ET}} + t_{\mathrm{MT}}\right) \qquad \text{(A.17-1)}$$

A.17.4.3 Support vessel requirements

No additional guidance is offered.

A.17.4.4 Continued implementation of ice management plan

The continued updating and maintenance of any ice management plan are a requirement for the prudence of ongoing operation. Equipment and well trained and experienced ice management personnel should remain available for service over the design service life of a project. This is not necessarily easy, given the turnover in trained marine crews. In this regard, succession plans are an important aspect.

A.17.4.5 Maintenance of ice management plan

No additional guidance is offered.

A.18 Escape, evacuation and rescue

A.18.1 General

A.18.1.1 Performance standard

A performance standard is the operator's specification of a solution for achieving a given performance goal. The performance standard is set by the operator and constitutes the basis of the operator's argument that safety goals can and will be met. It is a verifiable statement of the performance required of the equipment, procedure or system. Performance standards should be cast in terms of a relevant measure or measures, such as reliability, functionality, availability, survivability, independence, time or distance. They should manifestly contribute to the overall goal of reducing the risk of harm.

Each standard should provide a basis for monitoring and maintaining the requisite fit for purpose performance of the equipment, procedure, or system throughout the design service life, and should account for the specific circumstances particular to the installation and its operation.

The broad performance goals of the EER system are

a) to afford adequate means for personnel to protect themselves while escaping potential hazards posed by credible incident scenarios;

b) to afford adequate means for personnel, including injured personnel, to abandon the installation in a controlled manner;

c) to afford adequate means and support for the rescue of personnel.

A.18.1.2 EER terms

A.18.1.2.1
performance-based standard
standard that defines in qualitative and quantitative terms the specification of the requirements of safety-critical systems and their elements

A.18.1.2.2
hazard
set of conditions in the operation of a product or system with the potential for initiating an accident sequence that can lead to injury, environmental and/or property damage or any combination

A.18.1.2.3
hazard zone
largest possible area within which personnel safety is at risk due to the installation hazard

A.18.1.2.4
risk
combination of the probability that a specified undesirable event will occur combined with the severity of the consequences of that event

A.18.1.2.5
duty holder
individual, legal entity or organization holding legal title to the equipment or process and accountable for the safety and welfare of all associated personnel

NOTE The duty holder is also referred to as “owner”.

A.18.1.2.6
major accident
an event with potential for multiple personnel casualties, significant environmental damage, installation failure, or any combination of these consequences

A.18.1.2.7
escape route
normally available and unobstructed route from all locations where personnel can be present on the installation to the temporary refuge or alternative protected muster point

A.18.1.2.8
precautionary evacuation
controlled means of removing personnel from the installation prior to an uncontrolled or escalating incident that can otherwise dictate an emergency evacuation

A.18.1.2.9
preferred means of evacuation
method of choice for evacuating personnel based on the lowest risk and on the familiarity, frequency of use, availability and suitability for prevailing conditions

NOTE Normally, this is the method used to transfer personnel to and from the offshore location.

A.18.1.2.10
primary means of evacuation
method of evacuation that can be carried out in a controlled manner under the direction of the person in charge and the **preferred means of evacuation** (A.18.1.2.9) of the installation in an emergency

A.18.1.2.11
secondary means of evacuation
controlled means of removing personnel from the installation, which can be carried out independently of external support

A.18.1.2.12
tertiary means of evacuation
method of leaving the installation that relies heavily on an individual's own actions, is used when the primary and secondary methods are not available, and has an inherently higher risk

A.18.1.2.13
survival craft
marine craft that is used by installation personnel to evacuate to the sea or ice and provides evacuees with protection from the incident and the environment

NOTE This is a generic term.

A.18.1.3 Injury and survival

The escape, evacuation and rescue (EER) system should be designed such that there are no additional casualties beyond those that arise during the initial incident. The EER system should be addressed as part of the health, safety and environment (HSE) case.

A casualty in the context of EER is an injury or fatality resulting from an accident that occurs during EER, where the probability of occurrence can be reduced by informed decision-making. If a casualty relating to EER occurs, improved design and/or procedures should be implemented.

The “no injuries to personnel” provision applies to the period between first warning and all personnel reaching a place of safety. It does not refer to major accident-related casualties.

The “no injuries to personnel” provision applies during EER and is one of many criteria that it is necessary to include in performance standards for the installation's safety-critical elements and that should be included as part of the EER system “goal”.

It is, then, the responsibility of the asset owner/duty holder to demonstrate that the risks have been reduced to ALARP, thereby demonstrating a good prospect of avoiding a casualty during EER.

A.18.2 EER philosophy

A.18.2.1 General

An example of the hierarchy, or taxonomy, governing emergency response documents as described in the International Standards relating to emergency response is shown in Figure A.18-1.

NOTE 1 Examples of global emergency response standards include ISO 15544[A.18-1], ISO 17776[A.18-2] and ISO 13702[A.18-3].

NOTE 2 This emergency response taxonomy is made up of operator, corporate and facility-specific standards.

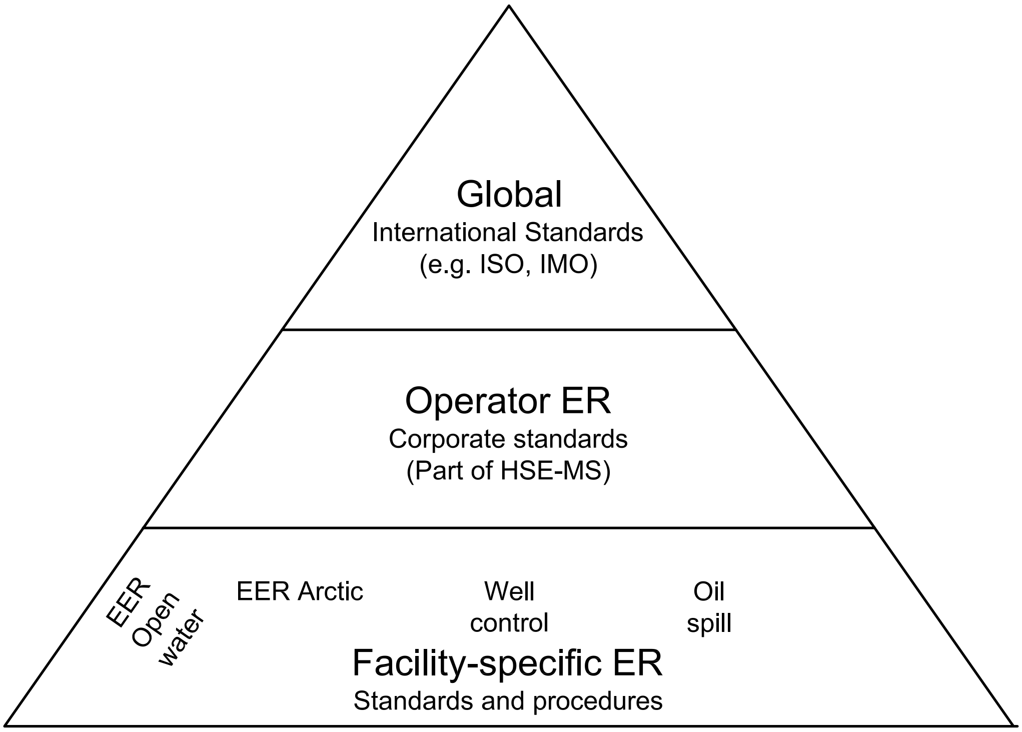


Figure A.18-1 — EER taxonomy

A.18.2.2 EER governing principles

A.18.2.2.1 Statement of principles and breakdown of components

The first governing principle is that the system for managing EER be designed and implemented using a systematic approach. This concept is illustrated in Figure A.18-2 in terms of an EER triangle having three main components: hardware integrity, personnel competence, and EER procedures and controls. These components play an equally important part in the design and operations phase of the EER system for an arctic or cold region hydrocarbon facility.

The second governing principle is that of continuous improvement process and assessment. This involves not only a static phase of designing the EER hardware system to meet EER performance criteria, but also a dynamic phase demonstrating continuous assessment and improvements. This latter aspect requires that the operator demonstrate that a performance-based improvement process is in place and that it can be verified via benchmarked industry data.

The three components shown in Figure A.18-2 are part of a continuous assessment process with respect to environmental condition preparedness and other risks that can be implemented as part of the overall HSE management system. The three principal components of the EER process are described in A.18.2.2.2 through A.18.2.2.4.

A.18.2.2.2 Hardware integrity

EER system development (and related minimum standards) starts with the hardware design components, such as escape routes, the temporary refuge, evacuation methods and other systems. The equipment should be adequately designed in compliance with EER system performance standards and maintained to meet the expected environmental, operational and emergency conditions.

A.18.2.2.3 Personnel competence

The second principal component that should be developed in parallel with the hardware design relates to EER personnel competence requirements. These should be defined up-front to allow for timely EER safety training, and for the development and assessment of critical roles and responsibilities of the EER chain of command. Personnel should be trained and organized to deal with the expected environmental operational and emergency conditions. Information regarding each deployment, training exercise/drill, inspection and maintenance activity should be documented in the installation's log.

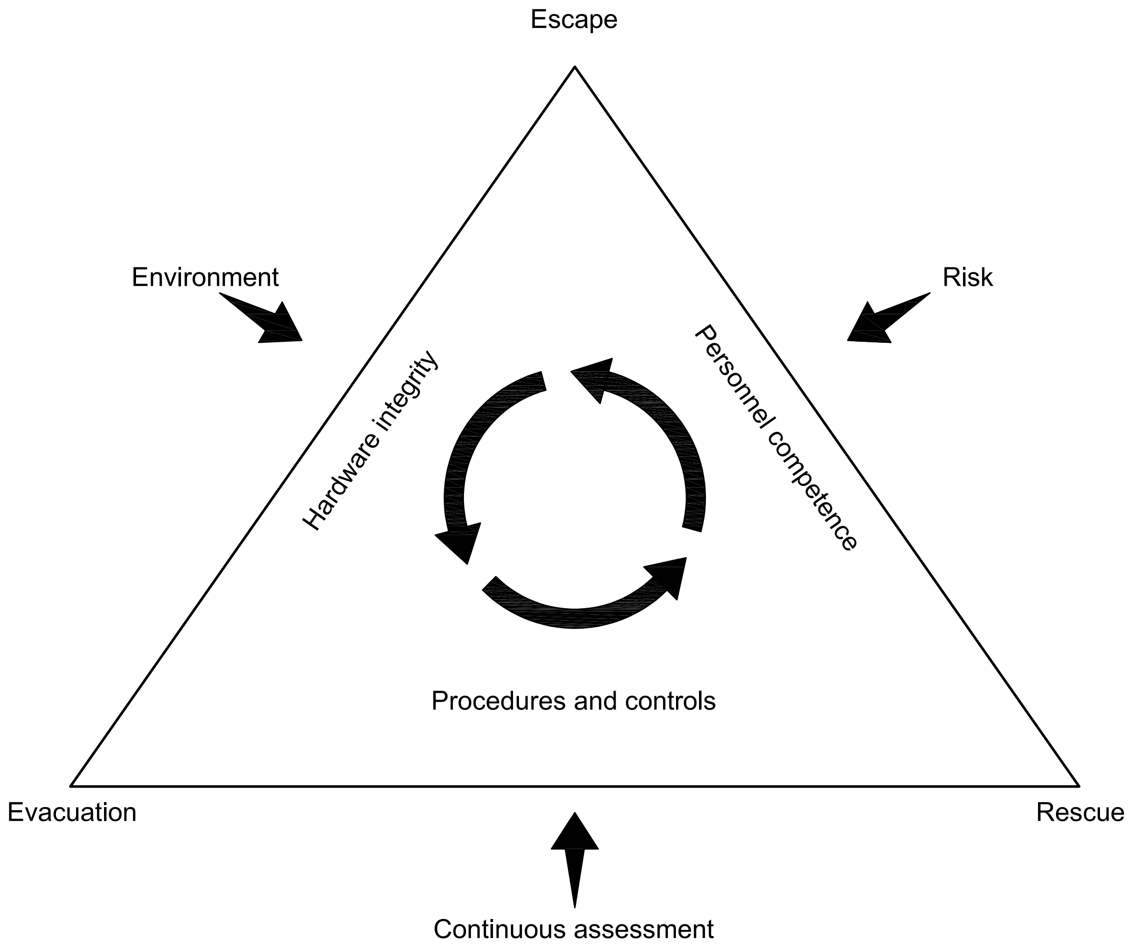


Figure A.18-2 — Schematic of the EER philosophy for hydrocarbon facilities

A.18.2.2.4 Procedures and controls

The third EER component relates to the timely development of EER procedures and controls to complement the hardware integrity and personnel competence components. Typically, these cover EER mustering procedures, communications requirements, EER scenario developments and related emergency drills, etc. Once in the operations phase, they also cover EER integrity maintenance procedures to address both hardware and maintaining personnel competence. These procedures should be designed for the range of expected conditions.

It is important to appreciate that all three of these components should be applied to each part of the EER triangle well in advance of the beginning of each distinct project phase, including simultaneous operations. Resultant procedures should be in place, checked and tested prior to personnel working offshore during any/all phases of the facility's design service life: initial survey, construction, commissioning, operation, decommissioning and abandonment. They form an integral part of the EER statement of operational readiness. These EER principles and principal components are normally captured in the facility-specific HSE case, typically containing a section describing the facility risk analysis and mitigation, the HSE critical roles and competency requirements, etc.

In certain operating regions, arctic and cold conditions are prevalent only at certain times of the year. EER elements (hardware, people, procedures and controls) should, therefore, also be developed to meet the requirements of non-arctic periods.

A.18.3 EER strategy

No additional guidance is offered.

A.18.4 Environment

A.18.4.1 General

The physical environment of arctic and cold regions can profoundly influence EER aspects. The relevant physical environmental conditions should be considered in the development and deployment of an EER plan. Guidance on factors for consideration in developing an EER system for an arctic structure in ice-covered waters is provided in A.18.4. Further guidance on selecting, designing and maintaining marine equipment for arctic and cold region operations is contained in Reference [A.18-4].

Conditions include the following environmental factors:

a) air temperature and wind chill, including the effects of material embrittlement, winterization and cold weather starting of mechanical and hydraulic systems, personal protection, reduced manual dexterity and the associated requirement for good ergonomic design for operation of exposed controls while wearing protective cold weather clothing;

   Either the ergonomics and human factors design can account for personnel wearing bulky arctic clothing or the clothing can be designed to be less bulky but still provide the wearer with adequate warmth. Lubricants, fuels and hydraulic fluids should be selected to suit the expected minimum temperature. Engines should be able to handle the additional demands of cold temperature starting (pre-heaters, high capacity batteries). Cooling systems (radiator and/or seawater) should be designed to prevent blockage from the freezing of inlets. Low temperatures also dictate that personnel should wear suitable warm clothing and footwear, which make movement more difficult. Face and head protection can impair communications. Operating machinery with heavy gloves can be difficult and sometimes impossible if the controls are not designed properly.

b) full range of natural daylight anticipated, including effects such as adequate lighting and good visibility for EER systems;

c) wind, including the effects of poor visibility for personnel on board and flying, surface mobility, personal protection and frostbite danger;

d) sea spray and atmospheric icing, including effects such as safe footing, escape route integrity, access to evacuation equipment, protection of critical mechanical components, frozen latches, small vessel stability, helicopter operations and deck operations;

e) visibility, including the effects of blowing snow, fog, ice mist, which affect flying conditions and local visibility due to parka hoods;

f) cold open water, including the effects of personal survival (potential for rapid, acute hypothermia without suitable survival suits), escape system performance and sea state limits on the reliability of evacuation and rescue systems;

g) ice-wave combinations, including effects of degraded EER system reliability where waves can impart substantial energy to small ice pieces (for example, the risk of impact and subsequent loss of structural integrity of a survival craft);

h) local residual, wind-driven and tidal currents, including their effect on the selection and implementation of an effective water motion and ice drift tracking model to support SAR operations;

   Issues include the difference in drift rate between immersed and ice-borne survivors, and that of deep draught ice features responding to currents at depth and surface winds.

i) ice conditions affecting the choice of evacuation systems and the potential availability of other options including, for example, the use of a stable ice cover at certain times of the year to serve as an intermediate place of safety or to support survival craft, if part of the evacuation strategy. Several factors related to the ice affect the reliability and performance of different evacuation systems. Survivability both in the water and on the ice surface should be taken into account for the escape systems. Several factors affect the type of EER system that can be used in different ice conditions including the following.

   - Ice concentration: ice concentration can have an impact on the evacuation and rescue systems used. Some systems can benefit in different ways from low, medium or higher concentrations, and certain systems can perform better at some ice concentrations than at others.

   - Ice speed: highly dynamic ice conditions can be the most challenging. For example, rapidly moving floes can interfere with launching survival craft. On the other hand, high drift speeds can aid in the rapid movement of survivors away from the platform. The ability to accurately predict ice drift is an important factor in planning and executing an effective SAR operation in arctic and cold regions.

   - Ice thickness: new, thin ice generally presents fewer problems but also precludes any consideration of direct evacuation onto the ice surface. Thick ice generally presents many challenging issues for small survival craft as well as powerful standby vessels. On the other hand, in some cases, thick ice can be used to support an evacuation craft or to provide a temporary refuge.

   - Ice type: some arctic and cold regions have a mix of first-year ice, second-year ice and multi-year ice. Old ice floes can be considerably stronger and thicker than first-year ice, and can affect the integrity of survival craft as well as the stationkeeping capability of icebreaking vessels. On the other hand, such floes can also be used as a stable platform for survivors.

   - Floe size: the size of the ice floes is important. Large thick floes (hundreds of metres in diameter) can offer places of refuge, while dynamic small floes in combination with high sea states and swell can threaten the stability and structural integrity of small survival craft.

   - Ice roughness: the roughness of the ice can create problems with over-ice mobility. This can be critical if it is required that survivors evacuate through ice rubble to reach a standby rescue vessel. Thick, rough ice can also prevent a standby vessel from approaching a platform for direct survivor recovery. Rough pack ice can provide additional problems for stationkeeping of standby vessels.

   - Ice pressure: internal pressure in the ice sheet can significantly affect the ability of survival craft to move away from the platform or make any headway. Severe pressure can result in overturning and potential destruction of a small survival craft.

   - Ice-wave conditions: in low ice concentrations, waves or swell can cause additional complications in launching a survival craft into the sea. Small floes can also compromise the integrity of survival craft, e.g. the wave energy combined with small ice fragments can create potentially high local impact loads.

   - Spring melt: this situation can introduce a number of evacuation issues depending on the type of evacuation system chosen. Mobility on the ice is severely curtailed by melt pools and open holes, and the ice surface can become too dangerous to consider direct evacuation as an option.

A.18.4.2 Environmental conditions

Competent decision-making through continuous EER assessment depends in part on access to accurate and timely meteorological, ocean and ice data.

Relevant existing codes and publications containing detailed requirements specific to cold water and arctic lifesaving and survival equipment, including immersion suits, and the impact of environmental conditions on the selection of equipment include Reference [A.18-5], ISO 15027[A.18-6] and Reference [A.18-7]. Additional guidance can be found in References [A.18-8] and [A.18-9].

A.18.5 Hazard and risk analysis

A.18.5.1 General

EER is a system designed to mitigate the effects of major accident hazards to personnel. The system begins with the earliest indication of a potential hazard, and ends when the hazard has been removed or when all personnel have been rescued and reach a place of safety.

The risk analysis process identifies hazards, assesses the frequencies and consequences and identifies adequate preventive, detection, control and mitigation measures. This is commonly referred to as the hazard and effects management process. The purpose of such analyses is to assess the design at key stages and the changes that can be proposed and to demonstrate that the overall design has reduced risks to personnel to a level at least as low as reasonably practicable (ALARP). Figure A.18-3 provides an example of the steps and sequence involved, and the relationships throughout the design process.

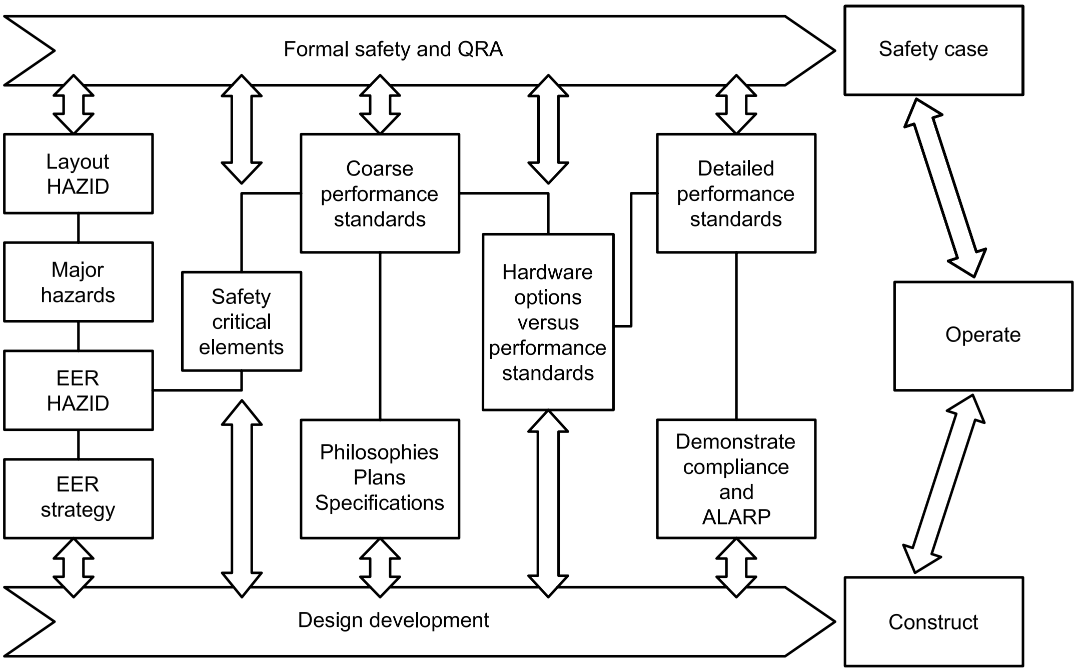


Figure A.18-3 — Process to achieve a performance-based EER system

Risk analysis should consider consequence scenarios and effects on marine activities. This can include: flotels, barges, standby vessels and any other structure or vessel that can be exposed to the installation hazards. Appreciating the area of the hazard zone and how this can change is fundamental to establishing an appropriate EER system.

EER performance standards define installation/location-specific criteria against which hardware and procedural options should be evaluated for compliance, during design and throughout the design service life of the installation. The EER design should be an integral process within and throughout the installation concept and detailed design phases to minimize personal risk during EER and reduce the likelihood of lost cost and schedule opportunities. The performance standards criteria are verifiable attributes or benchmarks that provide qualitative levels and/or quantitative measures of performance to be achieved. It is important to recognize that compliance with prescriptive regulations is not necessarily sufficient to ensure compliance with performance standards.

A written procedure for examinations that includes the EER system should specify the nature and frequency of the examination and, where appropriate, should provide for carrying out an examination prior to the equipment being used or after modification or repairs. These requirements can also be stated in the performance standards.

Provisions for life-safety appliances (LSA) can vary among installations as a function of their exposure to low temperatures, etc. The purpose of examining a life-saving appliance is to

- assess its suitability from the outset and its use in compatibility with other LSA or its continued suitability;
- assess its condition;
- determine any necessary remedial measures.

This is necessary to demonstrate that the most appropriate system components, procedures and support services have been selected to comply with the EER system performance standards and ALARP principles.

Timely implementation of any EER system recommendations, i.e. HAZID actions, within the appropriate phase and the demonstration thereof, is an important factor that is often underestimated and that requires special attention in arctic and cold region applications.

A.18.5.2 Hazard identification

Representatives from the key disciplines involved in EER should participate in HAZID studies. Where applicable, this includes operations, marine, aviation, evacuation and response specialists, ice advisors, etc. Wherever an interface exists, relevant representatives should be engaged.

Where risks are assessed to fall within the unacceptable region of a risk assessment matrix, redesign is necessary.

The assessment process should consider new technology and research into new and innovative methods of evacuation that can be more reliable and appropriate for arctic and cold regions than the conventional equipment currently available.

Techniques that can be used to support decision-making and to demonstrate adherence to ALARP principles include

- quantitative risk analysis (QRA);
- emergency system survivability analysis;
- consequence modelling/analysis;
- event trees (e.g. probabilistic logic networks for systematically deducing the probabilities of different outcomes from the occurrence of a given undesired event);
- consequence analysis (e.g. smoke and gas ingress analysis, gas plume dispersion analysis, fire and explosion risk analysis).

Appropriate techniques for optimizing EER design include three-dimensional modelling of consequences and escape/evacuation simulations.

In a QRA, both the frequency of an event and its consequences are quantified using appropriate techniques. QRA can be a useful tool to

a) identify which of the major accident hazards contribute most to the risk;

b) establish specific EER system components that have a safety-critical function to perform during particular emergency scenarios;

c) estimate the contribution of a proposed risk-reduction measure.

The results of the QRA for a particular set of EER system components are compared with the results using different components for the same installation events. The results of a QRA are normally coupled with a cost-benefit analysis, the inferred cost for averting a fatality and the frequency of temporary refuge impairment to determine whether a proposed risk-reduction measure (e.g. by applying new technology or additional evacuation methods) is justified. The outcome of a QRA process provides input to the EER performance standards.

A.18.5.3 Risk analysis

A.18.5.3.1 Risk analysis for escape

The layout and location of a specific offshore installation plays a major role in influencing the results of escape analysis.

Aspects for consideration include, but are not limited to:

- escape route impairment scenarios (e.g. ice, blowing snow, reduced visibility, cold temperatures, heat, toxic gas, smoke, explosion propelled and collapsed equipment);
- availability of protected/unaffected alternative routes to protected temporary refuge (TR) muster station;
- personnel distribution and locations at the time of the incident;
- mobilization time;
- travel time, vertical and horizontal ladders, stairs, level walkways, allowing for effects of low temperatures, icing, stability, dexterity, clothing, etc.;
- width of escape routes relative to personnel locations and possible bottlenecks causing congestion;
- time to muster all personnel, including an allowance for assistance to injured persons and for the level of personnel training;
- TR integrity, including fire resistance, structural integrity and air supply;
- integrity of the main TR support structure;
- boundary protection, suitably rated fire walls, blast walls, heating ventilation and air conditioning (HVAC) dampers;
- appropriate life support for mustered personnel for a maximum duration, giving due consideration to external dependencies;
- availability and locations of personal protective equipment/abandonment facilities;
- human factors, including physiological effects on error rate and the ability to perform functions under stress;
- process controls and hazard status monitoring and communication;
- communication with the command and control centre and support services;
- command and control, availability of necessary organizational emergency response structure when it is required.

A.18.5.3.2 Risk analysis for evacuation

A.18.5.3.2.1 Types of evacuation

Evacuation method(s) and process(es) should be selected as a function of the risk level. The capability of the system to satisfy performance standards should be analysed from the earliest warning of a potential incident (giving time for precautionary evacuation) to loss of control that threatens personnel safety (resulting in emergency evacuation).

A.18.5.3.2.2 Precautionary evacuation

Where prior warning of a potential incident is available, precautionary evacuation of non-essential personnel should be considered to reduce/remove exposure to the hazard. The operator should demonstrate that risks to evacuees during a precautionary evacuation are no greater than if they were to remain on the installation. The removal of personnel at this time is also referred to as precautionary down-manning. The most reliable means of evacuation available should be used during a precautionary evacuation. It is expected that this be the preferred means.

The risk analyses necessary to demonstrate the appropriate selection of precautionary evacuation method should include, but not be limited to, the following criteria:

- time estimated for a potential incident to lead to an emergency evacuation;
- time available to mobilize the evacuation method;
- time to effect the evacuation;
- determination of non-essential personnel that should be evacuated;
- travel distances to rescue platforms or safe havens;
- environmental conditions (weather, ice, ocean) prevailing and forecast, during the evacuation and rescue period;
- means available for embarkation and transfer of personnel;
- human factors, including personnel training;
- ability to transport evacuees beyond the maximum potential hazard zone.

A.18.5.3.2.3 Emergency evacuation

When there is an imminent danger to the installation personnel, an emergency evacuation should be carried out.

The risk analyses necessary to demonstrate the appropriate selection of emergency evacuation method(s) are likely to include, but are not limited to, consideration of the following criteria:

- preparations to evacuate while inside the TR, including assessment of personnel condition, accident hazards, prevailing and forecast environmental conditions, and proximity and availability of a rescue platform and/or place of safety;
- awareness of developing/changing hazard zone consequences during the evacuation process;
- protection of the installation evacuation route from the TR to the primary evacuation system(s);
- suitability of evacuation method and its compliance with performance standards (functionality, availability, reliability, survivability and inter-dependencies with other systems);

- embarkation times and sequencing relative to the location of personnel and the provision of assistance to injured personnel;
- distribution of personnel, their behaviour in the range of scenarios relative to the capacity of available systems;
- human factors under stress, including level of emergency training;
- stretcher access, casualties, access to medical support after leaving the TR during evacuation and for transfer to a rescue platform;
- effects of motion sickness on performance;
- capability of evacuation method in prevailing low temperatures and ice environments;
- transit visibility, collision risks at night, etc.;
- launch and departure route from installation to rendezvous points with rescue platforms.

A.18.5.3.3 Risk analysis for rescue

The rescue (and transfer) process commences when the evacuation has moved beyond the installation hazard zone. Rescue includes the survival and recovery of personnel directly from the sea and/or the ice surface, retrieval/transfer of survival system with persons on board either from the water or directly from the ice to a rescue platform. Rescue operations are considered complete when evacuees have reached a designated place of safety.

The risk analyses to evaluate the reliability and performance of available rescue and recovery methods should include the following criteria:

- environmental (weather, sea state and ice) limitations on performance of rescue and recovery craft and associated recovery aids (air and surface);
- abilities, including levels of training, of evacuees and rescue platform personnel;
- capacity and suitability of rescue platform (number of transfers, ability to operate inside incident hazard zone);
- time from evacuation to completion of rescue;
- rescue system search times, with associated limitations from low visibility and weather conditions;
- reliability of communications links between evacuees and the rescue platform or search system, including the accuracy of locator methods;
- levels of medical support (triage facilities) on rescue platform;
- facilities for stretcher recovery to the rescue platform;
- risk to rescue platform crews under prevailing ice and weather conditions (inter-dependencies with other systems);
- mortality curves versus personal protective equipment/rescue times for specific evacuation system.

A.18.6 Continuous assessment

A.18.6.1 Overview of continuous assessment

Continuous assessments help to ensure that, regardless of changes that can occur, compliance with the EER performance standards is maintained.

To validate the EER state of readiness, a simple “Yes (✓) No (X)” approach can be used to reflect the assessment and the state of readiness of these EER elements, as shown in Figure A.18-4.

Continuous assessment & improvement processes

	EER state
Environment (ice and metocean forecasting)	☑ or ☒
Risk analysis & mitigation (manual of permitted operations, EER matrix)	☑ or ☒
Hardware integrity (design, maintenance, winterization)	☑ or ☒
Personnel competence (training, drills, POB management)	☑ or ☒
Procedures and controls (communication, alarms, chain of command)	☑ or ☒

Figure A.18-4 — Illustration of the continuous assessment and improvement process for EER systems

This assessment encompasses the supporting processes as given in A.18.6.2 through A.18.6.6.

A.18.6.2 Environment

As discussed in A.18.5, part of the EER system controls is the development of an appropriate ice, metocean and environmental forecasting process. The forecasting process is used to assess external influences on the EER system performance to ensure that the EER design parameters are within the EER operating envelope. It is a continuous process, which includes providing regular updates on relevant parameters to the offshore installation manager (OIM), who is ultimately accountable for EER decision-making, command and controls.

A.18.6.3 Risk

Risk is the second external parameter impacting the EER assessment. A risk analysis should be initiated during the early part of the engineering design phase by the identification of the major installation (process) risks. Part of this risk assessment process is to identify mitigation measures such as can be required to achieve an ALARP condition. To maintain this ALARP condition and to form part of the EER process, guiding controls should be developed and put in place. This includes the development of a manual of permitted operations, preferably complemented by EER system selection criteria, in order to ensure continuous assessment by the OIM in the EER decision-making process. In other words, risk assessment is not a one-off process in design, but a recurring assurance process as part of the EER decision-making that contributes to or defines the state of preparedness.

A.18.6.4 Hardware integrity

Once the facility hardware (including the EER system) has been designed and constructed and is ready to operate, the design integrity requires that it be safeguarded to remain within the envisaged integrity envelope, regardless of the external environmental conditions. The EER system design should be complemented with the required routines for preventive maintenance. In the operations phase, timely execution of these preventive maintenance routines on the EER system, which should be classified as safety critical, is mandatory.

A.18.6.5 Personnel competence

Once EER personnel competence requirements have been defined (including the HSE critical tasks), a training and development programme should be implemented. Part of this training programme is the competency assessment of people, specifically those with HSE critical responsibilities such as the OIM, before their assignment to the installation. Medical/physical qualifications should be established for personnel assigned to arctic offshore facilities commensurate with their operational and EER responsibilities. A safety logbook can be established to record this HSE training and assessment. To remain competent, regular EER emergency scenario drills and exercises are required.

A.18.6.6 Procedures and controls

The EER system procedures and controls, as developed in the design phase, should be regularly reviewed for fitness and compliance using regular audits. These procedures typically include the assignment of EER system integrity accountability to an individual, establishment of an EER chain of command and the listing of HSE EER critical tasks. These are normally included in the installation HSE case. Regular emergency scenario exercises are critical in training and establishing the necessary state of readiness or preparedness of the facility and its personnel. Part of the EER HSE management system is the personnel on board (POB) locator system (e.g. a T-card or more advanced electronic tracking system). This helps ensure that adequate POB controls, including mustering, are in place.

A.18.7 EER system design

Account should be taken of the range of credible combinations of environmental conditions expected at the installation, including air and sea temperatures, winds, waves, currents, marine ice, icebergs and visibility. The design of the structure and its integrity for process operations takes into account those elements that can impact the EER system and how this compromises selection of the optimum EER components:

- whether or not the installation is normally manned, the expected peak and average manning level, shift schedule, personnel locations and crew changes; and visitation frequency and details if not normally manned;
- major accident scenarios and their effect on the EER system as identified in the installation risk assessment, including fire, explosion, toxic emissions, major structural failure, ship or iceberg collision, and other loss of essential support facilities;
- possible hazards to personnel in the scenarios considered, accounting for hazards at all potential personnel locations;
- measures to prevent the impairment of the EER system;
- location and integrity of muster areas and/or temporary refuges (TRs), routes to these and alternative muster points and from these to protected/unimpaired evacuation points;
- time required for personnel to escape from their workplace to the TR and to move from the TR to evacuation points under the credible emergency scenarios, taking into account the range of weather and environmental conditions;
- time required for installation personnel to evacuate;
- contingency plans, including the use of alternative muster points and evacuation methods;
- methods employed and times required to transfer from the primary, secondary or tertiary means of evacuation and to deliver the personnel to safety;
- immersion suits and other personal protective equipment required, as well as their numbers and locations on the installation, which should be appropriately located and specified to provide maximum protection against scenario hazards and environmental conditions;

- schedule and procedure for EER equipment maintenance, inspection, testing and operational drills to assure familiarity, reliability and availability in accordance with performance requirements;
- design of equipment to facilitate easy operation in cold conditions, with the aim of avoiding small or complicated equipment;
- schedule and procedure for personnel EER training, drills and major EER exercises commensurate with HSE critical roles;
- effect of stressors on human performance in EER;
- coordination with external emergency response support and communication during EER process.

Once the safety-critical element has been identified, it is necessary to define its critical function in terms of a performance standard. Based on the performance standard, assurance tasks can be defined in the maintenance system to ensure that the required performance is confirmed.

A performance standard can be applied to persons and procedures as well as hardware systems and items of equipment.

Examples of emergency response and lifesaving appliance related safety-critical elements plus a performance standard template are provided in Tables A.18-1 to A.18-3.

Table A.18-1 — Example of safety-critical element groups — Emergency response

Safety-critical element		Safety/environmental hazards														SCE role
Emergency response		Structural failure	Ship collision	Mooring failure	Dropped object	Loss of stability	LoC – Fire	LoC – Explosion	LoC – Haz substance	Vehicle/helicopter collision	Diving system failure	Subsidence	Soil/groundwater pollution	Seawater/river pollution	Air pollution	
ER001	Temporary refuge/ primary muster areas	✓	✓	✓	✓	✓	✓	✓	✓	✓	—	—	—	—	—	To provide a safe refuge, a place to muster and/or implement emergency procedures following an incident.
ER002	Escape and evacuation routes	✓	✓	✓	✓	✓	✓	✓	✓	✓	—	—	—	—	—	To allow escape and evacuation of personnel following an incident.
ER003	Emergency/ escape lighting	✓	✓	✓	✓	✓	✓	✓	✓	✓	—	—	—	—	—	To illuminate escape way routes following an incident.
ER004	Communication systems	✓	✓	✓	✓	✓	✓	✓	✓	✓	—	—	—	—	—	To provide means of communication during an incident and to coordinate emergency response.
ER005	Uninterrupted power supply (UPS)	✓	✓	✓	—	✓	✓	✓	✓	✓	✓	—	—	—	—	To ensure power supplies to essential services during an incident.
ER006	Helicopter facilities	✓	✓	✓	—	✓	✓	✓	✓	✓	—	—	—	—	—	To provide facilities to ensure safe helicopter operations and to avoid or mitigate the effects of a helicopter collision.
ER007	Emergency power	—	—	—	—	—	✓	✓	✓	✓	✓	—	—	—	—	To provide power to essential users and aid recovery from a major accident in the event of loss of main power.
ER010	Open hazardous drains system	—	—	—	—	—	✓	✓	✓	—	—	—	✓	✓	—	To remove a flammable or hazardous liquid inventory in a controlled manner to a safe location following a release.
ER011	Open non-hazardous drains system	—	—	—	—	—	✓	✓	✓	—	—	—	✓	✓	—	To prevent toxic or flammable gas migration to a non-hazardous area following a release.

NOTE SCEs for EER are included below as part of emergency response in this example.

Table A.18-2 — Safety-critical element groups — Lifesaving appliances

Safety-critical element		**Safety/environmental hazards**														**SCE role**
Lifesaving appliances		**Structural failure**	**Ship collision**	**Mooring failure**	**Dropped object**	**Loss of stability**	**LoC – Fire**	**LoC – Explosion**	**LoC – Haz substance**	**Vehicle/helicopter collision**	**Diving system failure**	**Subsidence**	**Soil/groundwater pollution**	**Seawater/river pollution**	**Air pollution**	
LS001	Personal survival equipment (PSE)	✓	✓	✓	—	✓	✓	✓	✓	—	—	—	—	—	—	To increase the likelihood of personnel to escape and evacuate the installation following an incident.
LS002	Rescue facilities – standby vessel	✓	✓	✓	—	✓	✓	✓	✓	✓	—	—	—	—	—	To increase the likelihood of rescue and recovery of persons from the sea.
LS003	Emergency evacuation craft	✓	✓	✓	—	✓	✓	✓	✓	—	—	—	—	—	—	To provide a means of evacuation for personnel from the platform independent of external facilities support.
LS004	Tertiary means of escape	✓	✓	✓	—	✓	✓	✓	✓	—	—	—	—	—	—	To provide a means of evacuation for personnel unable to use helicopter or lifeboats.

Table A.18-3 — Example of performance standard template

(INSTALLATION NAME) OPERATIONS PERFORMANCE STANDARD XXPS-E001		
SAFETY-CRITICAL ELEMENT:	ESCAPE AND EVACUATION ROUTES	
Goal: Goal of the SCE		
FUNCTIONALITY		
Assurance task ref.	Assurance task description	Acceptance (pass/fail) criteria
FUNCTION 1:	Description of function 1	
XXPS-E001-01-01 Assurance task link to maintenance activity	Description of assurance task (maintenance, test or inspection) activity	Details of measurable pass/fail criteria
RELIABILITY/AVAILABILITY		
Assurance task ref.	Assurance task description	Acceptance (pass/fail) criteria
FUNCTION 2:	Safety-critical element availability	
XXPS-E001-02-01	Details of availability requirements	Details of measurable pass/fail criteria
FUNCTION 3:	Safety-critical element reliability	
XXPS-E001-03-01	Details of reliability requirements	Details of measurable pass/fail criteria

Table A.18-3 (*continued*)

(INSTALLATION NAME) OPERATIONS PERFORMANCE STANDARD XXPS-E001		
SURVIVABILITY		
Event	Assurance task description	Acceptance (pass/fail) criteria
Fire & explosion	Details of survivability requirements against fire and explosion	Details of measurable pass/fail criteria
Structural failure	Details of survivability requirements against structural failure	Details of measurable pass/fail criteria
Ship collision	Details of survivability requirements against ship collision	Details of measurable pass/fail criteria
DEPENDENCY		
System	Criticality	Applicable performance standards
Dependency on other SCEs		

A.18.8 Emergency response organization

The station bill should describe the emergency alarms, the chain of command, locations of the temporary refuge and alternative muster points, appropriate leadership for every muster point, and the duties of every individual in each incident scenario.

A.18.9 Competency assurance

Competency assurance should be extended to include all support personnel not based on the installation (e.g. supporting vessel, aircraft and shore base personnel) whose actions are relied upon during emergency response.

A.18.10 Communications and alarms

The audible and visual emergency alarms should be standardized where practicable throughout the operating region.

The audible alarm should be supplemented with visual signals such as flashing beacons in high noise areas.

In addition to the condition of the installation, the process controls and detection systems, any other relevant information required by the OIM to make an informed decision whether and/or how to evacuate the installation should be available to the OIM in the TR.

If hand-held radios are used for communications, they should be fully charged and available for use at every muster station. The requirement for emergency personnel to have intrinsically safe communication devices should be assessed.

Methods of communicating platform status should be standardized where practicable.

A.18.11 Personal protective equipment

PPE configurations, including the numbers, types and storage locations, should be determined as part of the EER strategy. The quantity of personal protective equipment should include those placed in the accommodation module for the maximum POB compliment plus spares deployed at strategic locations on the installation.

The following minimum device types, subject to the EER analysis, should be provided for personnel in sufficient numbers:

- immersion suits, where stipulated by regulation and/or the EER strategy;
- lifejacket (harness type through the legs that do not dislodge if the wearer falls/jumps from a height);
- smoke hood (small maintenance-free bag, not respirator or air pack); the requirement for escape air packs should also be evaluated;
- flashlight.

Deployment locations should include the living quarters and other strategic areas.

If helicopters are used in the EER strategy, transit or immersion suits designed to prevent progressive body cooling are best for use during personnel transfers to and from the installation unless deemed unnecessary by the EER analysis. The amount of suit buoyancy required should also be considered when selecting a helicopter transit suit (egress versus survival).

The design of immersion suits, where required, should consider the requirement for an underwater breathing device to facilitate escape from a submerged helicopter, a wave splash shield to extend survival time and a strobe light, personnel locator and whistle to aid search and rescue operations.

The selection of PPE should take into account performance in freezing water and/or arctic air temperatures for the maximum anticipated survival time.

A.18.12 Man overboard recovery

Depending on the marine and ice environment, man overboard recovery can include a standby vessel (equipped with a fast rescue craft), a fast rescue craft aboard the installation, a marine evacuation craft, or other suitable means as established by the EER analysis.

The installation should be equipped with individual man overboard rescue aids, deployed at strategic locations where a man overboard incident can occur. The numbers of aids with water-activated lights, smoke and retrieving lines should be established as part of the EER analysis.

Where required, man overboard recovery aid designs and locations should account for the effects of sea spray icing, atmospheric ice and snow.

A.18.13 Escape design

A.18.13.1 General escape design

The goal of escape is to ensure that, in an emergency, personnel move to a place of relative safety on the installation, consistent with the specified performance standards.

A.18.13.2 Escape routes

Appropriate design of escape routes should consider the following:

- that sufficient escape routes remain available for the period of time necessary for the personnel to reach the TR or muster station;
- that the design of escape routes and stairways consider the movement of stretchers, rescue and fire fighting teams;

- suitable means for personnel wearing bulky PPE to descend quickly from remote locations such as the top of a drill derrick or flare stack to the main deck escape route;
- escape routes that are straight and horizontal to the extent possible with minimal stairs. Ladders should not be used along main escape routes. External route floors are self-draining or provided with other means to reduce ice build-up. A means is included to remove ice and snow from escape routes when the design cannot preclude its accumulation;
- exits situated as far apart as practicable. Internal room arrangements are evaluated for possible blocking of exits following an accident as well as external blockage to ensure that at least one exit remains available;
- airlock and watertight doors, when remotely operated, equipped with a suitable alarm that activates prior to remote door closing.

A.18.13.3 Temporary refuge

The design of a temporary refuge (TR) should take the following into consideration:

- sufficient capacity to accommodate the maximum permissible number of POB for the entire period in which it is occupied;
- an air supply to the TR taken from multiple locations, with each intake being individually closed upon local smoke or gas detection and protected from environmental effects; oxygen in sufficient quantities and storage modes to assure breathing air supply for the requisite period in fully isolated mode;
- medical facilities in the TR as determined by the EER design;
- emergency response organization and alarms documented on a station bill deployed at strategic locations on the installation;
- suitable personal protective equipment to undertake a search and rescue operation on the installation provided inside or in close proximity to the TR, protected against low temperatures and stored in a state of readiness;
- safety-critical elements including HVAC, seals and door locks/closure mechanisms.

A.18.13.4 Muster station

When sizing muster stations, consideration should be given to accommodating injured personnel as well as extra personnel arriving by helicopter in the event the helicopter cannot depart, personnel on the installation from a standby vessel, etc.

Alternative muster stations should provide protection from the effects of the incident and environment for a time sufficient to allow control of an emergency or until a decision is made to abandon the installation.

A.18.14 Evacuation design

A.18.14.1 Evacuation — General

The goal of evacuation is to ensure that personnel leave the installation to a place of relative safety outside the hazard zone consistent with the developed performance standards.

The matrix shown in Table A.18-4 provides an example of how an offshore installation manager operating in an arctic or cold region should have more than one evacuation option available, and an indication of the decision process involved.

Table A.18-4 — Example of evacuation method decision hierarchy — OIM evacuation decision matrix

Event: A well kick occurs giving time for PRECAUTIONARY down-manning of 80 non-essential personnel. 22 essential personnel remain to control the well, but fail. They escape and muster in the TR, where the OIM has made the decision to abandon the installation using one or more PRIMARY methods (if available and suitable for use in hazard conditions), SECONDARY means and even TERTIARY evacuation methods where one or more persons are unable to reach the TR.

Choice	Precautionary	Emergency		
	Primary	Primary	Secondary	Tertiary
1st[a]	Method A	Method B	Method C	Method D
2nd[a]	Method B	Method C	Method D	Method E
3rd[a]	N/A[b]	Method D	Method E	Method F

[a] In the event that the first choice is not available (or inappropriate given prevailing hazards), the OIM selects the next available and reliable option, and so on, until full complement of non-essential and essential personnel are evacuated.

[b] There might not be other available options that provide the required level of reliability during precautionary down-manning.

Embarkation areas and evacuation craft system access should be designed to allow rapid boarding of personnel while preventing ingress of hydrocarbon and toxic gases. The interior design should enable efficient personnel boarding, seating and tending to injured personnel.

A.18.14.2 Evacuation method design

The following issues should be considered in evacuation system design.

- Where deemed necessary, evacuation methods should have fenders to minimize the effect of impact with other structures or ice, or have inherent built-in strength. The design of launch arrangements should assure adequate function considering sea spray, atmospheric icing, cold temperatures and snow.
- Evacuation systems should be capable of being deployed and operated in the physical environment of the arctic or cold region in which they are located. Consideration should be given to access and boarding, winterization, icing (before and after launch), visibility, etc., in the design. Available evacuation systems have limitations with respect to operating in various ice environments. For example, conventional lifeboats (TEMPSC) are unable to make headway in ice concentrations greater than about 5/10. Marine evacuation systems should be selected or developed further to operate in all ice environments for which it is planned that they be used.
- In regions where ambient temperatures can negatively impact starting, appropriate winterization measures, including the use of low temperature lubricants and fuels, should be taken. The design should also evaluate the requirement for engine heaters, battery trickle chargers, etc.
- In most cases, it is necessary that the space required exceed 100 % of the maximum complement to account for injured personnel, non-functionality and/or unavailability of one or more evacuation methods due to an unexpected hazard scenario, etc. The space should be sufficient to accommodate personnel wearing PPE.
- Evacuation methods should be designed in accordance with established human engineering principles and their ergonomic adequacy, i.e. bulky PPE, for expected personnel configurations with consideration to performance in cold water and arctic temperatures.
- The design of evacuation methods should consider the requirement for a self-contained air support system and fire-protection and, if marine-based, their design should be self-righting and capable of survival when subjected to pressures transmitted through a converging ice field.

- The evacuation method should be provided with the equipment necessary for facilitating search and rescue success.
- Marine evacuation craft boarding area lighting should be uninterrupted during an emergency. This includes the sea or ice surface entry zone beneath the craft.
- Tertiary escape methods should be located and stored such that they are protected from the same event/escalation scenario that can impair a secondary means.
- Tertiary escape methods can include fixed stairs and ladders, rope ladders and personal abseiling devices only where their deployment and use cannot be impaired by environmental conditions.
- Secondary evacuation methods allow personnel-controlled access to the rescue platform without having to first enter the sea.
- If part of the evacuation strategy, multiple tertiary methods (as stipulated by the EER analysis) to facilitate direct access to the ice or the sea should be strategically located to enable the evacuation of personnel who have no other means of leaving the installation. It is necessary that evacuation routes across the ice consider the hazards posed by the ice cover and exposure of personnel to the incident and to the physical environment.
- Tertiary methods should accommodate the expected PPE required for cold weather and/or cold water.

A.18.15 Rescue design

The goal of rescue is to retrieve evacuees to a place of safety.

The design of the rescue system should include the following.

- Survival: it is necessary to take into account the range of anticipated environmental conditions, including seawater and air temperature, the effects of ice abrasion, etc.
- Shelters: strategies incorporating shelters deployed on stable ice should be considered where appropriate as part of the EER analysis.
- Design integrity: it is necessary to take into account both hardware and personnel components.
- Personnel recovery: it is necessary to provide means of transfer from the primary and secondary evacuation methods to the rescue platform that do not require personnel to enter the sea.
- Communications: primary and secondary evacuation systems should have the capability of communicating with the rescue platform during the recovery process.
- Lifting appliances for evacuee recovery: conditions and methods for recovery of evacuees from primary evacuation systems, secondary evacuation systems and/or in the sea or ice through the use of lifting appliances should be assessed in the EER analysis, and implemented accordingly.
- Tertiary evacuation system interface: where deemed necessary by the EER analysis, the tertiary evacuation mode should have the provision for lifting to a rescue platform or recovery to a primary or secondary evacuation means.
- Medical treatment requirements: the required level of medical treatment from the rescue platform should take into account the travel time to a medical facility, the capability of the medical facility for handling multiple casualties, etc.
- Vessel rescue platform: the vessel's bridge should be designed so as to enable the master (mariner, certified by the relevant authority, responsible for operation of a ship) to continuously monitor rescue operations.

- Materials: material properties in cold temperatures and in ice should be considered.
- Propulsion system: the rescue mission and range of natural and incident impacted environmental conditions expected should be taken into account.

Annex B
(informative)

Regional information

B.1 Introduction to regional information

Regional descriptions of the physical environment are provided in this annex for ice covered regions of the northern hemisphere. Each regional section starts with an overview text describing the general meteorological, oceanographic and ice environments that can be found in the region. This is followed by tables listing estimates of the highest (or lowest) values that are exceeded on average every year. Some parameters, such as wave period, are values that are associated with other parameters, such as significant wave height. When data to determine the parameter are unavailable, “ND” (for “No Data”) is shown for the parameter. In some cases, sufficient data are available to determine an average annual value, but not to determine a meaningful range of average annual values. In this case, “ND” is also used. In certain cases, NA (for “Not Applicable”) is used to signify that the parameter is not relevant for a portion of a larger geographical region.

The regional descriptions are meant to provide interested parties with an overview of the region but are not meant to provide parameter values appropriate for the design of offshore structures. While it is necessary to consider the parameters described in the design, some might not be important for the design of particular facilities. A full description of the appropriate parameters can require review and analysis of available data, collection of new data, interpretation of parameters found in nearby regions or similar ice regimes, and statistical evaluation of the data. Appropriate specialists should be consulted in the determination of parameters relating to the physical environment for use in the design of offshore facilities.

Not all ice parameters are shown in every region. If an ice parameter is not listed in the table, it is not found in that region. For example, since multi-year ice is not found in Cook Inlet in Alaska nor in the Okhotsk Sea off Russia, parameters related to multi-year ice are omitted from the accompanying table for these regions.

For some regions, there are sufficient data to provide additional detailed information on the parameters listed and these data are provided. An example is the number of ridges per kilometre, which is provided only for the offshore Russia regions.

Definitions for column headings in the regional descriptions are the following:

a) “Average annual value”: a value for the parameter in question averaged over the period of available data;

b) “Range of annual values”: the range of values of the parameter over the time period of available data.

ISO 19901-1 contains more specific metocean information for a small number of regions of the world where adequate data are available.

B.2 Baffin Bay and Davis Strait

B.2.1 Description of region

This region contains all of Baffin Bay north of 70° N and the western part of southern Baffin Bay and Davis Strait in Canadian waters south of 70° N.

A map of the Baffin Bay region is shown in Figure B.2-1.

Table B.2-1 — General information for Baffin Bay and Davis Strait

Area of coverage	61° N to 77° N, 55° W to 80° W
Length of ice covered season	late October to July
Length of open water season	late July to mid-October
Range of water depths, metres	100 to 400

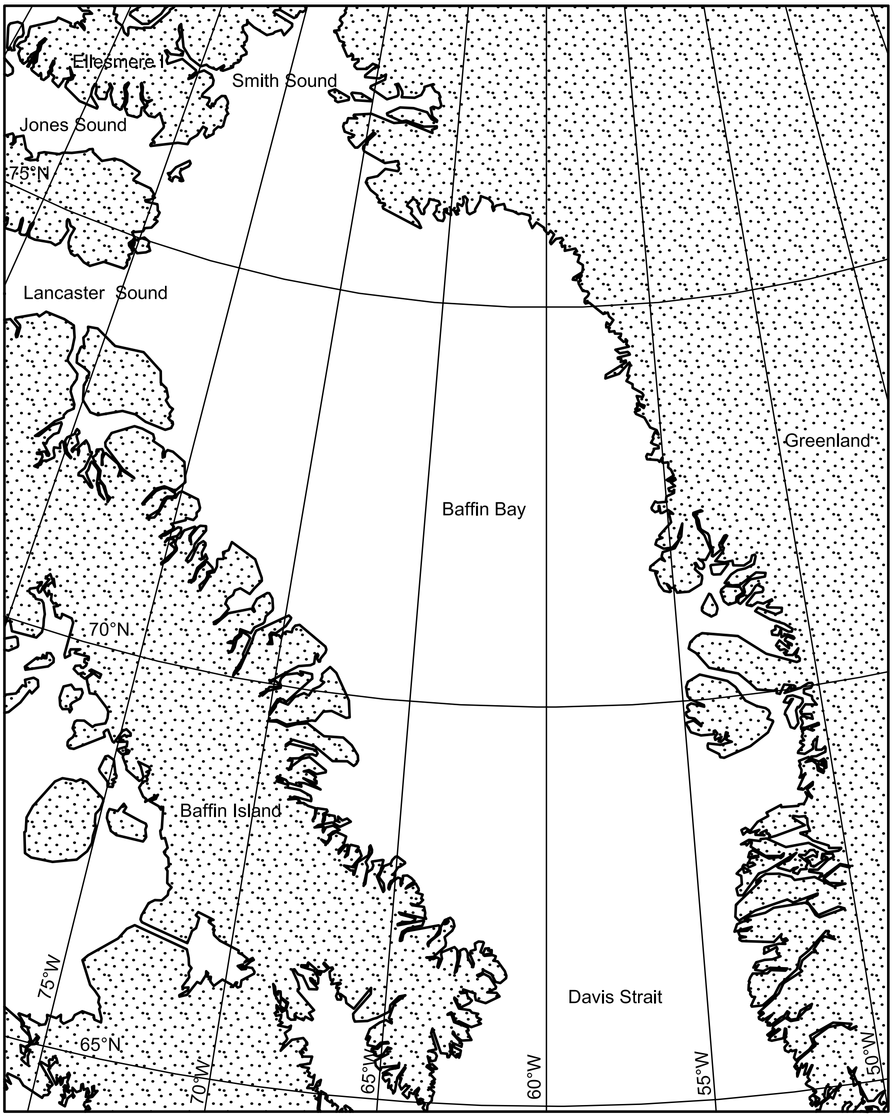


Figure B.2-1 — Map of the Baffin Bay and Davis Strait region

B.2.2 Baffin Bay and Davis Strait technical information

B.2.2.1 General

References [B.2-1] and [B.2-2] are good sources of information regarding the ice conditions in the Canadian waters of this region. Reference [B.2-3] provides information on the conditions in the Greenland portion of the region.

B.2.2.2 Climate

This region has an arctic climate with mean temperatures of approximately 4 °C in August and –24 °C in February. Precipitation varies from 10 mm/month to 80 mm/month with higher values in the summer months and in the southern regions. The annual mean wind speed ranges from 5 m/s in the northern regions to up to 10 m/s in the southern regions.

B.2.2.3 Hydrology

Observations of wave heights are scarce and little is known for this region. Estimated average wave heights range from 1,5 m to over 3 m, with higher values in the autumn months prior to complete ice freeze-up.

The pattern of water circulation in Baffin Bay and Davis Strait is cyclonic or anti-clockwise. A strong southward flow, the Baffin Island Current, exists along the west side, with a weaker northward flow, the West Greenland Current, along the east side. A large part of the West Greenland Current turns westward about latitude 63 °N and then southwestward to join with the Baffin Island Current. The remaining West Greenland Current flows northward in Baffin Bay, turning northwestward at the northern extremity of the bay. The Baffin Island Current consists of polar water from Lancaster Sound, Jones Sound and Smith Sound, plus an additional source from West Greenland. The mean velocity of these currents varies from 8 km/day to 20 km/day. The mean tidal range along the West Greenland coast is 1,9 m to 3,2 m. Along the Baffin Island coast, the range is 0,7 m to 7,3 m.

B.2.2.4 Ice conditions

Baffin Bay and Davis Strait have severe ice conditions with thick first-year ice and multi-year floes that can be highly ridged and rubbled. Sea ice can be relatively dynamic with speeds up to 0,4 m/s. Multi-year ice often enters the region through Smith Sound and Lancaster Sound. The region is a source for icebergs and it has a large number of icebergs year round. The annual maximum number of icebergs found in the region is greater than 2 000 per year. Iceberg sizes range up to a maximum annual value of approximately 20×10^6 tonnes.

A large polynya often forms between November and March in the northern section of Baffin Bay as a result of an ice bridge that forms in Smith Sound, between Greenland and Ellesmere Island[B.2-4].

Table B.2-2 — Baffin Bay and Davis Strait meteorological conditions

Parameter		Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	18	17 to 22
	Minimum, degrees Celsius	–39	–38 to –41
	Freezing degree days	5 000	4 000 to 6 000
Wind speed at 10 m elevation	10 min average, metres per second	18 (BB)[a] 24 (DS)[b]	14 to 24 (BB) 20 to 29 (DS)
Wind direction	Dominant winter direction	280° (BB) 335° (DS)	5° (DS)
	Dominant summer direction	154° (BB)	ND
Precipitation	Annual rainfall, millimetres	ND	ND
	Annual snowfall, millimetres	ND	ND
Visibility (fog, snow, etc.)	Annual number of days with visibility less than 5 miles	ND	ND

[a] “BB” indicates Baffin Bay.

[b] “DS” indicates Davis Strait.

Table B.2-3 — Baffin Bay and Davis Strait oceanographic conditions

Parameter		Average annual value	Range of annual values
Waves, offshore (> 100 m water depth)	Significant wave height, metres, annual maximum	4,1 (BB)[a] 7,9 (DS)[b]	1,8 to 6,8 (BB) 4,8 to 12,6 (DS)
	Range of zero-crossing periods, seconds	7,2 (BB) 9,8 (DS)	5,6 to 8,7 (BB) 8,6 to 11,3 (DS)
Current	Near-surface maximum speed, centimetres per second	10	10 to 20
	Bottom maximum speed, centimetres per second	ND	ND
Tidal current	Maximum surface speed, centimetres per second	ND	ND
Tide	Tidal range (total), metres	1,9 to 3,2 (G)[c] 0,7 to 7,3 (BI)[d]	ND
Wind-induced surge	Water depth increase range total, metres	ND	ND
Water salinity	Average surface salinity, parts per thousand	ND	ND
Water temperature	Summer surface maximum, degrees Celsius	ND	ND
	Summer surface average, degrees Celsius	ND	ND
Seabed geotechnical – Ice-induced gouge	Gouge depth, metres	< 2	ND
	Water depth range, metres	~ 220	ND
Seismic	Magnitude	ND	ND

[a] “BB” indicates Baffin Bay.

[b] “DS” indicates Davis Strait.

[c] “G” indicates Greenland.

[d] “BI” indicates Baffin Island.

Table B.2-4 — Baffin Bay and Davis Strait sea ice conditions

Parameter		Average annual value	Range of annual values
Sea ice			
Occurrence	First ice	mid-November (S) early October (N)	October to November
	Last ice	July (S) late August (N)	July to September
Level ice (first-year)	Landfast ice thickness, metres	1,6	1,5 to 2,0
	Floe thickness, metres	1,6	1,5 to 2,0
Rafted ice	Rafted ice thickness, metres	ND	ND
Rubble fields	Sail height, metres	ND	ND
	Length, metres	ND	ND
Ridges (first-year)	Sail height, metres	≈ 0,5 to 1,5	0,5 to 6
	Keel depth, metres	≈ 5 to 8	5 to 20
Level ice (second- and multi-year)	Floe thickness, metres	2,5 to 5	2,5 to 10
Ridges (second- and multi-year)	Sail height, metres	ND	ND
	Keel depth, metres	10	10 to 25
Rubble fields (second- and multi-year)	Average sail height, metres	ND	ND
	Length, metres	ND	ND
Ice movement	Speed in nearshore, metres per second	0,15	0,1 to 0,4
	Speed in offshore, metres per second	0,20	0,2 to 0,4
Icebergs			
Size	Mass (million tonnes)	20	10 to 50
Frequency	Months present	12	12
	Number per year	> 2 000	ND
	Maximum number per month	ND	ND

B.3 Labrador

B.3.1 Description of region

Offshore exploration took place in this region in the 1970s and reasonable-sized gas fields were discovered. The information from this exploration phase is very much in the “grey literature” and is not generally publicly available. Reference [B.3-1] is the best source of information for this region.

Table B.3-1 — General information for Labrador

Area of coverage	52° N to 60° N, 51° W to 65° W
Length of winter season	November to April
Length of summer season	June to October
Range of water depths, metres	20 to 1 000

A map of the offshore Labrador region is shown in Figure B.3-1.

B.3.2 Labrador technical information

B.3.2.1 Climate

The air temperature in this region ranges from approximately 30 °C in summer to –40 °C in winter, based on coastal sites. Wind speeds can range up to 30 m/s to 40 m/s (1 min average).

B.3.2.2 Hydrology

Waves in this region have significant heights up to 12,5 m with associated zero-crossing periods of 8,4 s to 11,8 s in the offshore region based on hindcast data.

Because of the intricacies of the coastline, currents nearshore are quite variable. The main Labrador Current has two branches: the cold Baffin Island Current, which is fresher and close to shore, and the West Greenland Current. There is a net southerly drift due to the Labrador Current (see Figure B.3-1). The mean tidal range along the Labrador coast varies from 0,4 m in Lake Melville to 4,6 m at Cape Chidley.

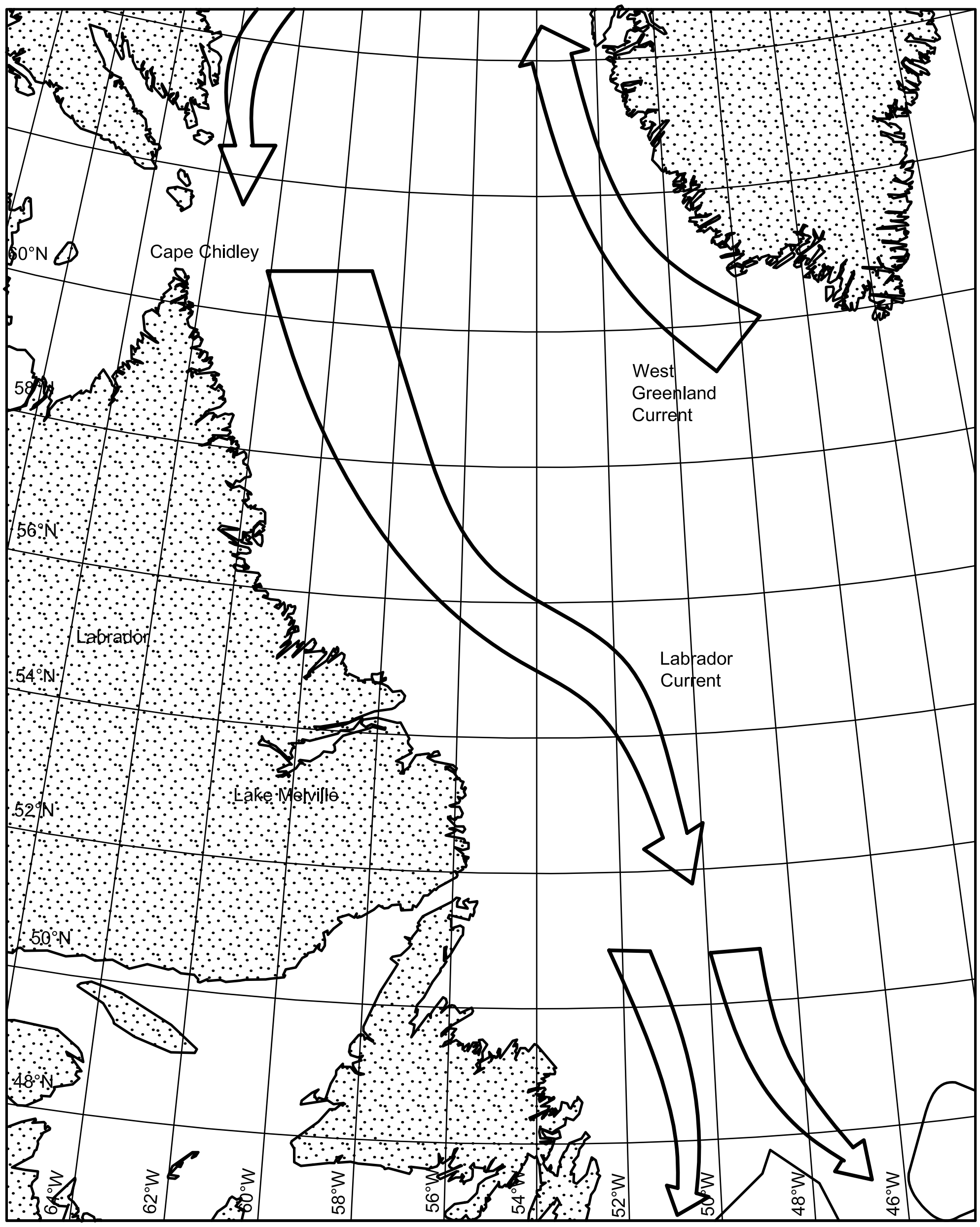


Figure B.3-1 — Map of offshore Labrador

B.3.2.3 Ice conditions

Offshore Labrador has a very harsh environmental climate with heavy pack ice, large icebergs and relatively high wave conditions in the summer months. The region is characterized by heavy pack ice that contains both first-year and multi-year floes. Sea ice can be quite dynamic with speeds up to 0,4 m/s. In sheltered harbours and bays, shore-fast ice grows to a thickness of about 120 cm during a normal winter. Offshore, level pack ice can reach thicknesses greater than this because of the southward drift of the ice from more northern areas. Ice thicknesses can significantly increase under conditions of pressure. Ice ridge sails of up to 3 m to 5 m high can easily develop in these circumstances but 1 m to 2 m is normal. Also, a considerable number of icebergs can be present year-round. Extremely large, tabular icebergs or ice islands (kilometres in length and greater than 20 × 10^6 tonnes) can be present.

Table B.3-2 — Labrador meteorological conditions

Parameter		Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	25	20 to 27
	Minimum, degrees Celsius	–26	–25 to –40
	Freezing degree days	1 600	1 000 to 2 000
Wind speed at 10 m elevation	10 min average, metres per second	30	26 to 38
Wind direction	Dominant winter direction, degrees	300	ND
	Dominant summer direction, degrees	210	ND
Precipitation	Annual rainfall, millimetres	ND	ND
	Annual snowfall, millimetres	ND	ND
Visibility (fog, snow, etc.)	Annual number of days with visibility less than 5 miles	90	ND

Table B.3-3 — Labrador oceanographic conditions

Parameter		Average annual value	Range of annual values
Waves, offshore (> 100 m water depth)	Significant wave height annual maximum, metres	11,4	8,2 to 14,0
	Range of zero-crossing periods, seconds	10,4	8,4 to 11,8
Current	Near-surface maximum speed, centimetres per second	20	15 to 40
	Bottom maximum speed, centimetres per second	ND	ND
Tidal current	Maximum surface speed, centimetres per second	ND	ND
Tide	Tidal range (total), metres	0,4 to 4,6	ND
Wind-induced surge	Water depth increase range total, metres	ND	ND
Water salinity	Average surface salinity, parts per thousand	ND	ND
Water temperature	Summer surface maximum, degrees Celsius	ND	ND
	Summer surface average, degrees Celsius	5	ND
Seabed geotechnical — Ice-induced gouge	Gouge depth, metres	< 2	ND
	Water depth range, metres	≈ 220	ND
Seismic	Magnitude	ND	ND

Table B.3-4 — Labrador sea ice conditions

Parameter		Average annual value	Range of annual values
Sea ice			
Occurrence	First ice	December	November to January
	Last ice	July	July to August
Level ice (first-year)	Landfast ice thickness, metres	1	0,8 to 1,2
	Floe thickness, metres	1,5	1 to 2
Rafted ice	Rafted ice thickness, metres	4	ND
Rubble fields	Sail height, metres	1,5	ND
	Length, metres	—	ND
Ridges (first-year)	Sail height, metres	2	1 to 5
	Keel depth, metres	8	3 to 15
Level ice (second- and multi-year)	Floe thickness, metres	5	2 to 8
Ridges (second- and multi-year)	Sail height, metres	2	1 to 5
	Keel depth, metres	10	5 to 32
Rubble fields (second- and multi-year)	Average sail height, metres	ND	ND
	Length, metres	ND	ND
Ice movement	Speed in nearshore, metres per second	0,1	0,1 to 0,3
	Speed in offshore, metres per second	0,2	0,2 to 0,4
Icebergs			
Size	Mass, million tonnes	5 to 10 (maximum)	1 to > 20
Frequency	Months present	12	12
	Number per year	1 000	500 to 5 000
	Maximum number per month (number per month)	numerous	ND

B.4 Newfoundland

B.4.1 Description of region

The Grand Banks region offshore of Newfoundland is considered to be a harsh environment due to the possibility of intense storms and the potential for ice (sea ice and icebergs). Superstructure icing can also occur between December and March because of the temperature and wind and wave conditions. Restricted visibility due to fog is also common, especially in the spring and summer months, when warm air masses overlie the cold ocean surface. The worst visibility conditions are experienced in July. During the winter months, restricted visibility can also be caused by snow in addition to fog and mist. Additional information can be found in ISO 19901-1 and Reference [B.4-1].

There has been significant exploration and development of the petroleum resources on the Grand Banks of Canada off the east coast of Newfoundland. Several companies are involved. Information on this area can be obtained from the Canada-Newfoundland Offshore Petroleum Board (C-NLOPB)[B.4-2]. Additional information on the ice environment on the Grand Banks is provided in Reference [B.4-3].

Table B.4-1 — General information for Newfoundland

Area of coverage	45° N to 52° N, 48° W to 56° W
Length of winter season	December to April
Length of summer season length	May to November
Range of water depths, metres	75 to 1 000

A map of the offshore Newfoundland region is shown as Figure B.4-1.

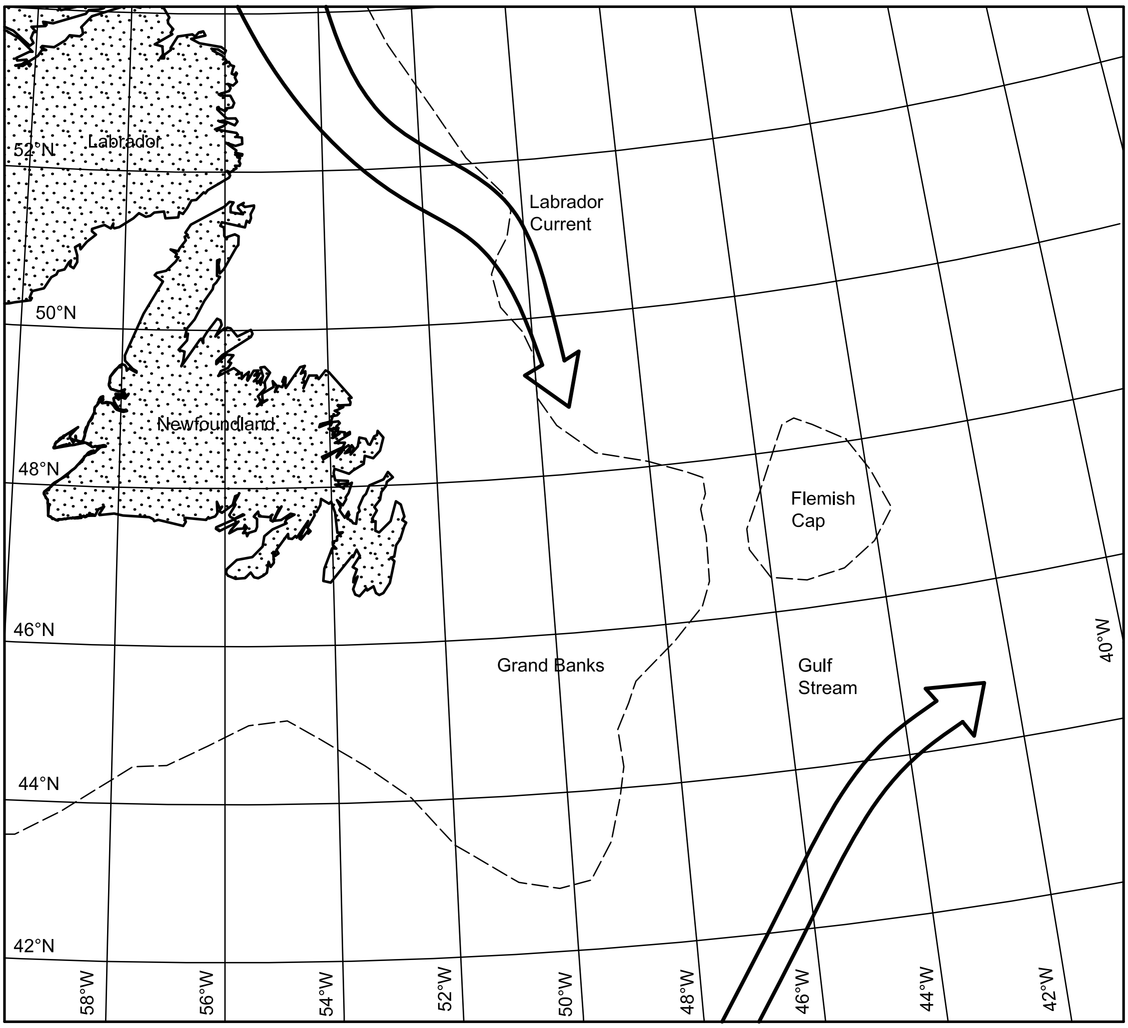


Figure B.4-1 — Map of Newfoundland and offshore regions

B.4.2 Newfoundland technical information

B.4.2.1 Climate

High winds and storms are common in eastern Canada during the winter months. Spring and summer months have fewer, less intense storms and moderate winds, and precipitation is usually in the form of fog, drizzle or rain showers. Hurricanes and tropical storms from the south can threaten the region in the autumn. The wind fields associated with extra-tropical and tropical cyclones excite a wide range of sea states. Extreme wave heights, with maximum individual waves up to 30 m, have been recorded in the region during previous severe storms (e.g. Hurricane Luis in 1995).

B.4.2.2 Hydrology

The Labrador Current is perhaps the most dominant current regime in the region. It plays a major role in the transport of colder water to the region and the regional current pattern is a function not only of this large current, but also of tides, encounters with the warmer eddies and meanders of the Gulf Stream and storm winds. The Labrador Current is also responsible for the transport of icebergs from northern areas to offshore Newfoundland.

B.4.2.3 Sea ice

Sea ice on the Grand Banks is mostly comprised of loose (typically 5/10 to 7/10) pack ice. It drifts in from the Labrador region under the influence of the Labrador Current. In a typical year, the ice edge reaches the northern tip of Newfoundland by early January and the northern Grand Banks by mid-February. The pack ice off Newfoundland generally reaches annual peak coverage in March but can remain at high levels through May. The amount of pack ice varies over the Grand Banks regions and it can vary widely from one year to the next. An offshore structure on the Grand Banks is expected to encounter pack ice several times during its design service life.

B.4.2.4 Icebergs

The Grand Banks has a relatively large population of icebergs that can vary considerably from year to year. The icebergs that travel past the east coast of Canada originate primarily from Greenland glaciers. After calving, the icebergs move north with the West Greenland Current, then south with the Baffin and Labrador Currents until they finally melt in the warmer waters of the southern Grand Banks and the Gulf Stream.

According to the International Ice Patrol, the number of icebergs crossing 48° N each year has varied from a low of 0 in 1966 to a high of 2 202 in 1984, with the average over the last ten years (1995-2004) of around 800 icebergs. Some of these icebergs can drift into the vicinity of the various existing oil production operations and require active iceberg management to reduce the probability of encounter. Iceberg speeds and drift directions on the Grand Banks as measured over 1 h to 3 h time intervals are less than 35 km/day and 47 % move toward the southwest.

Icebergs are characterized according to their height, length and mass estimate. Site-specific or project-specific studies to develop appropriate iceberg related criteria are required as these criteria change according to the region.

A large iceberg can drift into a region where its draught exceeds the water depth, resulting in scours and/or pit features. Iceberg scours occur in various locations on the Grand Banks and have been mapped with side scan sonar. The Grand Banks scour catalogue[B.4-4] is a compilation of data from previous seabed surveys. The average scouring frequency is approximately 1×10^{-4} to 1×10^{-3} scours/km^2/year depending on the region. The average scour length is approximately 650 m and the average scour width is approximately 25 m. The average depth of scour depends on the type of soil conditions present at the scour location. Stiff or compacted sediments can limit the scour depth. For a typical location on the Grand Banks, the average scour depth is about 0,3 m.

Table B.4-2 — Newfoundland meteorological conditions

Parameter		Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	22	20 to 25
	Minimum, degrees Celsius	−17	−15 to −19
	Freezing degree days	500	250 to 750
Wind speed at 10 m elevation	10 min average, metres per second	32	24 to 38
Wind direction	Dominant winter direction, degrees	260	ND
	Dominant summer direction, degrees	225	ND
Precipitation	Annual rainfall, millimetres	ND	ND
	Annual snowfall, millimetres	ND	ND
Visibility (fog, snow, etc.)	Annual number of days with visibility less than 5 nautical miles	40 % April to August 11 % September to March	ND

Table B.4-3 — Newfoundland oceanographic conditions

Parameter		Average annual value	Range of annual values
Waves, nearshore (> 100 m water depth)	Significant wave height annual maximum, metres	11,7	7,4 to 15,6
	Range of zero-crossing periods, seconds	10,6	8,3 to 12,3
Current	Near-surface maximum speed, centimetres per second	90	90 to 130
	Mid-layer maximum speed, centimetres per second	70	50 to 100
	Bottom maximum speed, centimetres per second	60	50 to 80
Tidal current	Maximum surface speed, centimetres per second	ND	ND
Tide	Tidal range (total), metres	ND	ND
Wind-induced surge	Water depth increase range total, metres	0,5	0,46 to 0,6
Water salinity	Average surface salinity, parts per thousand	ND	ND
Water temperature	Summer surface maximum, degrees Celsius	ND	ND
	Summer surface average, degrees Celsius	17	15 to 19
Seabed geotechnical – Ice-induced gouge	Gouge depth, metres	0,3	0,1 to 1,5
	Water depth range, metres	≈ 220	ND

Table B.4-4 — Newfoundland sea ice conditions

Parameter		Average annual value	Range of annual values
Sea ice			
Occurrence	First ice	January	December to January
	Last ice	May	May to June
Level ice (first-year)	Landfast ice thickness, metres	0,8	0,6 to 1
	Floe thickness, metres	1	0,7 to 1,2
Rafted ice	Rafted ice thickness, metres	2	ND
Rubble fields	Sail height, metres	1,1	ND
	Length, metres	ND	ND
Ridges (first-year)	Sail height, metres	1,5	1 to 2
	Keel depth, metres	5	3 to 8
Level ice (second- and multi-year)	Landfast ice thickness, metres	0	0
	Floe thickness, metres	1,5	1 to 2
Ice movement	Speed in nearshore, metres per second	ND	ND
	Speed in offshore, metres per second	ND	ND
Icebergs			
Size	Mass (million tonnes)	0,1 to 0,2 (mean)	0,05 to 6
Frequency	Months present	April to July	January to December
	Number per year	450	0 to 2 200
	Maximum number per month	ND	ND

B.5 Canadian Arctic Archipelago

B.5.1 Description of region

Panarctic Oils Limited and its partners drilled in the High Arctic Islands in the Sverdrup Basin for approximately 20 years from the late 1960s to the mid-1980s. While a considerable amount of industry experience and technology was gained in this region, the information is not well documented and information on it is very much in the “grey literature”.

There is a known earthquake epicentre northwest of Melville Island. Facilities designed for the Melville Island region of the Arctic Islands should consider the seismic risk.

Reference [B.5-1] is the best source of information on ice conditions in this region. The region is not as well characterized as other areas of the Canadian Arctic since there is very little shipping here.

A map of the Canadian Arctic Archipelago is shown in Figure B.5-1.

Table B.5-1 — General information for Canadian Arctic Archipelago

Area of coverage	68° N to 80° N, 80° W to 125° W
Length of winter season	September to May
Length of summer season	July to August
Range of water depths, metres	100 to 500

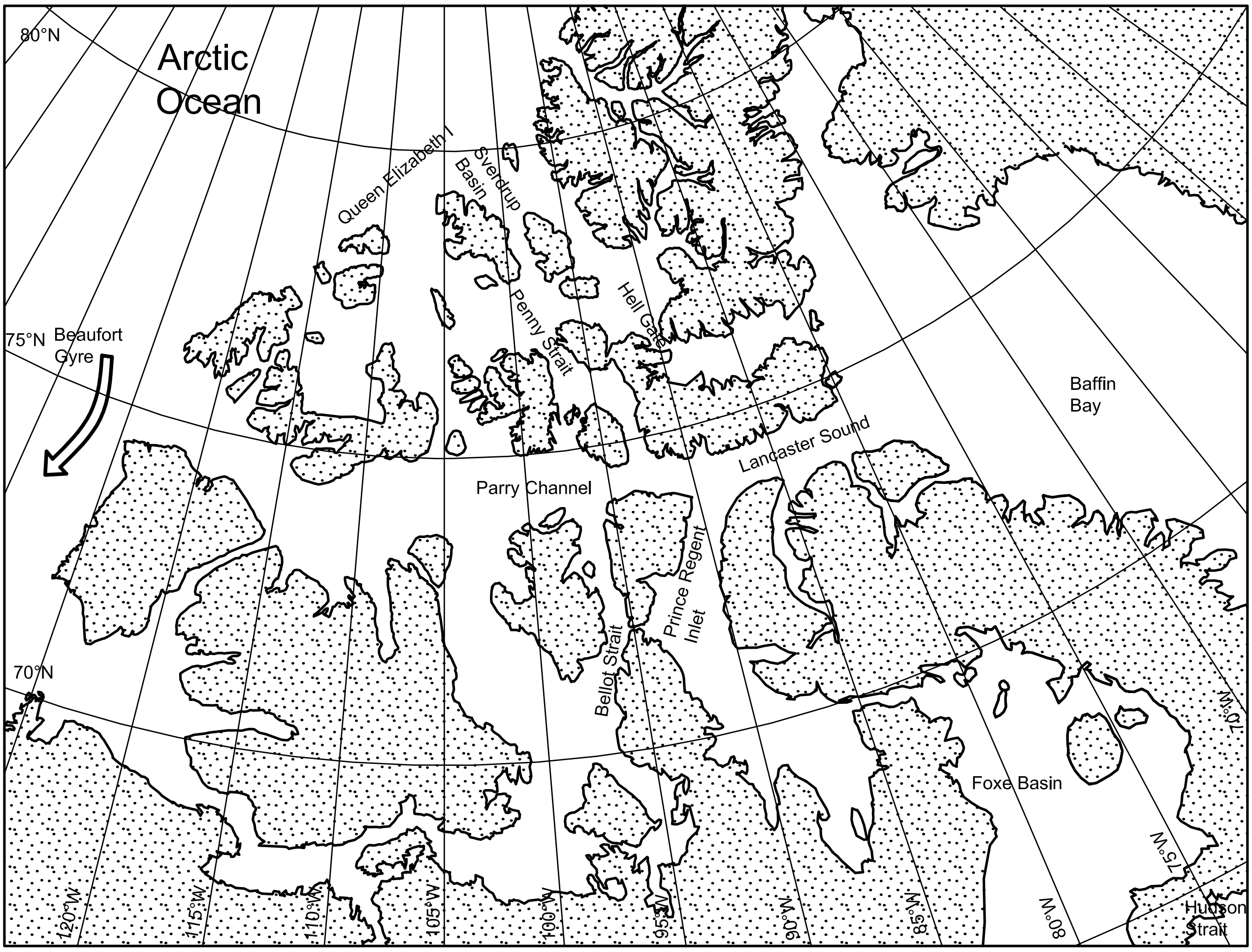


Figure B.5-1 — Map of the Canadian Arctic Archipelago

B.5.2 Canadian Arctic Archipelago technical information

B.5.2.1 Climate

The Canadian Arctic Archipelago has a very extreme climate with winter temperatures in the range of–30 °C to –40 °C and summer mean daily temperatures averaging approximately 10 °C. There are typically 7 000 freezing degree days in this region each year. Older data for the “ND” entries of Table B.5-1 can be found in Reference [B.5-2].

B.5.2.2 Hydrology

Water currents in the Arctic Archipelago are primarily the result of the outflow of water from the Arctic Basin. Some of this water emerges into Baffin Bay and some goes through the Foxe Basin and Hudson Strait into the Labrador Sea. The mean tidal range is generally from near 0 m in Slidre Fiord to 2,9 m in Smith Sound.

In many areas, tides are the principal contributor to current speed in the narrow passages between basins. The most extreme tidal flows occur in Bellot Strait (4 m/s), Hell Gate (3 m/s), Fury and Hecla Strait (2,5 m/s), Cardigan Strait (2,5 m/s) and Penny Strait (1,5 m/s). Further data can be obtained in Reference [B.5-3].

B.5.2.3 Sea ice

Most of the waterways of the Arctic Archipelago are dominated by a consolidated ice sheet during the winter months. The main exceptions are Lancaster Sound and central Prince Regent Inlet, where the ice remains in restricted motion. Small tidal openings are common in Penny Strait and Bellot Strait, while a significant open water polynya exists in Hell Gate all winter. During the first week of September, new ice usually begins to form among the old floes in the Queen Elizabeth Islands area. By the middle of September, it begins to spread from the northern and western sections, covering many of the waterways by the end of the month. Lancaster Sound is the last area to become ice covered, and this usually occurs by the middle of October. By the end of October, ice in many of the waterways has already consolidated. Knowledge of the ice regime of the Canadian Archipelago is based heavily on data acquired during the 1970s and early 1980s. Present conditions, particularly in relation to ice thickness, are poorly known. One can anticipate that conditions will change dramatically if the adjacent area of the Arctic Ocean does indeed lose all its multi-year ice, as some experts predict.

Reference [B.5-4] summarizes the existing information concerning the pack ice and relevant climate variables of the Canadian Arctic Archipelago north of Parry Channel. Pack ice in this area is a mix of multi-year, second-year, and first-year ice types, with the latter subordinate except in the southeast. Ice remains landfast for more than half the year, and summertime ice concentration is high (7/10 to 9/10). In a typical year, less than 20 % of the old ice and 50 % of the first-year ice melt. Figure B.5-2 shows the median concentration, expressed in tenths of ice coverage, in the Sverdrup Basin at the time of minimum extent (3 September). The chart is based on a 30 year climatology prepared by the Canadian Ice Service for 1970 to 1999.

There are large inter-annual fluctuations in ice coverage and some suggestion of a decadal cycle. The average ice thickness in late winter is 3,4 m but sub-regional means reach 5,5 m. References [B.5-5] and [B.5-6] document multi-year sea ice conditions in this area. The pack is a mix of two populations: one consisting largely of multi-year ice imported from the zone of heavy ridging along the periphery of the Beaufort gyre and the other consisting of a mix of relatively undeformed first-year, second-year, and multi-year ice types that grow and age within the basin. The ice of the Sverdrup Basin is strongly influenced by a flux of heat that originates in the Atlantic-derived waters of the Arctic Ocean. The drift of ice through the basin is controlled in the present climate by the formation of stable ice bridges across connecting channels. The drift is episodic. Relaxation of these controls in a warmer climate can cause deterioration in ice conditions in Canadian Arctic waters[B.5-4].

Table B.5-2 — Canadian Arctic Archipelago meteorological conditions

Parameter		Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	9	8 to 11
	Minimum, degrees Celsius	–40	–35 to –45
	Freezing degree days	7 000	5 500 to 8 000
Wind speed at 10 m elevation	10 min average, metres per second	ND	ND
Wind direction	Dominant winter direction	NW	ND
	Dominant summer direction	ND	ND
Precipitation	Annual rainfall, millimetres	ND	ND
	Annual snowfall, millimetres	ND	ND
Visibility (fog, snow, etc.)	Annual number of days with visibility less than 5 miles	ND	ND

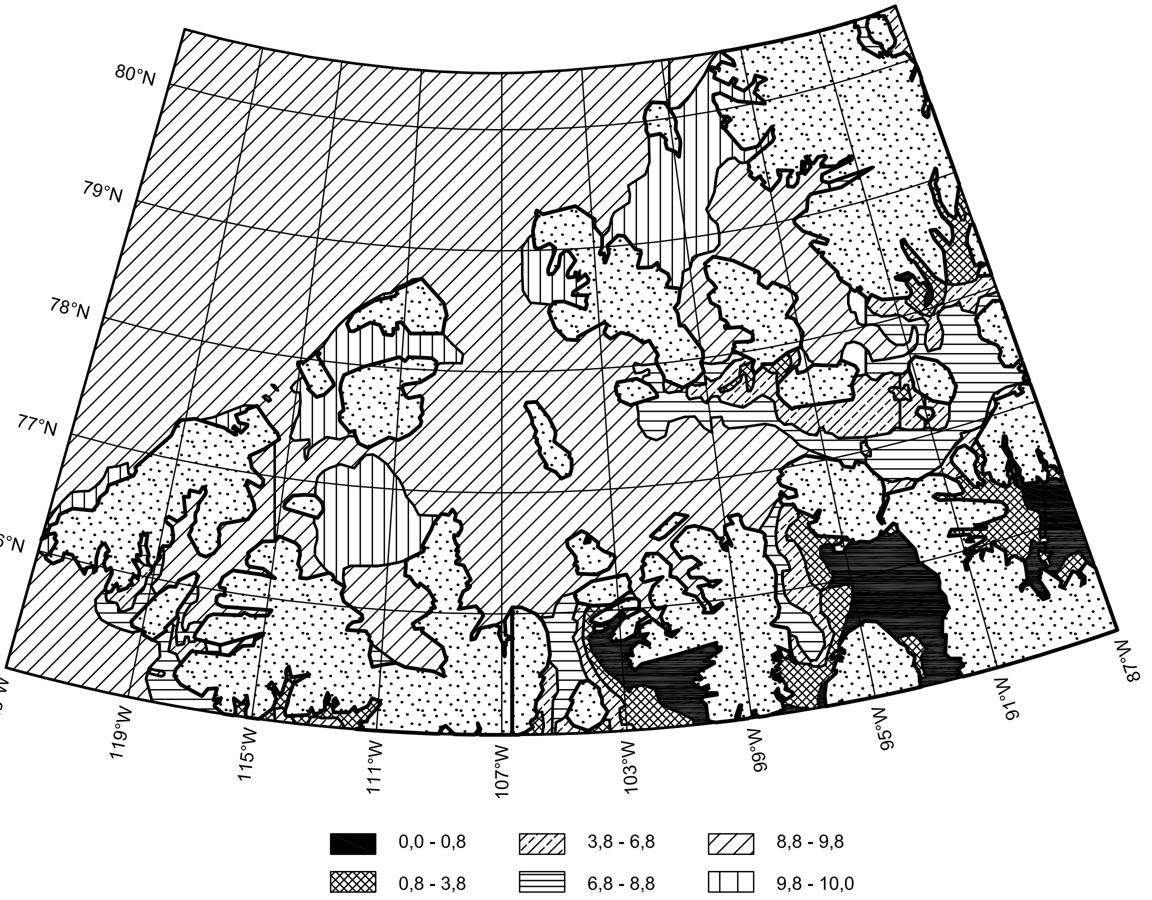


Figure B.5-2 — Median concentration, in tenths, of ice in the Sverdrup Basin at the time of minimum extent (3 September), based on a 30 year climatology for 1970 to 1999[B.5-1], [B.5-4]

Table B.5-3 — Canadian Arctic Archipelago oceanographic conditions

Parameter		Average annual value	Range of annual values
Waves, nearshore (> 100 m water depth)	Significant wave height, metres	ND	ND
	Range of zero-crossing periods, seconds	ND	ND
Current	Near-surface maximum speed, centimetres per second	10	400 (in narrow channels)
	Bottom maximum speed, centimetres per second	ND	ND
Tidal current	Maximum surface speed, centimetres per second	10	400 (in narrow channels)
Tide	Tidal range (total), metres	2,2	ND
Wind-induced surge	Water depth increase range total, metres	ND	ND
Water salinity	Average surface salinity, parts per thousand	ND	ND
Water temperature	Summer surface maximum, degrees Celsius	ND	ND
	Summer surface average, degrees Celsius	ND	ND
Seabed geotechnical – Ice-induced gouge	Gouge depth, metres	ND	ND
	Water depth range, metres	ND	ND
Seismic	Magnitude	5	3 to 7

Table B.5-4 — Canadian Arctic Archipelago sea ice conditions

Parameter		Average annual value	Range of annual values
Sea ice			
Occurrence	First ice	end August	—
	Last ice	August	August to September
Level ice (first-year)	Landfast ice thickness, metres	2,2	1,8 to 2,6
	Floe thickness, metres	2,2	1,8 to 2,6
Rafted ice	Rafted ice thickness, metres	ND	ND
Rubble fields	Sail height, metres	5	3 to 6
	Length, metres	ND	ND
Ridges (first-year)	Sail height, metres	4	4 to 5
	Keel depth, metres	20	20 to 25
Stamukhi	Water depth range, metres	20	15 to 30
	Sail height, metres	ND	ND
Level ice (second- and multi-year)	Landfast ice thickness, metres	3,5	2 to 11,3
	Floe thickness, metres	3,5	3 to 5
Ridges (second- and multi-year)	Sail height, metres	ND	ND
	Keel depth, metres	15	5 to 25

Table B.5-4 (*continued*)

Parameter		Average annual value	Range of annual values
Rubble fields (second- and multi-year)	Average sail height, metres	ND	ND
	Length, metres	6	3 to 20
Ice movement	Speed in nearshore, metres per second	0,1	0,05 to 0,2
	Speed in offshore, metres per second	0,15	0,1 to 0,3
Icebergs/ice islands			
Size	Mass, million tonnes	400	10 to 600
Frequency	Months present	12, northern half only	ND
	Number per year	few	ND
	Maximum number per month	few	ND

B.6 Greenland

B.6.1 Description of region

This region consists of Greenland waters in Baffin Bay south of 70° N and in Davis Strait to Cape Farewell at the southern tip of Greenland.

Table B.6-1 — General information for Greenland

Area of coverage	60° N to 70° N, 45° W to 60° W
Water depth, metres	≈ 1 100

A map of Greenland is provided in Figure B.6-1.

B.6.2 Greenland technical information

B.6.2.1 General circulation

In winter, an area of high pressure exists over the northernmost part of Greenland with northerly winds prevailing over the West Greenland waters. A low pressure area extending from Newfoundland via Iceland to the Norwegian Sea with a trough northwards along the west coast of Greenland reflects the main zone of cyclonic activity. In summer, the mean pressure gradient around Greenland is slack and no prevailing wind direction is discernible. During the year, the highest pressure and most settled weather normally occurs around April. The lowest pressure occurs in December/January.

B.6.2.2 Cyclone tracks

Two-thirds of all cyclones approaching South Greenland arrive from directions between west and south-southeast while most of the cyclones affecting West Greenland arrive from directions between south and west. Cyclones approaching southern Greenland from southwest or south usually split in the vicinity of Cape Farewell with one part moving northward along the west coast, causing very changeable and severe weather in the Davis Strait, while the other moves off towards Iceland.

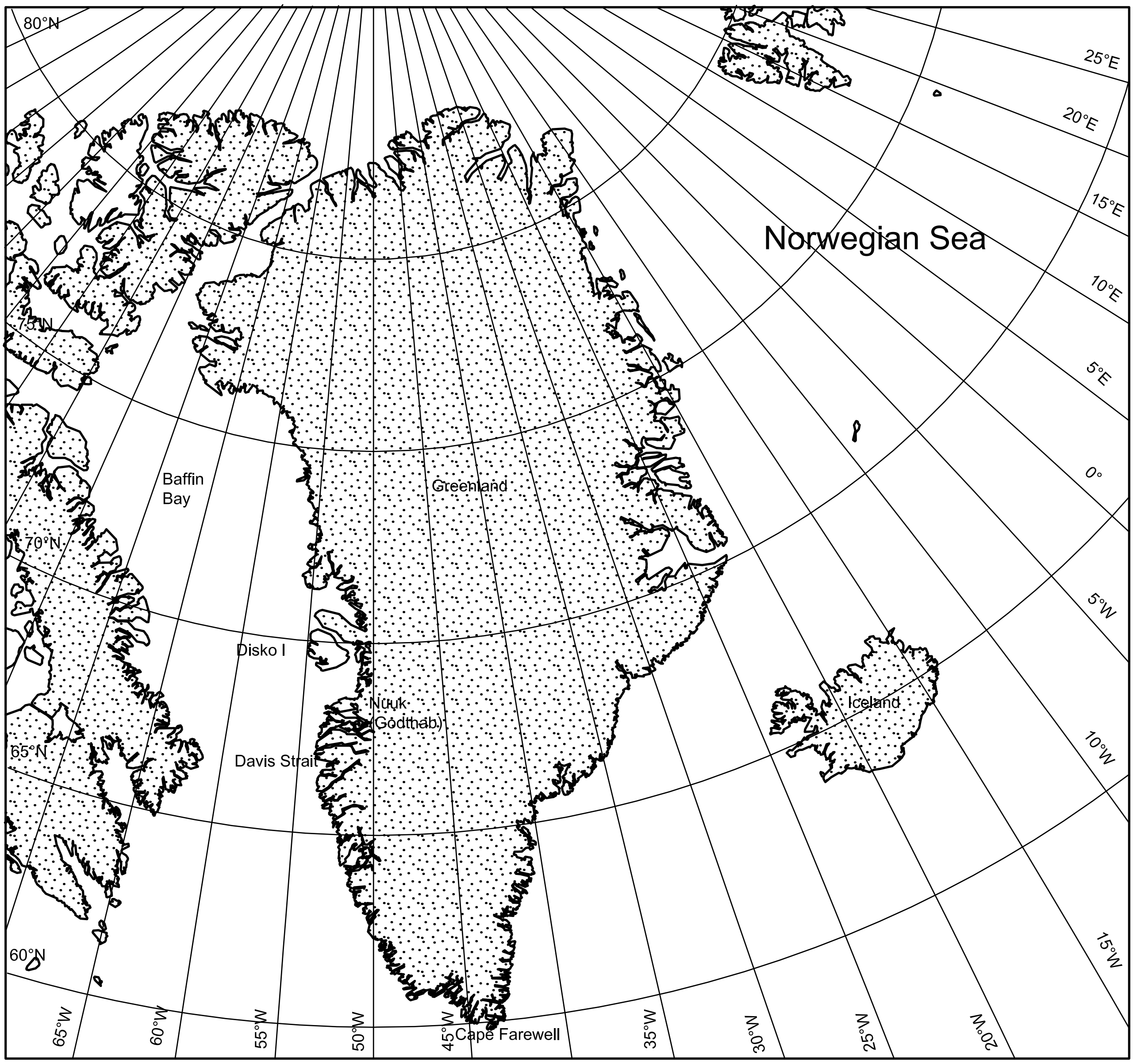


Figure B.6-1 — Map of Greenland

The intensity of pressure systems is greatest in winter. Southern Greenland, in particular, is influenced by severe weather connected with the North Atlantic winter cyclones. The northern part of the Davis Strait has the lightest winds due to the moderating effect of high pressure systems. In summer, the weather in West Greenland, although less severe, often appears more unsettled than in winter due to the northward displacement of the typical cyclone tracks.

Polar lows develop mostly during the winter over open water with very cold air aloft or near the sea ice edge. The diameter of a polar low generally is 200 km to 300 km and is accompanied by heavy snow showers, low temperatures and surface winds exceeding gale force. Occasionally, a polar low in its mature stage shows a structure resembling that of a tropical storm.

B.6.2.3 Individual meteorological parameters

B.6.2.3.1 Air temperatures

The sea west of Greenland has a mean air temperature below 10 °C year round. The coldest month is February and the warmest month is August (July in the coastal area). To the north, with sea ice occurring much of the year, cool summers and very cold winters occur, with a range between the coldest and warmest month of as large as 30 °C. To the south, over open water, cool summers and relatively mild winters with ranges of less than 10 °C occur. In summer, freezing temperatures can occur over sea ice and/or within fog. In winter, very low temperatures occur over snow covered solid sea ice. Over open water, air temperatures normally are below those of the sea surface due to the prevailing advection of cold air. In the coastal zone, summer temperatures as high as 15 °C or more can occur, under foehn (a warm, dry wind on the lee side of a mountain range) conditions, even in winter.

B.6.2.3.2 Visibility

Fog (visibility less than 1 km) is primarily a summer phenomenon. Its frequency increases during May, has its peak value in June/July and reduces in late August. The estimated frequency of fog in July is 20 % to 30 % of the total time over the coldest parts of the sea area. Fog is less frequent in the coastal region.

Temperatures within fog are often 1 °C to 2 °C below that of the sea surface. Freezing temperatures within the fog over a cold water surface are not unusual, and icing with rime ice or clear ice can occur. In winter, fog can form occasionally within a warm and moist air mass advected from the south. Sea smoke forms within cold air flowing from drift ice or from cold land out over open water. The occurrence is often very local but in a very cold air mass it can be more widespread.

In winter, snow showers are present much of the time over open water, causing moderate or poor visibility.

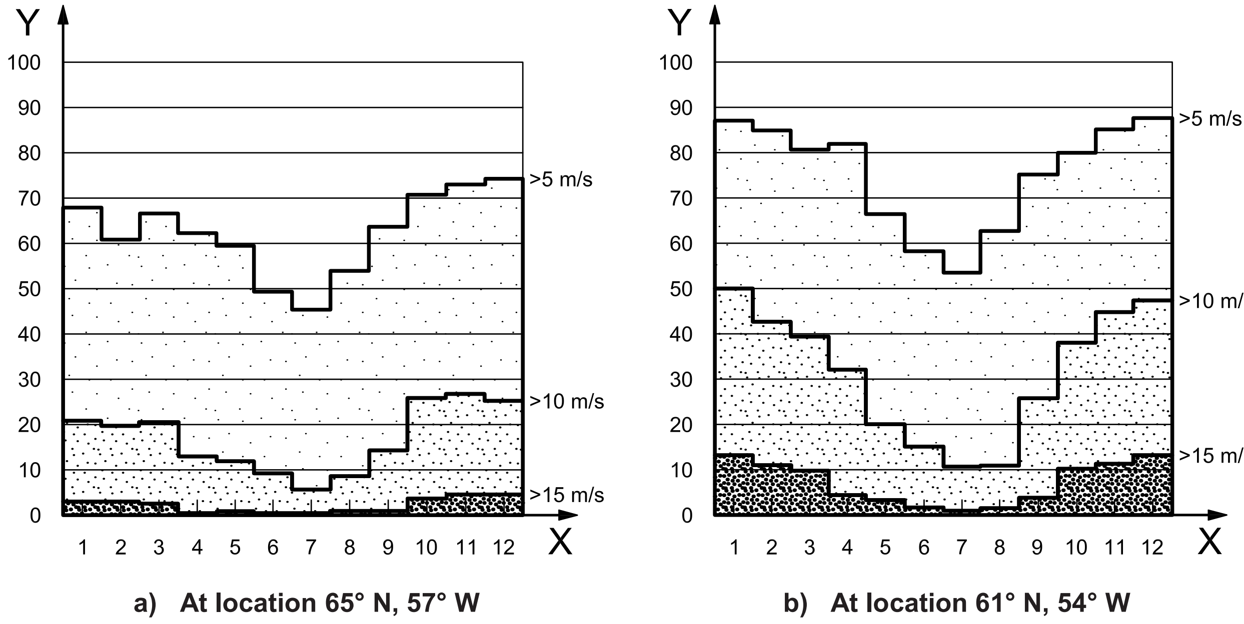
B.6.2.3.3 Precipitation

The amount of precipitation is high in the south due to open water and frequent cyclonic activity and low in the north, particularly in winter and spring. The annual amount of precipitation ranges from 200 mm to 300 mm in the Disko area to more than 1 000 mm in southernmost Greenland. In Nuuk (Godthåb), it is about 600 mm. Most of the precipitation falls in late summer or in autumn. In winter, precipitation usually is in the form of snow. In summer, light snow (or freezing drizzle) can fall from stratus clouds over drift ice or seawater with temperatures close to the freezing point. Otherwise, snowfall is limited to short spells of cold weather in the northern part of the area. Generally, October and June are the rain/snow transition months in the north, November and May are the transition months in the south.

B.6.2.3.4 Wind

North of latitude 65 °N, the annual mean wind speed is 5 m/s to 6 m/s, increasing south of latitude 65 °N to 7 m/s to 8 m/s and south of Cape Farewell to almost 10 m/s. The frequency by month of wind speeds exceeding 5 m/s, 10 m/s and 15 m/s for selected positions is shown in Figure B.6-2. The maximum speed in the northernmost part of the area occurs in October to November, elsewhere in midwinter. Gale-force winds (above 13,8 m/s) are relatively rare in the northern part of the area, less than 5 % in winter and less than 1 % in summer, increasing southward to a maximum of 30 % in winter and 4 % in summer in the southernmost part.

Figure B.6-3 shows wind roses for winter (November to March) and summer (June to August), based on ECMWF data. Winds of gale force in the Davis Strait in winter are mainly from northerly directions. In summer, there is a small predominance of southerly directions.

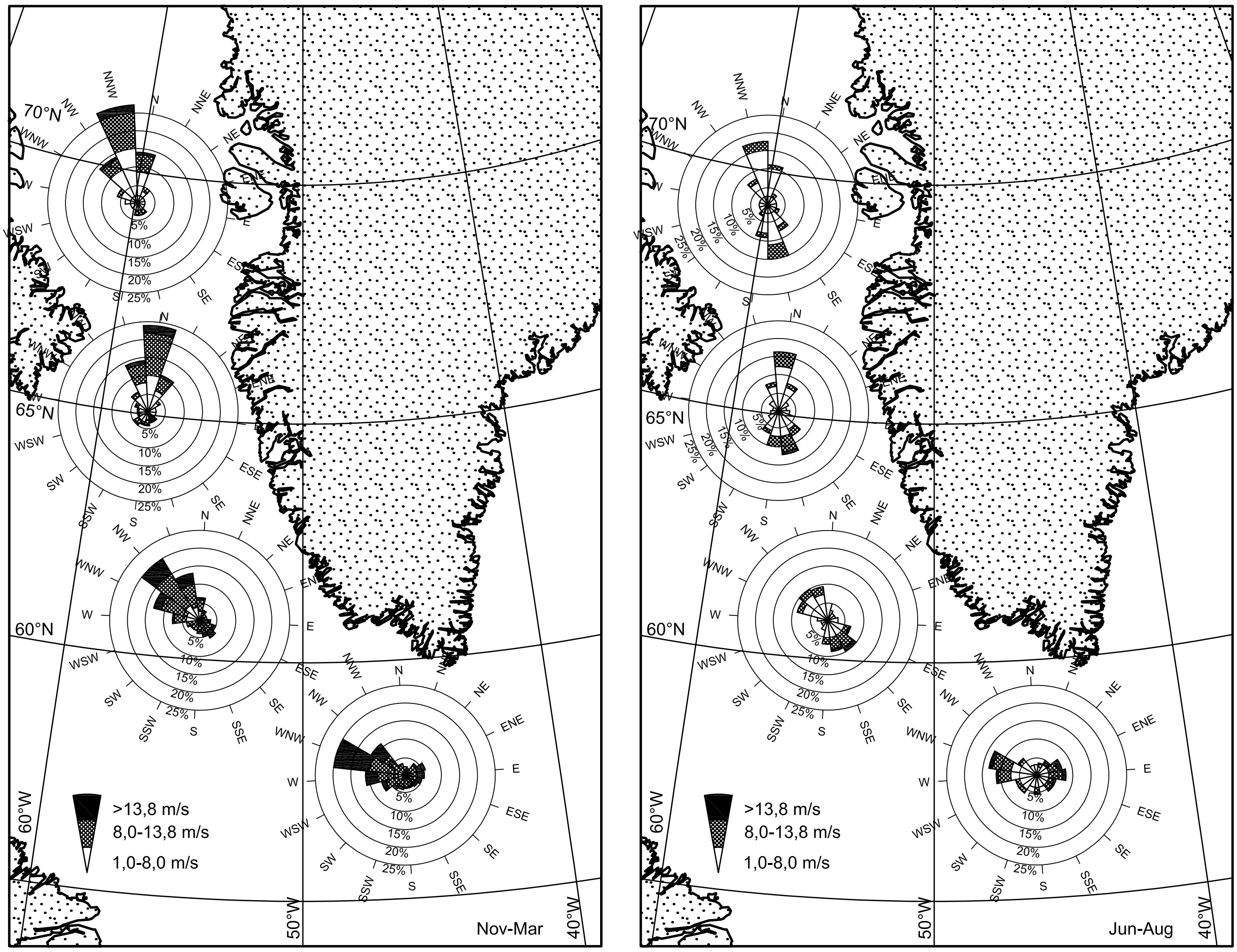


Key

X month

Y percentage of observations

Figure B.6-2 — Frequency by month of wind speeds exceeding 5 m/s, 10 m/s and 15 m/s
(from ECMWF[B.6-1])



a) Winter (November to March) **b) Summer (June to August)**

Figure B.6-3 — Wind roses showing direction and speed
(based on ECMWF data for 1980-1993)

B.6.2.3.5 Icing

In a 10 year period, freezing rain at the coastal stations occurred most frequently in Nuuk in 0,2 % of the observations in winter. Persistent freezing fog is typically a summer phenomenon occurring over vast ice fields and is not likely to occur over open water with a water temperature above +1 °C.

In open water, icing caused by sea spray is frequent from November to April and rare in October and May. Heavy icing can occur with persistent, strong northerly and northwesterly winds. Strong winds from other directions (particularly southwest) can cause heavy icing as well, though of short duration.

B.6.2.4 Oceanography

B.6.2.4.1 Ocean circulation

The North Atlantic Current, which is a continuation of the Gulf Stream, enters the area from the west. Before entering the Faroe-Shetland channel, part of the North Atlantic Current turns westward as the Irminger Current, which occupies the ocean area south of Iceland. Part of the Irminger Current turns towards Greenland south of the Denmark Strait, where it flows southward along the east coast of Greenland. Some of this water continues to Cape Farewell, which it rounds, while a second portion remains within the Irminger Sea, where it recirculates in a cyclonical gyre.

Cold water originating from the Arctic Ocean leaves the area mainly at two locations:

a) through the Fram Strait, i.e. the area between Greenland and Spitsbergen;

b) through the Canadian Arctic Archipelago, i.e. the area between Greenland and Canada.

In the Fram Strait, by far the more important of the two outflow regions, water is transported southward along the east coast of Greenland as the East Greenland Current. This current rounds Cape Farewell and continues northward along the west coast of Greenland up to a latitude of about 65 °N to 66 °N, where it turns westward and unites with the south-flowing current off the Canadian east coast. This current, called the Baffin Current, also transports water from the Arctic Ocean, leaving the area through the second major outflow region, the Canadian Arctic Archipelago.

Along the West Greenland banks, two current components dominate. Closer to the shore, the East Greenland Current component is diluted by run-off water from the various fjord systems. West and south of the polar water, currents include contributions from the Irminger Sea and the North Atlantic.

Current velocities are generally weak (< 0,10 m/s) except for areas close to the coast and the area just west of the West Greenland Banks. In this zone, the current velocities are generally above 0,25 m/s and values of 0,4 m/s to 0,5 m/s are not unusual.

B.6.2.4.2 Tides

The most important tidal constituent in the Davis Strait/Baffin Bay area is the semi-diurnal (M2) tide with an amphidromic point (i.e. point with no tidal amplitude around which co-tidal lines rotate anti-clockwise) at about 70 °N, almost in the middle of Baffin Bay. Along West Greenland, the greatest amplitude (120 cm) is found in the Nuuk area, decreasing to around 40 cm north of Disko Island.

B.6.2.5 Sea ice and icebergs in Davis Strait

B.6.2.5.1 General sea ice characteristics

The waters of the eastern Davis Strait are normally free from sea ice from April/May until November/December. Icebergs can occur infrequently throughout the sea ice free season and the easternmost waters have a significantly longer sea ice free period.

The West Greenland Current retards the time of sea ice formation in the eastern Davis Strait and results in a break-up earlier than in the western parts of the Davis Strait. During the winter and early spring months, sea ice normally covers most of the Davis Strait north of 65 °N, except close to the Greenland coast, where a flaw lead of varying width often appears as far north as latitude 67 °N between the shore and the drift ice offshore. South of 65 °N to 67 °N, sea ice free areas dominate throughout the year and the sea ice edge is normally oriented to the southwest towards Hudson Strait or the Labrador Coast.

The predominant sea ice type in the Davis Strait and southern Baffin Bay is first-year ice, but small amounts of multi-year ice of Arctic Ocean origin drift into the western parts of the area from Lancaster Sound or Nares Strait. At the end of the freeze-up season in March/April, the sea ice reaches its maximum thickness of about 50 cm to 90 cm in eastern parts (up to about 100 km from the Greenland coast). The western and central parts of Davis Strait are dominated by medium and thick first-year ice categories mixed with small amounts (1/10 to 3/10) of multi-year ice. The dominant size of the ice floes ranges from large floes about 1 km wide to vast floes larger than 10 km. In Greenland, this ice regime is recognized as the “West Ice”.

A wide belt of multi-year sea ice originating from the Arctic Ocean is normally present most of the year, covering the entire east coast of Greenland. Under normal conditions, the multi-year ice reaches the Cape Farewell area in December/January, depending on the intensity of the East Greenland Current and the amount of sea ice in it. Due to long periods with strong northwesterly winds, ice often passes Cape Farewell only for short periods. The amount of multi-year ice in the South Greenland waters peaks in early summer; lows can cause multi-year ice to drift northwestwards along the Southwest Greenland coast in the West Greenland Current. The width, concentration and position of this ice belt vary from year to year. Some years, the ice never passes Nunarsuit, while in other years it passes Nuuk and the Fyllas Banke area, but normally the northernmost position of the multi-year ice on the west coast is near Paamiut at 62 °N. The waters near or south of Paamiut are normally free from multi-year sea ice beginning in early August. The size of the multi-year ice floes is always less than 100 m, and normally about 5 m to 20 m. When multi-year ice occurs off southwest Greenland, it is normally characterized by low or medium concentrations averaged over large areas, but long, narrow belts of high concentrations are common. In Greenland, this ice regime is known as the "Storis" or "Great Ice", mainly because of the thickness of the ice.

B.6.2.5.2 Davis Strait between 65 °N and 68 °N

Sea ice drift has a significant offshore component and for this reason sea ice covers the Davis Strait only in the last half of a very cold winter.

If sea ice is present close to the Greenland coast, it is very sensitive to easterly winds and break-up happens quickly. When sea ice covers the entire strait, a narrow lead normally occurs close to the Greenland coast, just off the fast ice edge. The normal ice type in the area is young ice or thin first-year ice in varying floe sizes. Wide belts of small floes normally occur near the ice edge. Multi-year ice arriving from south of the Greenland east coast almost never drifts north of 65° 30' N. This particular event has not been observed during the last 46 years and has been observed only a few times in the 20th Century.

B.6.2.5.3 Fyllas Banke and Davis Strait, 63 °N to 65 °N

Fyllas Banke is the area around Greenland that is least affected by the occurrence of sea ice. Sometimes in the last half of winter, the West Ice drifts eastward into the Fyllas Banke area for periods ranging from only a few days to several weeks in severe winters. Locally formed sea ice in the Fyllas Banke area, normally in the thin and young ice category, sometimes disappears within only a few days.

In late spring and summer, belts of the multi-year ice or "Storis" in the Cape Farewell area normally drift along the West Greenland coast. On average, the "Storis" drifts north of 63 °N (into the Fyllas Banke area) every second year. Sometimes the multi-year ice is present only as a few narrow ice belts for a couple of days, while in other years the "Storis" covers large areas for several weeks. From 1958 to 2005, the Fyllas Banke has always been reported completely free of sea ice from mid-August until mid-December. In January 1982, multi-year ice drifted north of 63 °N due to extreme wind conditions in the last months of 1981.

Apart from this event, the "Storis" was never observed north of 63 °N earlier than late February during the period 1958 to 2003.

B.6.2.5.4 Davis Strait icebergs

Icebergs can occur everywhere in the West Greenland waters. In some areas they occur only rarely, e.g. off Sisimiut, while in other areas, e.g. in Disko Bay, icebergs are always present. A major source of icebergs is eastern Baffin Bay, north of latitude 73 °N, where over 10 000 icebergs are calved every year from 19 major glaciers. Nine of these are more than 8 km wide across their front and produce icebergs up to about 1 km long. South of 73 °N, the glaciers in Uummannaq Fjord and Disko Bay are the major source of 10 000 to 15 000 icebergs per year and these glacial outlets are very important for the iceberg input to the northern Davis Strait and Baffin Bay.

The most active glacier is Ilulissat (Jakobshavn). This glacier produces over 20 km^3 of ice each year in varying types and sizes of icebergs. Almost no icebergs are produced south of Disko Bay.

The majority of icebergs from Disko Bay are carried northward to eastern Baffin Bay before heading southward along the Baffin Island coast. Most of the icebergs from Baffin Bay drift southward into the western Davis Strait, joining the Labrador Current further south, while some of them can enter the eastern Davis Strait area, west of Disko Bay and Kangaatsiaq. Due to the dominant currents and the distribution of the major glacier outlets, the icebergs observed in the northern and western parts of the Davis Strait (north of Sisimiut) are expected to originate from the glaciers in Disko Bay and eastern Baffin Bay. In the southeastern Davis Strait, most of the observed icebergs are of East Greenland origin.

The seasonal maximum of icebergs in the southeastern Davis Strait is normally in July and August, closely related to the actual distribution of the "Storis" in the South Greenland waters. Off the ice edge of the "Storis", the melt of glacial ice increases significantly and, therefore, the seasonal minimum of glacial ice near the Fyllas Banke area is normally during the autumn and early winter months of September to December.

An important factor controlling the iceberg environment off southwest Greenland is the input of icebergs to the East Greenland Current at high latitudes during the summer. Thousands of large icebergs are calved every year from several glacier outlets on the Greenland east coast. The icebergs drift southward in the East Greenland Current, which contains large amounts of sea ice from the Arctic Ocean most of the year. Large variations in the number and size of icebergs passing Cape Farewell can be expected because of the variability of the currents, the amounts of protecting sea ice, and the extreme weather conditions here during the winter.

The maximum iceberg density off southwest Greenland is expected in early and mid-summer.

Most of the icebergs drifting southward from Baffin Bay in the western part of the Davis Strait occur within 100 km to 150 km of the Baffin Island shore. The large-scale drift of icebergs is often related to the presence and drift of the surrounding sea ice cover.

Based on observations[B.6-2], the largest icebergs are most frequently found in separate areas: south of 64 °N and north of 66 °N. South of 64 °N, the mass near the 200 m depth contour varies between $1{,}4 \times 10^6$ tonnes and $4{,}1 \times 10^6$ tonnes with a maximum mass of $8{,}0 \times 10^6$ tonnes. The mean draught is 60 m to 80 m and maximum draught is 138 m. North of 66 °N, the largest icebergs are found north and west of Store Hellefiske Banke, where the mean iceberg mass is about 2×10^6 tonnes and maximum mass 15×10^6 tonnes. In Disko Bay, the masses are in the range of 5×10^6 tonnes to 11×10^6 tonnes with a maximum recorded mass of 32×10^6 tonnes. Mean draught is 80 m to 125 m and maximum draught is 187 m. Between 64 °N and 66 °N, masses are between $0{,}3 \times 10^6$ tonnes and $0{,}7 \times 10^6$ tonnes. The maximum mass is $2{,}8 \times 10^6$ tonnes. Mean draught is 50 m to 70 m and maximum draught 125 m.

It is worth noting that many icebergs have a deep draught and, due to the bathymetry, large icebergs cannot drift into the shallow water regions, e.g. at Fyllas Banke, where the water depth over large areas is only about 100 m. The measurements of iceberg draughts north of 62 °N indicate that an upper limit for a draught of 230 m is exceeded only very rarely. Several submarine cable crushes or breaks have occurred at water depths of about 150 m to 200 m with a maximum depth of 208 m southwest of Cape Farewell.

Table B.6-2 — Greenland meteorological conditions

Parameter		Average annual value
Air temperature	Maximum, degrees Celsius	6
	Minimum, degrees Celsius	–35
Wind speed at 10 m elevation[B.6-3]	10 min average, metres per second	25
Wind direction[B.6-3]	Dominant (direction/percentage occurrence)	NNW/14,4

Table B.6-3 — Greenland oceanographic conditions

Parameter		Average annual value
Waves	Significant wave height, metres	7
	Spectral peak period, seconds	11,9
	Maximum individual wave height, metres	13
	Average direction of extreme waves (from)	SSE
Current	Near-surface maximum speed, centimetres per second	100
	Mid-layer maximum speed, centimetres per second	45
	Bottom maximum speed, centimetres per second	30
Water temperature[B.6-4]	Annual surface maximum, degrees Celsius	7,5
	Summer surface average, degrees Celsius	3,7
	Annual bottom maximum, degrees Celsius	4
	Annual bottom average, degrees Celsius	3,7

Table B.6-4 — Greenland sea ice conditions

Parameter		Average annual value
Sea ice[B.6-5]		
Occurrence	First ice	January
	Last ice	May
Level ice (first-year)	Landfast ice thickness, metres	0,3 to 0,7
Multi-year ice flow	Floe thickness, metres	2 to 3
Icebergs		
Size	Mean mass, million tonnes	0,5 to 1
	Maximum mass, million tonnes	8
	Mean draught, metres	60 to 80
	Maximum draught, metres	120 to 130 (depending on water depth)
Drift	Mean direction (to)	NW
Frequency	Months present	All year

B.7 Beaufort Sea

B.7.1 Description of region

During the intense exploration of the Beaufort Sea in the 1970s and 1980s, a considerable amount of environmental information was collected by the oil industry. A large amount of the data were processed and published as part of the Environmental Impact Statement[B.7-1]. Copies of this report are not easily obtained, but they can be viewed at the Arctic Institute of North America at the University of Calgary, Alberta.

More recently, Devon Canada developed an environmental assessment for its operations[B.7-2].

There are three main bathymetric features in the southeastern Beaufort Sea:

a) the continental shelf, which slopes gently from the coastline to water depths of approximately 100 m;

b) the continental slope, angling steeply from the edge of this shelf to depths of 1 000 m;

c) the trench-like Mackenzie (or Herschel) Canyon, which transects a portion of the shelf.

In most Beaufort locations, the seabed consists of 0,5 m to 35 m of recent marine clays or silty clays that have been carried onto the continental shelf from the mouth of the Mackenzie River. These sediments are grey to black, soft to firm and often contain traces of fine sand and organics. Coarse materials such as sands and fine gravels can also be encountered.

Permafrost is widespread beneath the Beaufort Sea. A relict permafrost layer, formed during the Wisconsin era, is typically encountered between 50 m and 150 m below the seafloor, which can be several hundred metres (or more) in thickness. Permafrost can also be found in fairly close proximity to the seafloor, with ice lensing and visible inter-granular ice often being observed in shallow boreholes. In addition, there are a number of large pingo-like features on the floor of the southern Beaufort Sea. The Canadian Hydrographic Service has identified over 200 of these features between the 20 m and the 200 m isobaths and from 128 °W to 136 °W. Most of these features are between 200 m and 1 000 m in diameter, have sloped sides of less than 5°, and can rise to within 18 m of the sea surface. Pockets of shallow gas and deeper gas hydrate formations are additional factors of note.

The seabed of the Beaufort Sea is heavily scoured by large ice features, both first-year and multi-year ice ridges. The maximum recent gouge depth is 5 m, measured in 30 m water depth on the basis of repetitive mapping surveys in 1978-2008. The spatial frequency of ice gouges varies significantly across the Beaufort shelf. Sonar records indicate that the maximum spatial frequency is almost 20 gouges per kilometre per year for water depths of 0 m to 10 m (over a survey route length of 8 km) and is approximately 6 gouges per kilometre per year for water depths of 20 m to 30 m (over a survey route length of 5 km). New technology using multi-beam sonar is continually improving the knowledge of the scouring in the Beaufort Sea. The Geological Survey of Canada at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia, maintains an up to date database on information related to scouring in the Beaufort Sea.

Table B.7-1 — General information for the Beaufort Sea

Area of coverage	69° N to 75 °N, 125° W to 152° W
Length of ice covered season	early October to late July
Length of open water season	August to early October
Range of water depths, metres	2 to 90, to several thousand

A map of the Beaufort Sea is provided in Figure B.7-1.

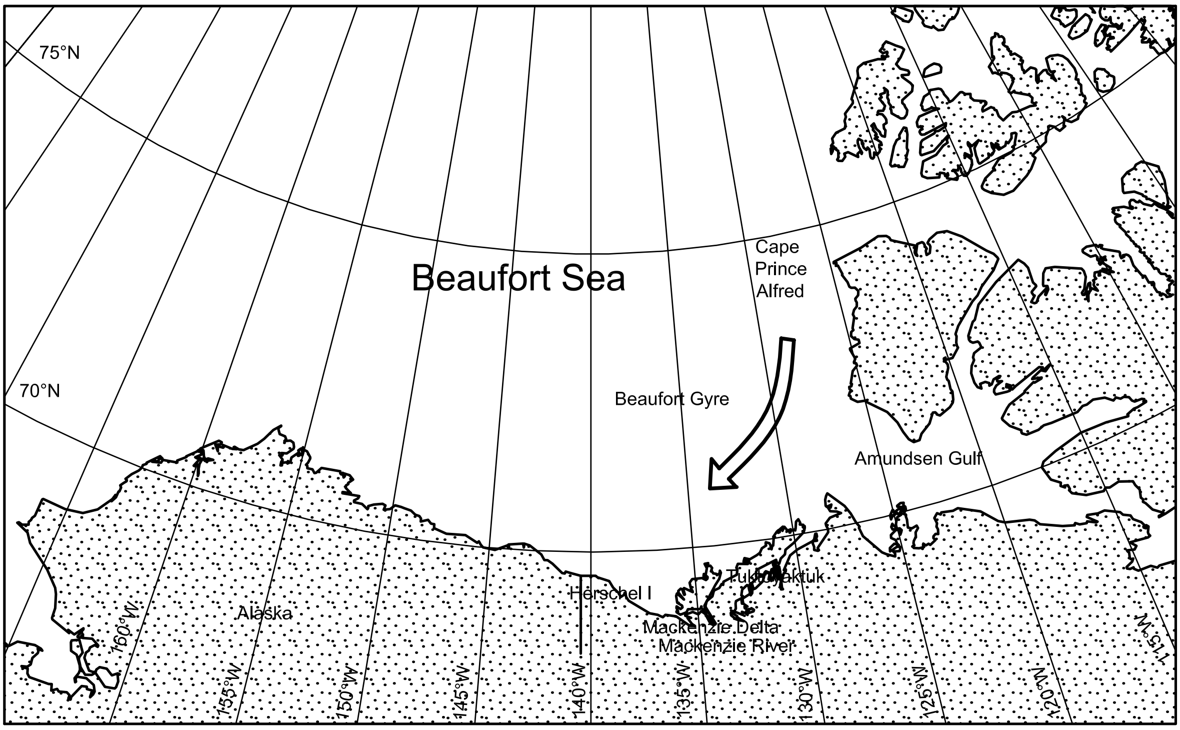


Figure B.7-1 — Map of the Beaufort Sea

B.7.2 Beaufort Sea technical information

B.7.2.1 Climate

Winds in the Beaufort Sea are influenced by the sharp thermal contrast of the land and water to the high coastal lands. Once every 50 years, winds with an hourly average of 29 m/s and a 1 min average of 39 m/s can be expected. The dominant wind direction ranges from the northeast to southeast during any month of the year. Southerly winds are rare during the summer months. From July to September, extended periods of easterly winds are common, although westerly to northwesterly winds in excess of 10 m/s can become persistent. Half of all strong winds with speeds exceeding 14 m/s are from the west or northwest. These winds are responsible for the multi-year ice intrusions into the coastal waters.

B.7.2.2 Hydrology

In the offshore Beaufort, the ocean surface flow is dominated by the clockwise circulation of the Beaufort Gyre, with flow speeds of 5 cm/s to 10 cm/s but which can reach over 100 cm/s during storms, at the southern rim of the Gyre over the western Beaufort Sea.

In the Beaufort Sea, extreme wind, wave, and surge conditions occur during autumn storms prior to freeze-up. Easterly storms are related to a steepening of the surface pressure gradient over the north coast of Alaska, as lows enter the Alaskan Peninsula from the Bering Sea or Gulf of Alaska and are blocked by the polar anticyclone. Easterly storms are characterized by strong winds of long duration (usually several days). Westerly storms are associated with extra-tropical cyclones that track from west to east or northwest to southeast across the Beaufort Sea. The strong winds associated with westerly storms are typically of shorter duration than those for easterly storms. Westerly storms produce positive storm surges along the coast, while easterly storms produce negative surges. Outside the breaker zone, easterly storms produce somewhat higher waves than westerly storms. Close to shore where wave heights are limited by breaking, westerly storms can produce higher waves.

The data in Table B.7-3 are from the Canadian offshore. Although limited tide, current and surge data are available for the Alaskan offshore (with 15 year record at Prudhoe Bay), these data are not included in the table.

B.7.2.3 Ice conditions

The ice in the Beaufort Sea can be subdivided into three regions:

a) arctic polar pack zone;

b) seasonal or transitional (shear) zone;

c) landfast ice zone.

The arctic polar pack is composed of old or multi-year ice with a level ice thickness up to 4,5 m to 5 m and ridges that can be 25 m thick. The polar pack continuously circulates with the currents and winds in the Arctic Ocean, and is present year round. Its degree of penetration into the Beaufort Sea at any given time is dependent on the wind regime. On average, the boundary of the arctic pack lies from near Cape Prince Alfred off Banks Island southwestward to some 200 km north of Herschel Island and then westward some 200 km off the Alaska north coast.

The seasonal transitional zone extends from the edge of the (stationary) landfast ice to the edge of the moving polar pack ice. The width of this zone can vary from a few kilometres to over 300 km, both within a season and from year to year. Although this region is primarily composed of first-year ice, there can be a large number of multi-year and second-year ice floes. This ice is highly dynamic and movement can take place throughout the winter with movements of 3 km/day to 13 km/day. The moving ice results in deformations in the ice sheet and the creation of both ridges and leads. The number of ridges increases rapidly in the first part of the winter and remains relatively constant after February. Ridge heights (sails) can range up to 6 m. If the ridge survives the summer season, it largely desalinates and consolidates to form a multi-year ice ridge.

The landfast ice is extensive and forms out to a water depth of approximately 20 m. This region is composed primarily of first-year ice. Multi-year ice, if present during the freeze-up period, is frozen into the sheet. The ice begins to grow over the late September to mid-October period and reaches a maximum thickness of approximately 1,9 m in late April. In spring, the northwest winds die off and the east and southeast winds become predominant, so that a polynya develops along the edge of the landfast ice. In June, melt begins in the Mackenzie delta and an open water area also develops quickly there. Typically, the Amundsen Gulf fractures in late June and the ice drifts out and decays. The fast ice along the Tuktoyaktuk Peninsula fractures in early July. During a cold summer, the landfast ice along the Tuktoyaktuk Peninsula might not completely break until mid-July. These cold summers occur because northwesterly winds keep the arctic pack close to shore.

Open drift ice conditions do not develop along the entire coastline from Point Barrow to the Canadian Beaufort Sea until the first week of August and an open water route does not develop until the first week of September. Freeze-up in the Beaufort depends to a very great extent on the location of the southern limit of the arctic pack. New ice formation starts among the multi-year floes in late September and spreads both southward and seaward from the coast. By late October much of the ice is at the first-year stage (i.e. > 30 cm thick) right out to the arctic pack.

Ice islands and multi-year hummock fields represent the extreme ice features in this region. Ice islands are of glacial origin and, although rare, are extremely large. Ice islands with an area of up to 697 km^2 and a thickness of up to 60 m have been documented. They present a potential threat to offshore structures in waters greater than 20 m deep.

The most comprehensive and up to date source of information on ice conditions for the Canadian Arctic (including the Beaufort Sea) can be obtained by contacting the Canadian Ice Service[B.7-3]. Information on ice properties and ice strength can be obtained from the Canadian Hydraulics Centre of the National Research Council of Canada[B.7-4] and the DFO Bedford Institute of Oceanography[B.7-5].

Table B.7-2 — Beaufort Sea meteorological conditions

Parameter		Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	20	10 to 30
	Minimum, degrees Celsius	–30	–20 to –40
	Freezing degree days	4 500	3 500 to 5 500
Wind speed at 10 m elevation	10 min average, metres per second	24	18 to 32
Wind direction	Dominant winter direction, degrees	95	ND
	Dominant summer direction, degrees	50 (50 % of strong winds are from N and NW)	ND
Precipitation	Annual rainfall, millimetres	150	100 to 200
	Annual snowfall, millimetres	750	600 to 1 100
Visibility (fog, snow, etc.)	Annual number of days with visibility less than 5 miles	20 % of the time	ND

Table B.7-3 — Beaufort Sea oceanographic conditions

Parameter		Average annual value	Range of annual values
Waves, offshore (> 100 m water depth)	Significant wave height annual maximum, metres	3,7	1,8 to 8,5
	Range of zero-crossing periods, seconds	6,7	4,5 to 9,8
Current	Near-surface maximum speed, centimetres per second	40	20 to 100
	Bottom maximum speed, centimetres per second	2 to 5	1 to 50
Tidal current	Maximum surface speed, centimetres per second	low	ND
Tide	Tidal range (total), metres	0,3	0,3 to 0,6
Wind-induced surge	Water depth increase range total, metres	1	1 to 4
Water salinity	Average surface salinity, parts per thousand	2 to 30	0 to 33
Water temperature	Summer surface maximum, degrees Celsius	10	2 to 12
	Summer surface average, degrees Celsius	5 to 7	0 to 10
Seabed geotechnical – Ice-induced gouge	Gouge depth, metres	0,6	0,1 to 5
	Water depth range, metres	≈ 30	≈ 50
Seismic	Magnitude	3 to 5	5,5 (in 1937) and 6,5 (in 1920)

Table B.7-4 — Beaufort Sea sea ice conditions

Parameter		Average annual value	Range of annual values
Sea ice			
Occurrence	First ice	October	Late September to late October
	Last ice	July	Early July to mid-August
Level ice (first-year)	Landfast ice thickness, metres	1,8	1,5 to 2,3
	Floe thickness, metres	1,8	1,5 to 2,3
Rafted ice	Rafted ice thickness, metres	3	2,5 to 4,5
Rubble fields	Sail height, metres	5	3 to 6
	Length, metres	100 to 1 000	100 to 1 000
Ridges (first-year)	Sail height, metres	5	3 to 6
	Keel depth, metres	25	15 to 28
Stamukhi	Water depth range, metres	20	15 to 30
	Sail height, metres	5 to 10	up to 20
Level ice (second- and multi-year)	Ice thickness, metres	3 to 6	2 to 11
	Floe thickness, metres	5	2 to 20
Ridges (second- and multi-year)	Sail height, metres	Significant	Significant
	Keel depth, metres	20	10 to 35
Rubble fields (second- and multi-year)	Average sail height, metres	2 to 5	3 to 6
	Length annual maximum, metres	750	50 to 2300
Ice movement	Speed in nearshore, metres per second	0,06	0,04 to 0,2
	Speed in offshore, metres per second	0,08	0,06 to 1,0
Icebergs/ice islands			
Size	Mass, million tonnes	10	ND
Frequency	Months present	Poorly known	Poorly known
	Number per year	Poorly known	Poorly known
	Maximum number per month	Rare	Rare

B.8 Chukchi Sea

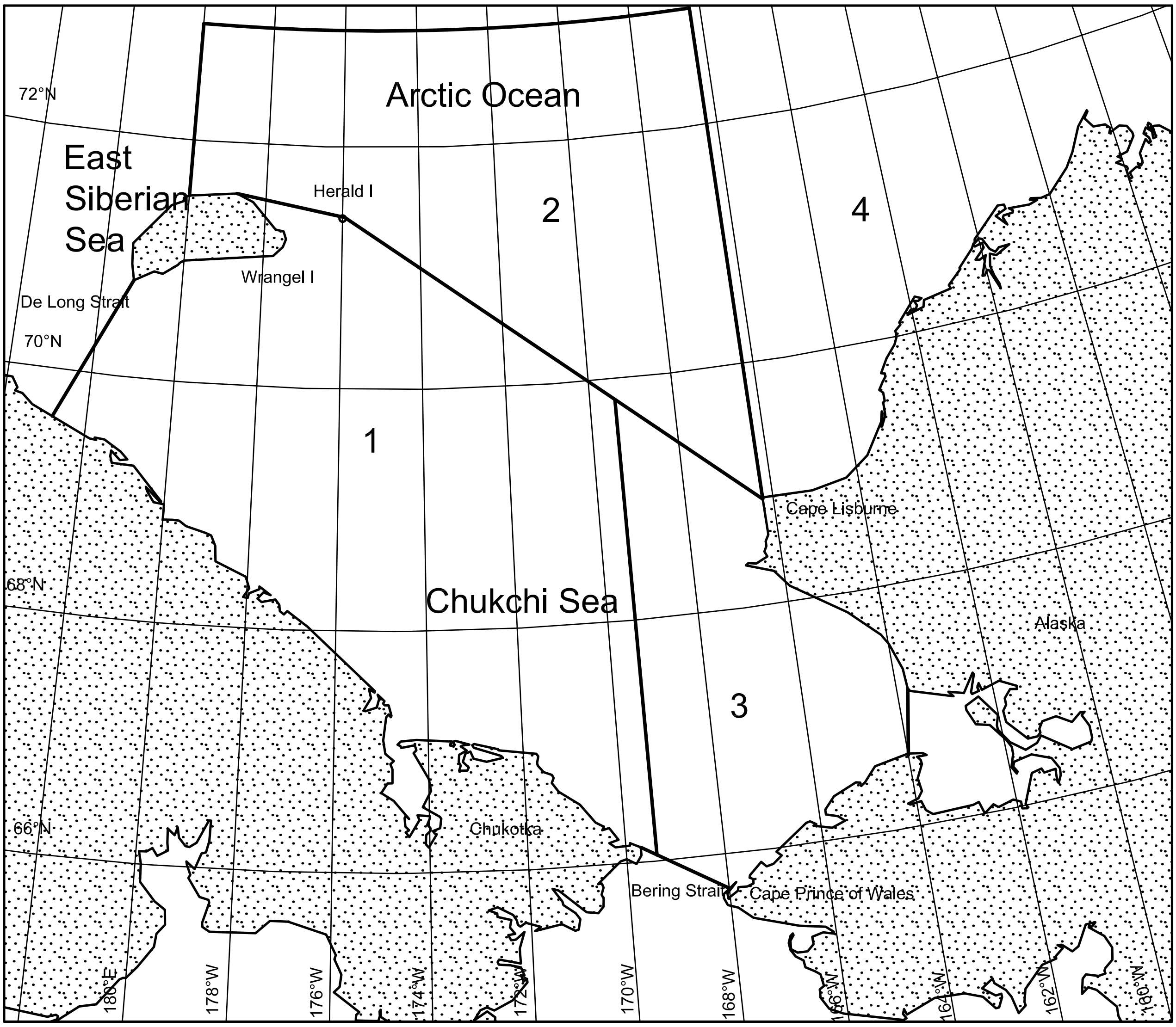
B.8.1 Description of region

The Chukchi Sea is situated between two continents: Asia and America. In the west, the sea adjoins the East Siberian Sea; in the east, it adjoins the Beaufort Sea; and in the south, it is connected with the Bering Sea through the Bering Strait. In the north, the Chukchi Sea has an open border with the Arctic Basin. This northern border is generally defined as the edge of the continental shelf.

Table B.8-1 — General information for the Chukchi Sea

Parameter	Region			
	Southwestern	Northwestern	Southeastern	Northeastern
Area of coverage (See Figure B.8-2)	Key item 1	Key item 2	Key item 3	Key item 4
Length of winter season	10 to 12 months	10 to 12 months	November to mid-June	October to mid-July
Length of summer season	August to September in the southern regions	0 to 2 months	Mid-June to October	Mid-July to September
Water depth range, metres	0 to 50	50 to 100	0 to 50	0 to 50

The sea is divided into four parts for the purpose of this International Standard: southwestern (see Figure B.8-1, key item 1), northwestern (see Figure B.8-1, key item 2), southeastern (see Figure B.8-1, key item 3) and northeastern (see Figure B.8-1, key item 4).



Key

1	southwestern part	3	southeastern part
2	northwestern part	4	northeastern part

Figure B.8-1 — Borders and parts of the Chukchi Sea

B.8.2 Chukchi Sea technical information

B.8.2.1 Climate

The climate of the Chukchi Sea is influenced by the two oceans – the Arctic and Pacific – and the two continents – Asia and America – that surround it. Due to its latitude and large north-south extent, the period of 24 h of darkness lasts 60 days to 80 days in the northern regions but only a few days near the Bering Strait.

Atmospheric circulation, which plays an important role in forming the Chukchi Sea climate, is controlled by the interaction of three centres of atmospheric action: the Arctic High, the Siberian High (in summer it is a low) and the Aleutian Low.

In winter, three to four storms per month, generally coming from the southwest, pass over the sea. Storm passage is usually accompanied by sharp increases in air temperature, increasing cloudiness, strong winds and fog. In spring and summer when the Aleutian Low weakens, the number of storms decreases to about one or two per month, all of which come from the south.

Easterly winds predominate during the major part of the year. In autumn and winter, easterly winds have a northerly component. In the June-July time frame, southwesterly winds are observed over the northern portion of the sea, while southerly winds are observed near the Bering Strait.

In winter months, the mean wind speed is about 6 m/s to 7 m/s; in spring and summer, it is 5 m/s to 6 m/s; and in autumn it increases to 7 m/s to 8 m/s. In the autumn-winter time period, the maximum wind speed can reach 35 m/s to 40 m/s. From May until August, the maximum wind speed does not exceed 28 m/s to 30 m/s.

The number of days with winds $\geqslant 15$ m/s at the coast is about 40 days per year to 70 days per year; the majority occur in October and November, which have such winds for 8 days per month to 10 days per month. Further off the coast in the open sea, winds with these speeds are observed less frequently.

The annual number of days with winds $\leqslant 5$ m/s varies from 40 days in the south to 60 days to 65 days in the north.

For a large portion of the year, freezing air temperatures (< 0 °C) are observed. The duration of air temperature > 0 °C varies from four months near the Bering Strait to one month in the north. The monthly mean air temperature in the winter months varies from –18 °C to –22 °C near the Bering Strait to –26 °C to –28 °C in the north. In April and May, the monthly mean air temperature increases to –8 °C in April and to –2 °C in May. The monthly mean air temperature in July and August is 3 °C to 4 °C in the south and 0 °C to –1 °C in the north. In October, the region cools quickly and the air temperature in the north drops to –10 °C to –12 °C.

The lowest air temperature observed in winter is in the range of –40 °C to –45 °C. The summer high air temperature in the coastal zone and the region near the Bering Strait reaches 28 °C to 30 °C, while in the open sea it does not exceed 15 °C to 20 °C.

B.8.2.2 Hydrology

The vertical water structure of the Chukchi Sea is a result of the interaction of northward flowing Pacific water, surface Arctic water and subsurface Atlantic water. Pacific water flows north through the Bering Strait and propagates in three northerly flowing branches: the Alaska branch in the east, the Herald branch and the De Long branch in the west. The warm water of the Pacific flow is sufficient to fully melt the ice in the southern half of the area. In the western part of the Chukchi Sea, the Chukotka Coastal Current flows southward along the Russian coastline from the East Siberian Sea through the De Long Strait. In winter, this cold water current transports ice southward to the Bering Sea through the western part of the Bering Strait; see Figure B.8-2.

In summer, the warmest water is observed in the southern and eastern regions where the mean water temperature reaches 5 °C to 6 °C. To the north, the water temperature decreases near the marginal ice zone to 0 °C. Along the Alaskan coast, the water temperature sometimes reaches 10 °C to 15 °C. Northward-flowing Bering Sea water, with 31 ‰ salinity, occupies the southern and central parts of the Chukchi Sea. Salinity decreases to the west and, in the De Long Strait, it is on average 27 ‰ to 28 ‰.

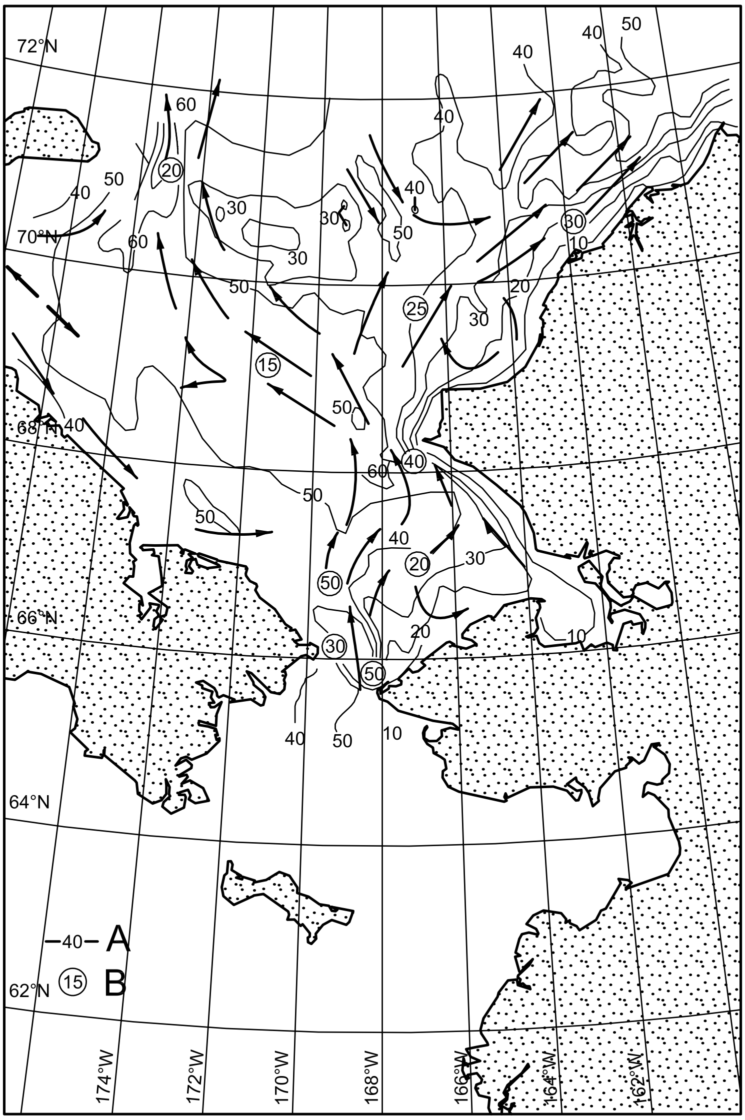
Semi-diurnal tides prevail in the region; tidal currents do not exceed 10 cm/s to 20 cm/s in the open sea and increase slightly in the bays and gulfs. Wind caused fluctuations of sea level are significant and range from 2 m to 3 m in the coastal zones. The maximum sea level fluctuations due to wind are connected with storm transits.

The open water period generally starts in the June-July time frame and lasts through October. The highest wave heights are observed in September until the beginning of October.

Additional data can be found in References [B.8-2] and [B.8-3].

B.8.2.3 Sea ice

The Chukchi Sea is entirely covered by ice from the November-December time frame until the May-June time frame. Prior to water being open, a large part of the Chukchi Sea is covered by thick first-year ice with a predominant thickness of 120 cm to 140 cm. Old ice (multi-year and second-year) can be found in concentrations up to 4/10 in the northern portions. In the south, in severe ice years, the multi-year ice concentration is slightly less than 2/10.



Key

A water depths, expressed in metres

B current speeds, expressed in centimetres per second

Figure B.8-2 — Diagram of the surface currents of the Chukchi Sea[B.8-1]

Landfast ice is not generally found along the Chukotka and Alaska coasts due to the presence of deep water in the coastal zone. Generally, when present, the landfast ice width along the Chukotka coast varies within a range of 5 km to 20 km. The landfast ice width along the Alaskan coast is greater and can reach 40 km to 60 km, but its variability on a monthly or annual scale is large. Shear ridges form on an annual basis northeast of Cape Lisburne. The outer edge of this shear zone migrates seaward as the season progresses and the entire region is subject to seabed gouging from ice ridge keels.

Due to the predominance of easterly winds, a polynya (flaw lead) can be formed beyond the Alaska landfast ice. A similar polynya forms beyond the landfast ice of the Russian coastline under westerly winds.

In winter, concentrations of ridged and deformed ice can reach 6/10 in the southern regions. In the Russian coastal zone, the deformed ice concentration can reach 10/10 coverage.

Ice decay begins in mid-May starting in the south at the Bering Strait. The Herald branch of the northward-flowing current divides the ice cover into two ice parts: the Northern Chukchi massif (to the north of 72 °N) consisting mainly of old ice and the Wrangel ice massif located in the west. By the end of June, all landfast ice is gone.

On average, by the end of September, 8/10 of the sea is ice free. In unfavourable years, ice occupies about half of the sea and the Wrangel ice massif blocks the De Long Strait. During the last three summers (2007-2009), the Chukchi Sea has been totally ice free.

On average, stable ice formation begins in late October along the northern Russian coastline and progresses steadily to the south. The mean time for 10/10 ice coverage is 15 November. Around the end of October to the beginning of November, landfast ice starts to form along the Chukotka coast. Due to the large amount of open water during the last three summers, ice freeze-up was delayed and it was not until mid-December that the Chukchi Sea was 100 % ice covered.

Table B.8-2 — Chukchi Sea meteorological conditions

Parameter		**Region**							
		Southwestern		**Northwestern**		**Southeastern**		**Northeastern**	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**
Air temperature	Maximum, degrees Celsius	27,5	20 to 30	18,2	15 to 20	20	15 to 25	16	10 to 20
	Minimum, degrees Celsius	–46	–40 to –50	–45	–40 to –48	–40	–35 to –45	–44	–40 to –50
	Freezing degree days	ND	ND	ND	ND	3 300	2 500 to 3 600	4 000	3 500 to 4 500
Wind speed at 10 m elevation	10 min average, metres per second	39	ND	43	ND	ND	ND	ND	ND
Wind direction	Dominant winter (direction/ percentage occurrence)	NE/33	ND	NE/33	ND	E/25 to 35	ND	SE/25 to 30	ND
	Dominant summer (direction/ percentage occurrence)	E/29	ND	E/29	ND	W to NW/25 to 30	ND	E/25 to 40	ND

Table B.8-2 (*continued*)

Parameter		Region							
		Southwestern		Northwestern		Southeastern		Northeastern	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**
Precipitation	Annual rainfall, millimetres	380	ND	265	ND	221	150 to 300	157	100 to 200
	Annual snowfall, millimetres	ND	ND	ND	ND	1 143	900 to 1 400	530	300 to 700
Visibility (fog, snow, etc.)	Annual number days with visibility < 1 km	65	ND	75	ND	> 30	20 to 40	> 30	20 to 40

Table B.8-3 — Chukchi Sea oceanographic conditions

Parameter		Region							
		Southwestern		Northwestern		Southeastern		Northeastern	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**
Waves, nearshore (< 100 m water depth)	Significant wave height, metres	6,0 to 8,0	12,0 to 14,0	ND	ND	8	6 to 10	6	5 to 8
	Range of zero-crossing periods, seconds	6 to 7	6 to 10	ND	ND	8 to 12	8 to 14	8 to 10	8 to 12
Current	Near-surface maximum speed, metres per second	15 to 20	ND	ND	ND	> 50	~ 100 (localized regions only)	> 50	~ 100 (localized regions only)
	Bottom maximum speed, metres per second	ND	ND	ND	ND	< 10	8 to 10	< 10	8 to 10
Tidal current	Maximum surface speed, metres per second	ND	ND	ND	ND	15	10 to 20	15	10 to 20
Tide	Tidal range (total), metres	0,3 to 0,6	ND	ND	ND	ND	ND	0,4	0,3 to 0,5
Wind induced surge	Water depth range, total, metres	3,0 to 3,7	ND	ND	ND	30 to 32	29 to 33	30 to 32	29 to 33
Water salinity	Average surface salinity, parts per thousand	28 to 31	ND	ND	ND	8	6 to 10	6	5 to 8

Table B.8-3 (*continued*)

Parameter		Region							
		Southwestern		Northwestern		Southeastern		Northeastern	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Water temperature	Summer surface maximum, degrees Celsius	6 to 7	ND	ND	ND	16	14 to 18	11	10 to 12
	Summer surface average, degrees Celsius	1 to 5	ND	ND	ND	10	8 to 12	6	5 to 7
Seabed geotechnical – Ice-induced gouge	Gouge depth, metres	ND	ND	ND	ND	ND	ND	ND	ND
	Water depth range, metres	ND	ND	ND	ND	ND	ND	ND	ND
Seismic	Magnitude	ND	ND	ND	ND	ND	ND	ND	ND

Table B.8-4 — Chukchi Sea sea ice conditions

Parameter		Region							
		Southwestern		Northwestern		Southeastern		Northeastern	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Occurrence	First ice	Mid-Nov.	Early to late Nov.	Early Oct.	All year	Dec.	Late Nov. to late Dec.	Nov.	Late Oct. to early December
	Last ice	Late June	Early June to late July	Early Aug.	All year	May	Late April to late May	July	Mid-June to late August
Level ice (first-year)	Landfast ice thickness, metres	1,6 to 1,8	1,5 to 2,0	None	None	1,2	0,9 to 1,2	1,5	1,3 to 1,7
	Floe thickness, metres	0,7 to 1,2	0,1 to 1,8	1,2 to 1,8	0,5 to 2,0	0,5 to 1,2	0,5 to 1,8	0,7 to 1,4	0,7 to 1,8
Rafted ice	Rafted ice thickness, metres	ND	ND	ND	ND	1,0 to 2,0	1,0 to 3,0	1,0 to 2,0	1,0 to 3,0
Rubble fields	Sail height, metres	ND	ND	ND	ND	1 to 2	1 to 3	2	1 to 3
	Length, metres	ND	ND	ND	ND	300 to 1 000	300 to 1 000	300 to 1 000	300 to 1 000
Ridges (first-year)	Sail height, metres	1,7 to 2,0	1,5 to 2,5	2,0 to 2,2	1,0 to 2,5	1 to 2	1 to 3	2	1 to 3
	Keel depth, metres	ND	ND	ND	ND	10	8 to 15	10	8 to 15

Table B.8-4 (*continued*)

Parameter		Region							
		Southwestern		Northwestern		Southeastern		Northeastern	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Stamukhi	Water depth range, metres	ND	ND	None	None	None	None	None	None
	Sail height, metres	ND	ND	None	None	None	None	None	None
Level ice (second- and multi-year)	Floe thickness, metres	1,8 to 2,4	ND	3,4 to 3,9	2,0 to 5,0	None	None	2 to 4	2 to 6
Ridges (second- and multi-year)	Sail height, metres	ND	ND	ND	ND	None	None	1 to 2	1 to 3
	Keel depth, metres	ND	ND	ND	ND	None	None	4 to 8	4 to 10
Ice movement	Speed in nearshore, metres per second	ND	ND	ND	ND	0,2 to 0,3	0,1 to 0,3	0,1 to 0,2	0,1 to 0,3
	Speed in offshore, metres per second	0,10 to 0,15	ND	0,15 to 0,20	ND	0,3 to 0,5	0,3 to 0,5	0,2 to 0,3	0,2 to 0,3

B.9 Bering Sea

B.9.1 Description of region

The Bering Sea separates the northern portion of the North American continent, i.e. Alaska, from the Asian continent, specifically the Russian mainland provinces of Chukotka and Kamchatka. The southern boundary of the Bering Sea is the Aleutian Island chain (at approximately 51 °N) and the northern boundary is the Bering Strait at 66 °N.

The Bering Sea is composed of a northeastern shelf with water depths shallower than 200 m and a deep basin in the southwest with water depths greater than 3 000 m. Deep channels in the Aleutian Island chain allow waters from the North Pacific Ocean to mix with Bering Sea water, while the Bering Strait, with a water depth of 50 m and less, provides exchange with the Arctic Ocean.

Table B.9-1 — General information for the Bering Sea

Area of coverage	60 °N **to** 65 °N, **US regions east of** 180 °W	55 °N **to** 60 °N, 169 °W **to** 180 °W	55 °N **to** 60 °N, 169 °W **to** 180 °W	60 °N **to** 65 °N, **Russian regions west of** 180 °W
Length of winter season, days	180	135	180	210
Length of summer season, days	185	230	185	155
Water depth range, metres	50 to 200	50 to 3 000	0 to 200	0 to 200

Only the northern portion of the Bering Sea, generally the region north of the 200 m isobath, is ice covered during the winter. Figure B.9-1 shows regions for which environmental information is provided in the table. Information for the Russian coastal region north of the 60° latitude line is also provided.

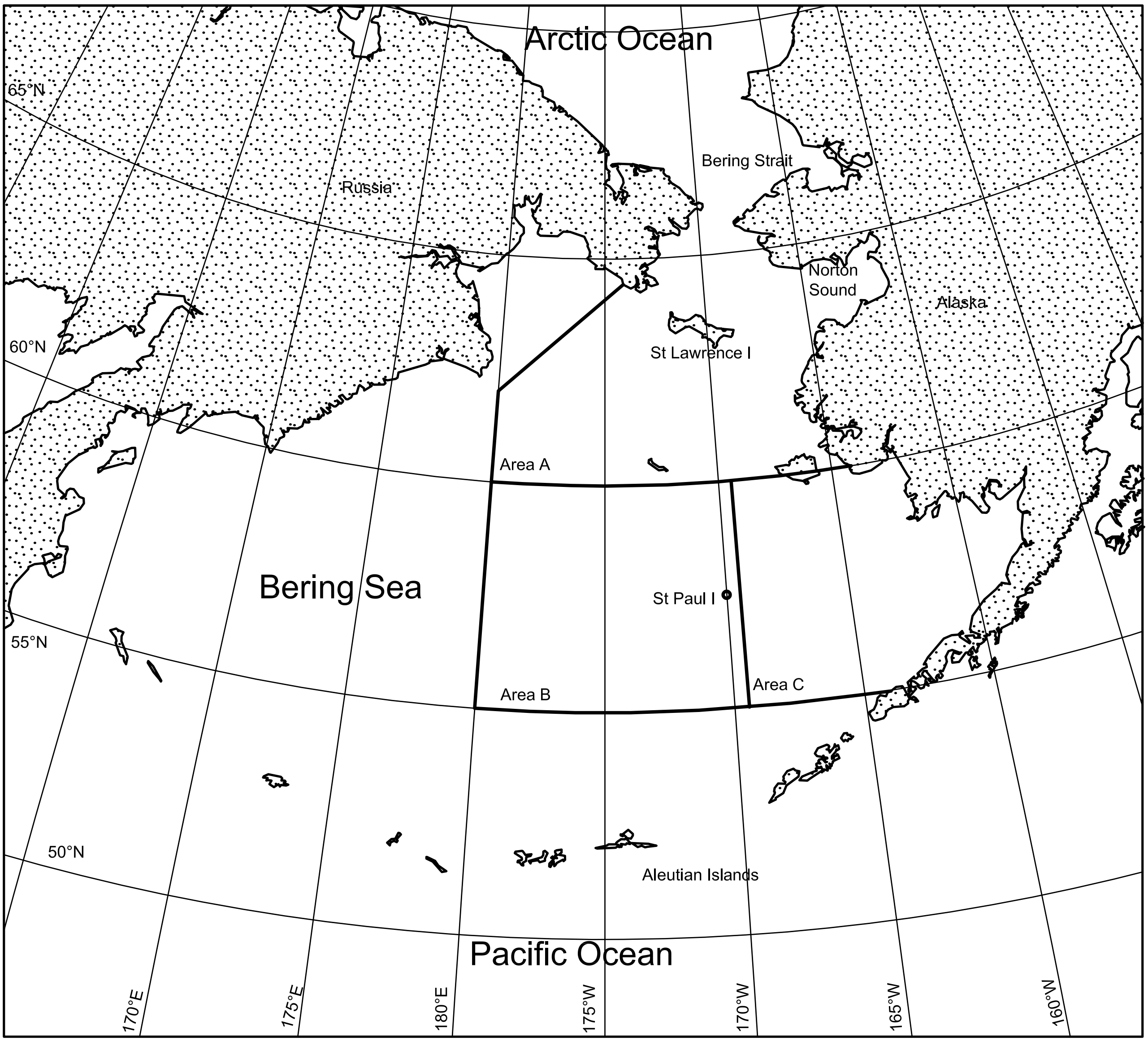


Figure B.9-1 — Map of the Bering Sea[B.9-1]

B.9.2 Bering Sea technical information

B.9.2.1 Climate

The climate of the Bering Sea is affected by storms coming from the Pacific Ocean that enter the Bering Sea in the southwest and head towards the Bering Strait or the Norton Sound region. A secondary storm track, more common in winter, is for storms to come off the Russian mainland and head southeast. Storms are most severe in autumn and winter.

Due to the presence of open water in the southwest, the winter air temperature is generally warmer in the southwest and colder in the ice covered regions of the northeast. In December, the minimum temperatures are –4 °C to –6 °C in the southwest and –38 °C to –40 °C in the northeast. Minimum air temperatures along the Russian coast are slightly warmer and are in the range of −28 °C to −32 °C. Maximum air temperatures are highest in July to August when temperatures of 12 °C are found in the central Bering Sea and 16 °C to 20 °C are found in coastal regions.

Water temperatures range from lows of −2 °C (northeast) to 8 °C (south central) in winter to highs of 2 °C (Bering Strait) to 14 °C (off the Aleutian Islands) in summer.

Precipitation is lightest in June and July with less than 10 % of all observations reporting any form of precipitation except for coastal regions, where this value increases to 20 % off the Russian coast and to 30 % off the Alaskan coast. Reports of precipitation increase subsequently until December when 40 % of all observations in the central Bering Sea report some form of precipitation. A decrease in precipitation of 15 % to 20 % is reported along the coastal regions. These values remain fairly constant through the winter then start to decrease in April and May.

The presence of fog increases from the ice covered periods when it is rarely found (less than 5 % of all observations reported fog) to July and August, when 10 % to 15 % of all observations report visibility of less than 1 km. In September, the presence of fog decreases significantly with 5 % of all observations reporting visibility of less than 1 km. These values hold through autumn until the period of ice formation, when 5 % to 10 % of all observations report visibility of less than 1 km. After ice formation, the presence of fog again decreases.

Wind speeds are lowest in June and July with average speeds around 6 m/s found in the northern and central parts of the sea and slightly higher speeds along the Aleutian Islands. Wind speeds increase through autumn and by November average greater than 10 m/s, except along the Russian coast where they are slightly lower, 8 m/s to 9 m/s. Average wind speeds stay at speeds greater than 10 m/s through winter, except for the northern ice covered regions where they decrease to 8 m/s to 9 m/s. In March and April, speeds again start to decrease towards the low values of June and July, except for the Aleutian Islands where average speeds remain in the greater than 10 m/s range.

Winter winds in the northern Bering Sea are generally from the north and northwest, while the southern regions have a fairly evenly distributed direction. Summer winds in all regions have an even wind direction distribution.

B.9.2.2 Hydrology

Currents in the Bering Sea are variable, with significant exchange of water with the North Pacific Ocean through channels in the Aleutian Islands. There have been reports that, during the summer, there is a closed anti-clockwise eddy type feature in the southwest deep basin with speeds of less than 0,5 m/s, northward flowing waters in the central Bering Sea with speeds of greater than 0,5 m/s, a second anti-clockwise eddy feature south of St Paul Island with speeds less than 0,2 m/s and a weaker anti-clockwise flow in area C of Figure B.9-1. In the northern Bering Strait, current flow is mainly northwards, sometimes at speeds greater than 1,0 m/s, but reversals of flow through the strait have been reported[B.9-2], [B.9-3]. In winter, these features are less pronounced and the entire open water region in the southwest appears to have an anti-clockwise flow. Flow in the north is still mainly towards the Bering Strait, but at a reduced speed of less than 0,2 m/s with reversals due to the passage of storms.

The tracking of ice floes has shown that in winter, the Bering Sea surface currents are generally north to south due mainly to northerly winds. Ice is continually grown in the north, drifts south under the influence of these winds and melts at the southern ice edge near the 200 m isobath[B.9-4].

Most of the Bering Sea is of the mixed tide type, but Norton Sound has a diurnal tide and some of the central Alaskan coast and northern Russian coast have a semi-diurnal tide. The tidal range in most of the Bering Sea is less than 0,6 m. A slightly higher tidal range of 0,6 m to 1,2 m is found in Norton Sound, but in the inner regions of area C of Figure B.9-1 the tidal range can reach 5 m.

The mean wave height from May to August is less than 1,0 m, but starts to increase in September. By November, it is greater than 2,0 m and it stays at this value in the open water regions until March, when it starts to decrease back to a value less than 1,0 m.

Ice starts to form in northern coastal regions in October and, by November, sea ice starts to grow in the northern offshore region. It reaches its maximum extent by late March and by June is found only in the northern and Bering Strait regions. The Bering Sea is entirely ice-free by the middle to the end of July. The extent of sea ice is greatly influenced by wind, as a prolonged northerly wind pushes ice further southward at reduced concentrations while a prolonged southerly wind compresses the ice northwards and creates high ice concentrations. The wind also creates polynyas behind the large islands of the Bering Sea, some of which can be up to tens of kilometres in extent.

Most of the ice found in the Bering Sea is locally grown and, since it is ice-free in summer, the ice is of the first-year type. Reports of multi-year ice passing through the Bering Strait during a reversal can be found in the literature, but this ice generally stays north of St Lawrence Island. Stamukha type features can be found in Norton Sound, especially in the eastern and southern regions where a higher tidal range is present. All first-year ice features are present in the Bering Sea. As there are no glaciers found in the Bering Sea coastal regions, icebergs are not a concern.

Table B.9-2 — Bering Sea meteorological conditions

Parameter		**Offshore Alaska area A**		**Offshore Alaska area B**		**Offshore Alaska area C**		**Offshore coastal Russia**	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**
Air temperature	Maximum, degrees Celsius	16	14 to 20	14	12 to 16	18	14 to 20	16	14 to 20
	Minimum, degrees Celsius	–36	–32 to –40	–20	–18 to –24	–28	–24 to –32	–30	–24 to –36
	Freezing degree days	2 300	ND	200	ND	1 500	ND	ND	ND
Wind speed at 10 m elevation	10 min average, metres per second	25	23 to 28	28	27 to 30	29	27 to 30	32	29 to 35
Wind direction	Dominant winter (direction/ percentage occurrence)	NE/40	ND	NE/25	ND	N to NE/40	ND	N to NE/45	ND
	Dominant summer (direction/ percentage occurrence)	SW/20	ND	SE to W/60	ND	SW to W/45	ND	None	ND
Precipitation	Annual rainfall, millimetres	600	ND	590	ND	500	ND	ND	ND
	Annual snowfall, millimetres	1 400	ND	1400	ND	1 200	ND	ND	ND
Visibility (fog, snow, etc.)	Annual number days with visibility < 1 km	115	ND	130	ND	110	ND	120	ND

Table B.9-3 — Bering Sea oceanographic conditions

Parameter		Offshore Alaska area A		Offshore Alaska area B		Offshore Alaska area C		Offshore coastal Russia	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**
Waves, nearshore (< 100 m water depth, except as noted)	Significant wave height, metres	5 (50 m water depth)	4 to 7	7	5 to 8	7	5 to 8	7	5 to 8
	Range of zero-crossing periods, seconds	ND	ND	ND	ND	ND	ND	ND	ND
Current	Near-surface maximum speed, centimetres per second	60	50 to 75	ND	ND	ND	ND	ND	ND
	Bottom maximum speed, centimetres per second	60	50 to 70	ND	ND	ND	ND	ND	ND
Tidal current	Maximum surface speed, centimetres per second	ND	ND	ND	ND	ND	ND	ND	ND
Tide	Tidal range (total), metres	0,6 to 1,2	ND	0,6	ND	1,2 to 5	ND	ND	ND
Wind induced surge	Water depth range total, metres	ND	ND	ND	ND	ND	ND	ND	ND
Water salinity	Average surface salinity, parts per thousand	32	30 to 33	32	30 to 33	32	30 to 33	32	30 to 33
Water temperature	Summer surface maximum, degrees Celsius	16	10 to 18	12	10 to 14	13	10 to 14	12	10 to 14
	Summer surface average, degrees Celsius	10	7 to 14	8	7 to 9	9	8 to 11	8	7 to 9
Seabed geotechnical – Ice-induced gouge	Gouge depth, metres	0,25	0,25 to 1,0	NA	NA	ND	ND	ND	ND
	Water depth range, metres	0 to 20	0 to 30	NA	NA	ND	ND	ND	ND
Seismic	Magnitude	ND	ND	ND	ND	ND	ND	ND	ND

Table B.9-4 — Bering Sea sea ice conditions

Parameter		Offshore Alaska area A		Offshore Alaska area B		Offshore Alaska area C		Offshore coastal Russia	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Occurrence	First ice	1 Dec	1 Nov. to 15 Dec.	1 Jan.	15 Dec. to 1 Feb.	15 Dec.	1 Dec. to 1 Jan.	1 Dec.	15 Nov. to 15 Dec.
	Last ice	1 June	1 May to 1 July	15 May	1 May to 1 June	15 May	1 May to 1 June	1 July	15 June to 15 July
Level ice (first-year)	Landfast ice thickness, metres	1,0	0,9 to 1,5	NA	NA	0,6	0,5 to 0,8	1,0	0,9 to 1,5
	Floe thickness, metres	1,0	0,9 to 1,2	1,0	0,9 to 1,2	0,5	0,3 to 0,6	1,0	0,9 to 1,2
Rafted ice	Rafted ice thickness, metres	3,0	2,5 to 4,0	3,0	2,5 to 4,0	2,0	1,5 to 3,0	3,0	2,5 to 4,0
Rubble fields	Sail height, metres	2,5	2 to 3	3 to 4	3 to 5	2	2 to 3	2,5	2 to 3
	Length, metres	100 to 200	100 to 400	100 to 200	100 to 500	100 to 200	100 to 400	100 to 200	100 to 400
Ridges (first-year)	Sail height, metres	2,5	2 to 3	3 to 4	3 to 5	2	2 to 3	2,5	2 to 3
	Keel depth, metres	10	10 to 20	15	15 to 25	10 to 15	10 to 20	10	10 to 20
Stamukhi	Water depth range, metres	5 to 15	5 to 20	NA	NA	NA	NA	5 to 15	5 to 20
	Sail height, metres	5	4 to 10	NA	NA	NA	NA	5	4 to 10
	Length, metres	50 to 100	50 to 150	NA	NA	NA	NA	50 to 100	50 to 150
Ice movement	Speed nearshore, metres per second	0,5	0,5 to 1,0	NA	NA	0,5	0,5 to 1,0	0,5	0,5 to 1,0
	Speed offshore, metres per second	0,5	0,5 to 1,0	0,5	0,5 to 1,0	0,5	0,5 to 1,0	0,5	0,5 to 1,0

B.10 Cook Inlet

B.10.1 Description of region

Cook Inlet is a southwest-northeast trending 350 km long estuary on the southern coast of Alaska approximately centred at 60 °N, 152 °W. The inlet is divided into the Head, Upper and Lower regions. The Head, or northernmost region, is comprised of two long narrow bays both of which have large tidal flats at low tide. Upper Cook Inlet is 95 km long and its width varies from 20 km to 30 km with a 16 km wide restriction at its southern end. Lower Cook Inlet, the southernmost region, is over 200 km in length and its width varies from 20 km to 30 km in the north to over 90 km in the south. There are three entrances to the Gulf of Alaska in the southeast end of Lower Cook Inlet. The region surrounding Cook Inlet is mainly composed of tidal marshlands.

Water depths within the inlet are variable, with shallow tidal regions in the Head region, having water depths generally less than 70 m in the Upper Inlet and water depths generally less than 150 m in the Lower Inlet. Near the mouth of the inlet, water depths drop to greater than 300 m.

Daylight ranges from 5,7 h in December to 19,1 h in June.

Table B.10-1 — General information for Cook Inlet

Area of coverage	Head and Upper Cook Inlet only
Length of winter season	October to April
Length of summer season	May to September
Range of water depths, metres	0 to 100

A map of Cook Inlet is provided in Figure B.10-1.

B.10.2 Cook Inlet technical information

B.10.2.1 Climate

The climate of Cook Inlet is predominantly maritime as influenced by the presence of ocean waters. Summer air temperatures are generally cooler and winter air temperatures generally warmer than the inland portions of Alaska. Rainfall and snowfall are also influenced by the ocean presence and both are higher than inland regions.

Summer runs from May to August, with July being the warmest month on average. In autumn (September to mid-October), the mean daily air temperature tends to fall below 0 °C towards the end of this period. Winter is from mid-October to early April, with January being the coldest month on average; the mean daily air temperature tends to rise above 0 °C at the end of this period. Spring is from April to May.

Late spring and early summer are the driest periods; rainfall starts in summer and increases through autumn, which is considered the rainy season. Snowfall starts in late autumn and continues into early spring. Monthly average and maximum wind speeds are relatively constant throughout the year, with the mildest conditions being found in July and August. Winds in the summer months are generally from the south or southwest, while those in the winter months come from the north or northeast. Coastal areas can be subject to strong topographically enhanced winds during the winter season.

B.10.2.2 Hydrology

Cook Inlet receives on average slightly over 1 500 m^3/s fresh water from the rivers that empty into it. Contained within this water is a large amount of sediment that flows towards the south. In the summer period, due to increased river flow, a net freshwater outflow to the Gulf of Alaska of over 100 000 m^3/s occurs.

The Upper and Lower Inlets have a weak anti-clockwise circulation that brings warmer and clearer ocean water up their east side and cold sediment-laden water down their west side. The net southward flow has a peak in summer at about 0,2 m/s and a low in winter of about 0,1 m/s. The net northward flow averages about 0,05 m/s in both seasons.

Tidal currents dominate current speeds in the inlet. Tidal currents in the Upper Inlet are considered reversing, with a period of no motion before accelerating in the opposite direction. Tidal currents in the Lower Inlet are considered rotary, and never go slack while changing directions. Maximum tidal currents are 1,0 m/s to 1,5 m/s in the Lower Inlet and greater than 2,0 m/s in the Upper Inlet. Spring tides can result in currents greater than 4,0 m/s in constrictions such as the Forelands between the Upper and Lower Inlets.

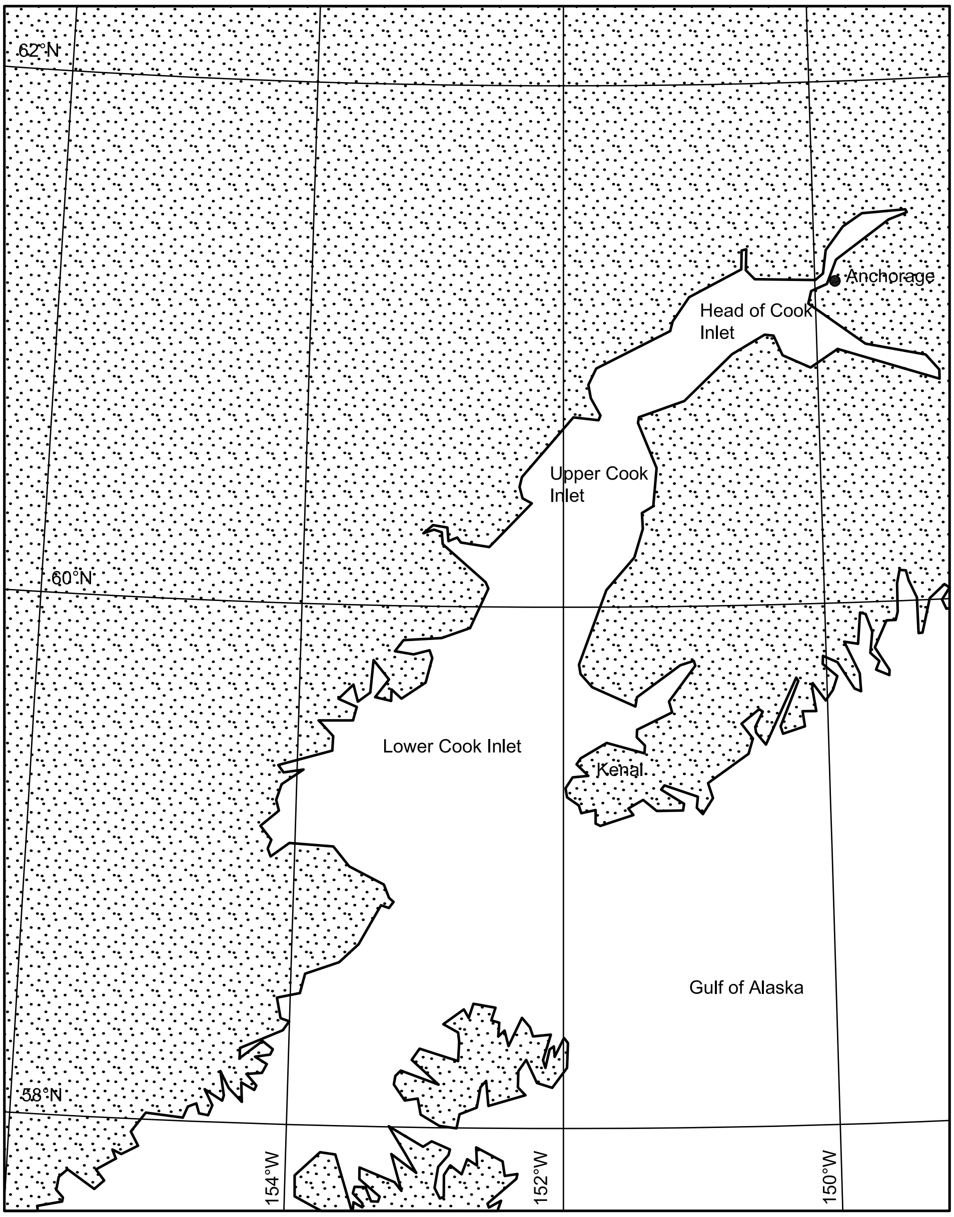


Figure B.10-1 — Map of Cook Inlet

Tidal ranges in Cook Inlet are some of the largest in the world. Tides are semi-diurnal, with two highs and two lows each lunar day. Tidal range varies through the inlet, with a mean range of 3,47 m at Kennedy Inlet in the south to a mean range of 7,9 m at Anchorage in the north. Spring tide ranges can be 1,5 m larger than the mean ranges. Tidal ranges tend to be larger on the east side of the inlet as compared to the west side.

The inlet is subject to seasonal ice cover. Ice starts to form in October and by mid-December covers a large portion of the Upper Inlet. The maximum ice extent occurs by late February or early March, while generally by mid-April all ice has melted.

Ice is found in the inlet, especially in the Head and Upper regions, even in mild years. In severe years, ice drifting out of the northern regions is also found in Lower Cook Inlet. Due to the high tidal range and fast currents, the ice environment tends to be very dynamic and there is very little landfast ice cover found in the inlet. Drifting ice is continually in motion, with a predominant north to south drift.

River, estuarine and sea ice are found in Cook Inlet. Features encountered include level ice, rafts, ridges and rubble/stamukhi. Pieces of freshwater river and estuarine ice can become entrained in the floating pack ice, posing an additional hazard due to the higher strength of these fragments. Ice tends to form on the frozen tidal flats (beach ice); under action of the tide, the ice floats free and becomes rubble or forms stamukhi.

B.10.2.3 Environment parameters

Tables B.10-2 to B.10-4 contain example environment parameters for the Head and Upper Cook Inlet regions. The meteorological parameters are based largely on measurements made at land stations at Kenai and Anchorage. Oceanographic data have been extracted from References [B.10-1] and [B.10-2].

Table B.10-2 — Cook Inlet meteorological conditions

Parameter		Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	17	30
	Minimum, degrees Celsius	–20	–43
	Freezing degree days (with respect to 0 °C)	1 168	ND
Wind speed at 10 m elevation, 10 min average	Maximum, metres per second	20	32
Wind direction	Dominant winter (direction/percentage occurrence)	N to NE/65	ND
	Dominant summer (direction/percentage occurrence)	S to SW/60	ND
Precipitation	Annual rainfall, millimetres	430	350 to 700
	Annual snowfall, millimetres	1 370	1 000 to 1 600
Visibility	Days with fog	76	40 to 120
	Days with visibility less than 5 miles	4	0 to 20

Table B.10-3 — Cook Inlet oceanographic conditions

Parameter		Average annual value	Range of annual values
Waves	Maximum significant wave height, metres	4	5,5
	Range of associated zero-crossing periods, seconds	6 to 7	8 to 9
Current	Maximum tide and circulation, metres per second	4	0 to 4
Tide	Maximum total range, metres	8	0 to 8
Wind-induced surge	Maximum total range, metres	1	0,1 to 1,5
Water salinity	Maximum surface, parts per thousand	30	25 to 35
	Minimum surface, parts per thousand	10	5 to 15
Water temperature	Maximum surface, degrees Celsius	14	12 to 16
	Minimum surface, degrees Celsius	–2	–2
Seabed geotechnical – Ice-induced gouge	Gouge depth, metres	ND	ND
	Water depth range, metres	ND	ND
Seismic, ISO spectrum	Spectral acceleration, $T = 0{,}2$ sec (g)	ND	1
	Spectral acceleration, $T = 1{,}0$ sec (g)	ND	0,4

Table B.10-4 — Cook Inlet sea ice conditions

Parameter		Average annual value	Range of annual values
Occurrence	First ice	25 Nov.	17 Oct. to 17 Dec.
	Last ice	7 April	10 March to 15 May
Level ice (first-year)	Landfast ice thickness, metres	0,5	0,2 to 0,6
	Floe thickness, metres	0,8	0,6 to 0,9
Rafted ice	Thickness, metres	1,3	1,2 to 1,5
Rubble fields	Sail height, metres	1	0,5 to 2
	Length, metres	100s	100s
Ridges (first-year)	Sail height, metres	1	1 to 2
	Keel depth, metres	4 to 6	4 to 10
Stamukhi	Water depth range, metres	0 to 8	0 to 8
	Sail height, metres	5	4 to 12
Ice movement	Speed, metres	4	3 to 4,5

B.11 Okhotsk Sea

B.11.1 Description of region

The Okhotsk Sea is a sea of the Pacific Ocean located in its northwestern regions. The Kuril Islands separate it from the Pacific Ocean, the Kamchatka Peninsula is its eastern boundary and the coast of Asia is its northern and western boundary.

The Okhotsk Sea is about 2 500 km in width from the southwest to the northeast and is 1 500 km wide from the east to the west. The area of the Okhotsk Sea, including islands, is over $1,5 \times 10^6$ km^2, its maximum depth is 3 374 m, and the average depth is about 800 m.

Total annual volume of river water flowing into the Okhotsk Sea is 586 km^3, of which the Amur River contributes 371 km^3.

A map of the Okhotsk Sea is provided in Figure B.11-1.

Table B.11-1 — General information for the Okhotsk Sea

Parameter	Northern Okhotsk Sea — Magadan region	Southern Okhotsk Sea off the northeastern Sakhalin Island coast	Southern Okhotsk Sea off the southeastern Sakhalin Island coast
Area of coverage	58 °N to 62 °N	51 °N to 56 °N	46 °N to 51 °N
Length of winter season, months	6 to 7	7	7
Length of summer season, months	5 to 6	5	5
Water depth range, metres	0 to 700	0 to 300	0 to 200

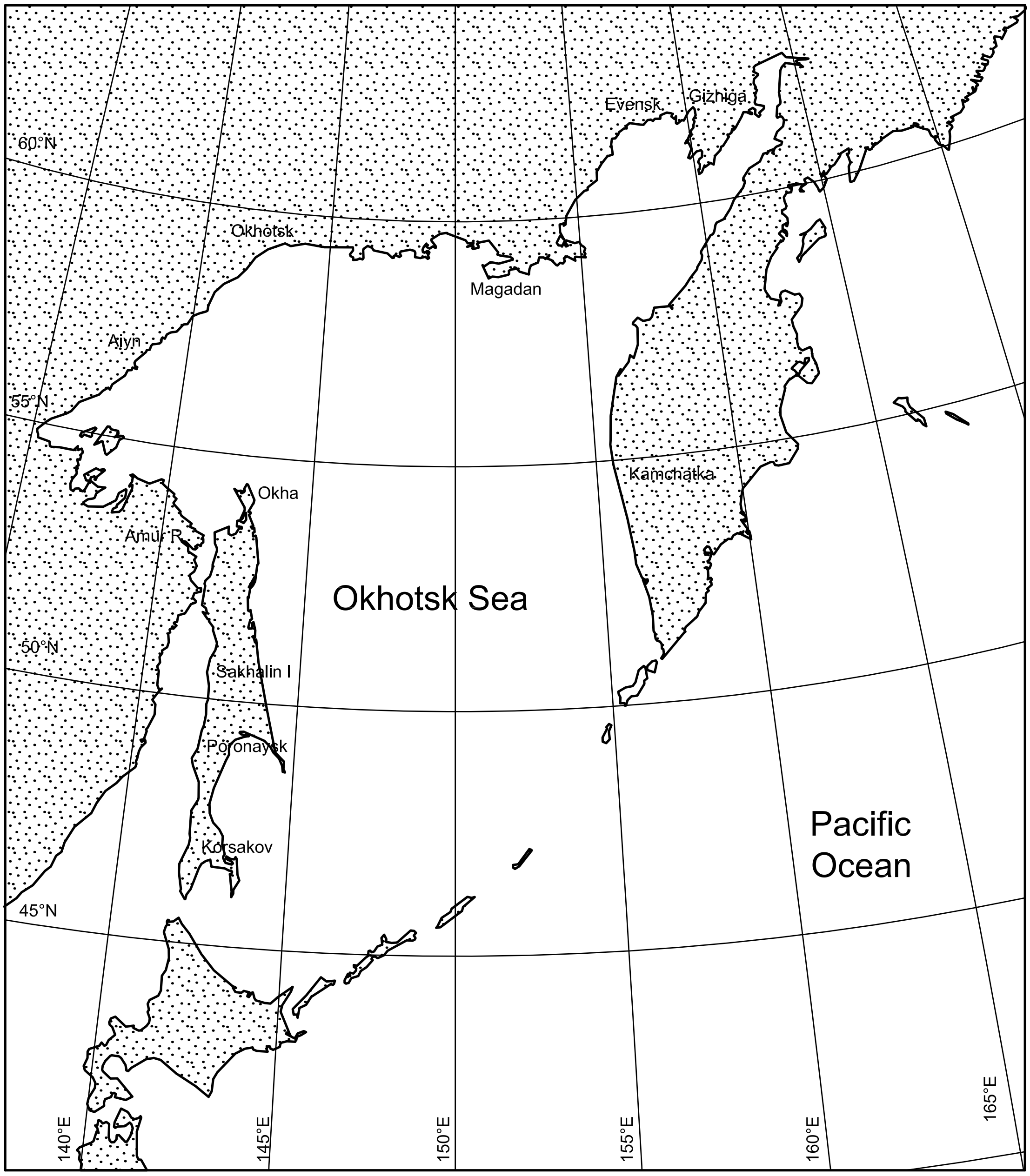


Figure B.11-1 — Map of the Okhotsk Sea

B.11.2 Okhotsk Sea technical information

B.11.2.1 Climate

The Okhotsk Sea is situated in the monsoon climatic zone of the temperate latitudes. The major part of the sea is characterized by cold and long winters. Hence, the Okhotsk Sea marine climate is similar to a polar sea type climate. The average annual air temperature ranges from –7 °C in the north to 5 °C in the south.

During the period from October to April, the marine area is affected by the winter monsoon, characterized by north and northwest winds about 75 % of the time. The summer monsoon prevails from May to September and is characterized by south and southeastern winds.

The average annual amount of precipitation in the north is 230 mm to 300 mm; in the south it is 800 mm to 1 000 mm.

B.11.2.2 Hydrological conditions

The temperature of the Okhotsk Sea surface water ranges from –1,8 °C to 2,0 °C in winter and from 10 °C to 18 °C in summer. In summer, warmer water temperatures reach to a depth of 30 m to 75 m, but do not reach the strata cooled during winter. Hence, at the depth of about 150 m a negative temperature stratum is present (–1,6 °C). Warmer waters of the Pacific Ocean form the lower stratum with temperatures of 2,0 °C to 2,5 °C at a depth of 750 m to 1 500 m.

The average water salinity is 33 ‰ to 34 ‰.

The Okhotsk seawater masses are characterized by a cyclonic (i.e. anti-clockwise) circulation, caused by the atmospheric cyclone circulation above the seawater. Apart from the main cyclonic circulation system in the central part of the sea and minor ones eastwards and northeastwards off Sakhalin Island, three permanent anti-cyclonic circulation systems are observed. Two of them are located offshore of the Kamchatka Peninsula, and the third is located in the southern part of the sea.

Offshore of the Kamchatka Peninsula and off Sakhalin Island, permanent cyclonic currents are observed with a speed range from 15 cm/s to 90 cm/s.

The Okhotsk Sea water dynamics are significantly influenced by tides accompanied by strong currents. The tides, caused by the tidal wave coming from the Pacific Ocean, are characterized by their mixed character with the daily component prevailing. The biggest tidal amplitude (about 13 m) is observed in the Penzhin Gulf. In other parts of the Okhotsk Sea, it varies from 1 m to 7 m.

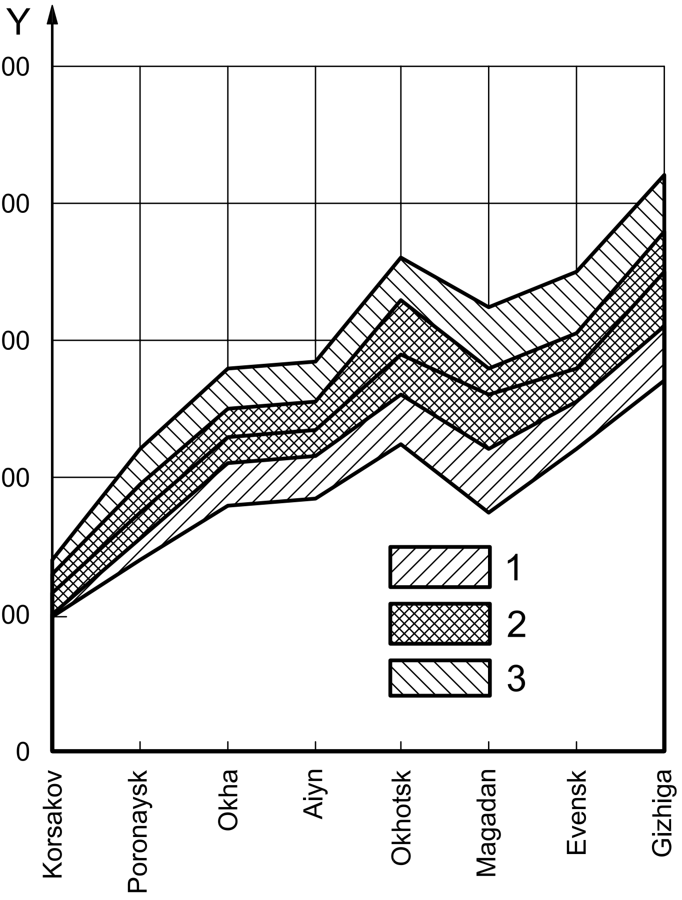
The wave climate is highly dynamic, particularly during the autumn and early winter periods and during typhoons. Individual wave heights can reach 12 m to 20 m during these periods.

A large portion of the Okhotsk Sea, 60 % to 97 % depending upon the winter severity, is covered with ice. Ice can be found in the area for six months per year to seven months per year on average.

Icebergs do not occur in the Okhotsk Sea.

Earthquakes can occur in the Okhotsk Sea and surrounding islands. Both earthquakes and tsunamis should be considered as part of the design process.

Figure B.11-2 presents a range of freezing degree days for a number of stations around the Okhotsk Sea.



Key

X station

Y C_{FDD}

1 mild winter

2 average winter

3 severe winter

Figure B.11-2 — Range of freezing degree days for a number of stations around the Okhotsk Sea

Table B.11-2 — Okhotsk Sea meteorological conditions

Parameter		Northern Okhotsk Sea – Magadan region		Southern Okhotsk Sea off the northeastern Sakhalin Island coast		Southern Okhotsk Sea off the southeastern Sakhalin Island coast	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	28	25 to 31	33	32 to 34	32	26 to 36
	Minimum, degrees Celsius	–45	–38 to –51	–40	–36 to –44	–36	–29 to –42
	Freezing degree days	3 000	1 900 to 4 200	2 400	2 000 to 2 800	1 950	1 500 to 2 450
Wind speed at 10 m elevation	10 min average, metres per second	30	24 to 36	28	24 to 34	29	22 to 37
Wind direction	Dominant winter (direction/percentage occurrence)	NNE/82	NNE/66 to 91	WNW/73	WNW/54 to 85	WNW/73	WNW/54 to 85
	Dominant summer (direction/percentage occurrence)	SSW/50	SSW/42 to 57	SSE/41	SSE/28 to 50	ESE/47	ESE/36 to 67
Precipitation	Annual rainfall, millimetres	490	467 to 521	551	517 to 593	729	582 to 962
	Annual snowfall, millimetres	91	80 to 100	339	313 to 386	309	268 to 361
Visibility (fog, snow, etc.)	Annual number days with visibility < 1 km	75	61 to 88	82	58 to 101	72	45 to 129

Table B.11-3 — Okhotsk Sea oceanographic conditions

Parameter		Northern Okhotsk Sea — Magadan region		Southern Okhotsk Sea off the northeastern Sakhalin Island coast		Southern Okhotsk Sea off the southeastern Sakhalin Island coast	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Waves, nearshore (< 100 m water depth)	Significant wave height, metres	9,0	7,0 to 11,5	11,2	9,5 to 14,0	11,2	9,5 to 14,1
	Range of zero-crossing periods, seconds	9,1	8,0 to 11,9	10,1	9,1 to 14,9	10,1	9,0 to 15,0
Waves, nearshore (> 100 m water depth)	Significant wave height, metres	9,8	7,0 to 13,0	12,2	9,7 to 14,5	12,3	9,9 to 15,2
	Range of zero-crossing periods, seconds	10,1	8,1 to 12,3	10,3	9,2 to 15,0	10,4	9,4 to 15,3
Current	Near-surface maximum speed, centimetres per second	120	80 to 211	171	139 to 338	110	90 to 130
	Mid-layer maximum speed, centimetres per second	90	70 to 130	101	89 to 112	90	70 to 110
	Bottom maximum speed, centimetres per second	50	40 to 90	75	61 to 130	60	30 to 70
Tidal current	Maximum surface speed, centimetres per second	60	45 to 100	110	110	80	80
Tide	Tidal range (total), metres	5,4	5,0 to 11,0	2,4	2,0 to 2,8	2,0	1,7 to 2,2
Wind-induced surge	Water depth range total, metres	0,8	0,6 to 1,1	0,7	0,6 to 1,1	0,9	0,5 to 1,5
Water salinity	Average surface salinity, parts per thousand	32	30 to 35	32,3	31,7 to 32,6	32,1	31,5 to 32,7
	Average mid-layer salinity, parts per thousand	33	30 to 35	33,3	31,8 to 34,6	33,2	31,7 to 34,5
Water temperature	Summer surface maximum, degrees Celsius	9,9	8,0 to 10,7	14,8	12,2 to 16,8	15,4	13,0 to 16,2
	Summer surface average, degrees Celsius	2,0	1,8 to 3,0	10,8	10,4 to 11,5	11,2	10,5 to 12,1
Seabed geotechnical — Ice-induced gouge	Gouge depth, metres	0,6	ND	1,8	1,5 to 2,5	0,3	0,2 to 0,4
	Water depth range, metres	0 to 25	0 to 25	0 to 26	0 to 26	0 to 10	0 to 10
Seismic	Magnitude	ND	6,5 to 7,2	ND	7,0 to 7,5	ND	7,0 to 7,5

Table B.11-4 — Okhotsk Sea sea ice conditions

Parameter		Northern Okhotsk Sea — Magadan region		Southern Okhotsk Sea off the northeastern Sakhalin Island coast		Southern Okhotsk Sea off the southeastern Sakhalin Island coast	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Occurrence	First ice	15 Oct.	10 to 30 Oct.	1 Nov.	25 Oct. to 10 Nov.	30 Oct.	25 Oct. to 20 Nov.
	Last ice	30 June	10 June to 15 July	30 May	20 May to 25 June	30 April	20 April to 30 May
Level ice (first-year)	Landfast ice thickness, metres	1,3	1,1 to 1,6	1,13	1,06 to 1,21	0,6	0,45 to 0,85
	Floe thickness, metres	1,3	1,1 to 1,6	0,9	0,7 to 1,3	0,9	0,8 to 1,20
Rafted ice	Rafted ice thickness, metres	2,2	1,9 to 2,9	2,40	2,00 to 3,30	1,1	1,0 to 2,5
Rubble fields	Sail height, metres	4,0	3,3 to 5,1	5,1	4,4 to 6,0	5,0	4,5 to 6,0
	Length, metres	NA	NA	110	80 to 160	100	70 to 150
Ridges (first-year)	Sail height, metres	4,8	3,9 to 5,4	6,2	5,4 to 8,1	5,5	4,5 to 7,0
	Keel depth, metres	16,0	12,0 to 20,0	20,7	19,8 to 23,2	17	16 to 20
Stamukhi	Water depth range, metres	0 to 20	0 to 20	0 to 26	0 to 26	0 to 20	0 to 20
	Sail height, metres	8,0	6,0 to 10,0	11,5	9,3 to 18,0	6,0	5,5 to 8,0
Ice movement	Speed nearshore, metres per second	0,6	0 to 1,0	1,79	1,60 to 2,01	1,1	0,9 to 1,4
	Speed offshore, metres per second	0,5	0 to 1,0	1,60	1,5 to 1,8	1,0	0,9 to 1,4

B.12 Tatar Strait

B.12.1 Description of region

The Tatar Strait is the northern part of the Sea of Japan and lies between Sakhalin and the Asian mainland.

The Tatar Strait varies in width from less than 10 km at its northern extent to over 300 km at the southern tip of Sakhalin Island. The area of the Tatar Strait is 35 000 km^2 and its water depth ranges from less than 10 m in the north to over 1 000 m at the southern tip of Sakhalin Island.

The main inflow of water is from the Amur River water, which flows through its northern end. The average annual discharge varies from 6 000 m^3/s (1980) to 12 000 m^3/s (1957), leading to an average of 9 800 m^3/s or 310 km^3 per year.

Table B.12-1 — General information for the Tatar Strait

Parameter	Offshore Russian mainland	West coast of Sakhalin Island
Area of coverage	46 °N to 52 °N	48 °N to 52 °N
Length of winter season, months	6 to 7	6 to 7
Length of summer season, months	5 to 6	5 to 6
Water depth range, metres	10 to 400	10 to 400

A map of the Tatar Strait is provided in Figure B.12-1.

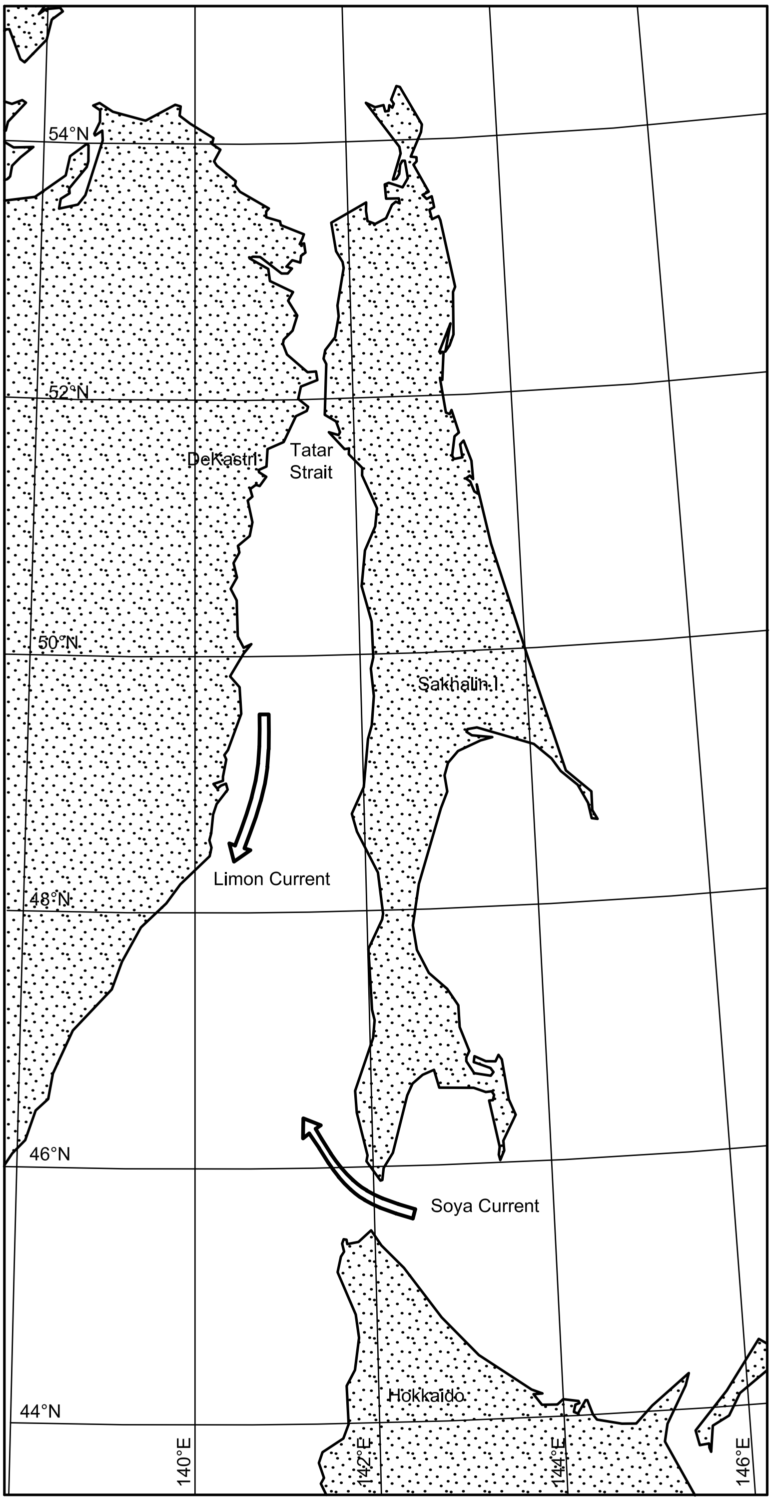


Figure B.12-1 — Map of the Tatar Strait (Northern Sea of Japan) region

B.12.2 Tatar Strait technical information

B.12.2.1 Climate

The Tatar Strait is situated in the monsoon climatic zone of the temperate latitudes. During the period October to April, winds from the north and northwest prevail for about 50 % to 75 % of the time. During the remaining months, from May to September, winds from the southeast and south prevail.

The average annual air temperature ranges from –2,2 °C in the north to 4,5 °C in the south.

B.12.2.2 Hydrological conditions

The surface water temperature of the Tatar Strait ranges from –1,8 °C to 2,0 °C in winter and from 10 °C to 22 °C in summer.

The water salinity is 33 ‰ to 34 ‰.

Currents in the Tatar Strait are influenced by the Limon Current flowing south along the Russian mainland coast and the remains of the Soya Current flowing north along the western coast of Sakhalin Island. A weak, cyclonic gyre is found at approximately 50 °N in the northern portion of the strait. Maximum current speed ranges from 1,0 m/s to 1,5 m/s.

Tides have a mixed character, with the daily component prevailing. The largest tidal amplitude, about 4 m, is observed at the port of DeKastri. The maximum storm surge height is 0,7 m.

Ice formation in the Tatar Strait begins in November and the process spreads from the north to the south. By late December, the drifting ice edge reaches 49 °N. February is normally the peak of southern extent and the ice edge reaches 48 °N in the centre of the strait. The ice along the mainland Russian coast can extend further south due to the Limon Current, while ice off the Sakhalin coast can be further north due to the Soya Current. By early April, the ice edge retreats to about 50 °N and the region is free of ice by May.

Generally, the ice within the Tatar Strait moves from the north to the south at an average speed of 25 cm/s to 30 cm/s.

Table B.12-2 — Tatar Strait meteorological conditions

Parameter		**Offshore Russian mainland**		**Offshore west coast of Sakhalin Island**	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**
Air temperature	Maximum, degrees Celsius	34	30 to 39	28,5	27 to 30
	Minimum, degrees Celsius	–38	–34 to –42	–36	–33 to –41
	Freezing degree days	2 370	2 220 to 2 525	2 485	2 260 to 2 814
Wind speed at 10 m elevation	10 min average, metres per second	32	21 to 41	30	27 to 36
Wind direction	Dominant winter (direction/ percentage occurrence)	NNW/70	NNW/42 to 89	NNW/56	NNW/49 to 67
	Dominant summer (direction/ percentage occurrence)	NNE/50	NNE/44 to 57	SSE/47	SSE/37 to 53
Precipitation	Annual rainfall, millimetres	779	739 to 863	597	511 to 717
	Annual snowfall, millimetres	278	211 to 363	309	202 to 442
Visibility (fog, snow, etc.)	Annual number days with visibility < 1 km	40	33 to 46	53	37 to 83

Table B.12-3 — Tatar Strait oceanographic conditions

Parameter		Offshore Russian mainland		Offshore west coast of Sakhalin Island	
		Average annual value	Range of annual values	Average annual value	Range of annual values
Waves, nearshore (< 100 m water depth)	Significant wave height, metres	6,3	5,0 to 9,2	6,3	5,5 to 6,9
	Range of zero-crossing periods, seconds	10,0	9,1 to 11,9	10,1	9,1 to 10,7
Waves, nearshore (> 100 m water depth)	Significant wave height, metres	7,9	6,9 to 12,9	7,1	6,6 to 7,9
	Range of zero-crossing periods, seconds	11,2	9,2 to 13,9	11,2	10,1 to 11,9
Current	Near-surface maximum speed, centimetres	130	ND	90	ND
	Mid-layer maximum speed, centimetres	120	ND	70	ND
	Bottom maximum speed, centimetres	100	ND	50	ND
Tidal current	Maximum surface speed, centimetres	60	60	60	60
Tide	Tidal range (total), metres	1,8	1,4 to 4,1	1,8	1,1 to 2,4
Wind-induced surge	Water depth range total, metres	0,6	0,4 to 1,1	0,7	0,4 to 0,9
Water salinity	Average surface salinity, parts per thousand	33	30 to 35	34	30 to 35
	Average mid-layer salinity, parts per thousand	34	30 to 35	34	30 to 35
Water temperature	Summer surface maximum, degrees Celsius	11,5	9,0 to 16,2	18,1	14,1 to 20,9
	Summer surface average, degrees Celsius	7,1	5 to 10	9,0	8,1 to 13,2
Seabed geotechnical – Ice-induced gouge	Gouge depth, metres	0,3	0,2 to 0,7	0 to 15	ND
	Water depth range, metres	0 to 12	0 to 12	ND	ND
Seismic	Magnitude	ND	6,0 to 7,0	ND	6,0 to 7,0

Table B.12-4 — Tatar Strait sea ice conditions

Parameter		Offshore Russian mainland		Offshore west coast of Sakhalin Island	
		Average annual value	Range of annual values	Average annual value	Range of annual values
Occurrence	First ice	1 Nov.	20 Oct. to 20 Nov.	1 Nov.	25 Oct. to 20 Nov.
	Last ice	15 April	30 March to 10 May	15 April	20 March to 30 April
Level ice (first-year)	Landfast ice thickness, metres	0,90	0,70 to 1,2	0,8	0,7 to 1,1
	Floe thickness, metres	0,85	0,10 to 1,0	0,7	0,7 to 0,9
Rafted ice	Rafted ice thickness, metres	0,9	0,7 to 1,8	0,9	0,7 to 1,8
Rubble fields	Sail height, metres	2,5	2,2 to 4,0	3,0	2,2 to 4,1
	Length, metres	ND	ND	ND	ND
Ridges (first-year)	Sail height, metres	3,0	1,8 to 4,5	3,5	2,2 to 4,5
	Keel depth, metres	7,0	5,0 to 12,0	7,0	5,0 to 11,0
Stamukhi	Water depth range, metres	0 to 12	0 to 12	0 to 15	0 to 15
	Sail height, metres	4,0	2,5 to 6,0	4,0	2,5 to 6,0
Ice movement	Speed nearshore, metres per second	0,6	0 to 100	0,75	0 to 100
	Speed offshore, metres per second	0,6	0 to 100	0,75	0 to 100

B.13 Bohai Sea

B.13.1 Description of region

The Bohai Sea is the innermost gulf of the Yellow Sea off the Chinese northeastern coast (see Figure B.13-1). It is also known as the Bohai Gulf. The Bohai Sea has an area of 77 000 km^2, the average water depth is 18 m and the maximum depth is 78 m.

The Bohai Sea is one of the most southern locations where sea ice is found. Although sea ice is generally found only in Liaodong Bay, the following description is attributed to the Bohai Sea. Due to its southern location, the ice season length is short, ice temperatures are warm and ice properties are on the mild side. Oil and gas activities have been under way in the region for over 35 years and ice has had an effect on the development of facilities to extract hydrocarbons.

Table B.13-1 — General information for the Bohai Sea

Area of coverage	37 °N to 41 °N, 122 °E to 119 °E
Length of winter season, days	90 to 130 in the north (Liaodong Bay) 70 in the south (Laizhou Bay)
Length of summer season, days	235 to 275 in the north 295 in the south
Range of water depths, metres	0 to 78

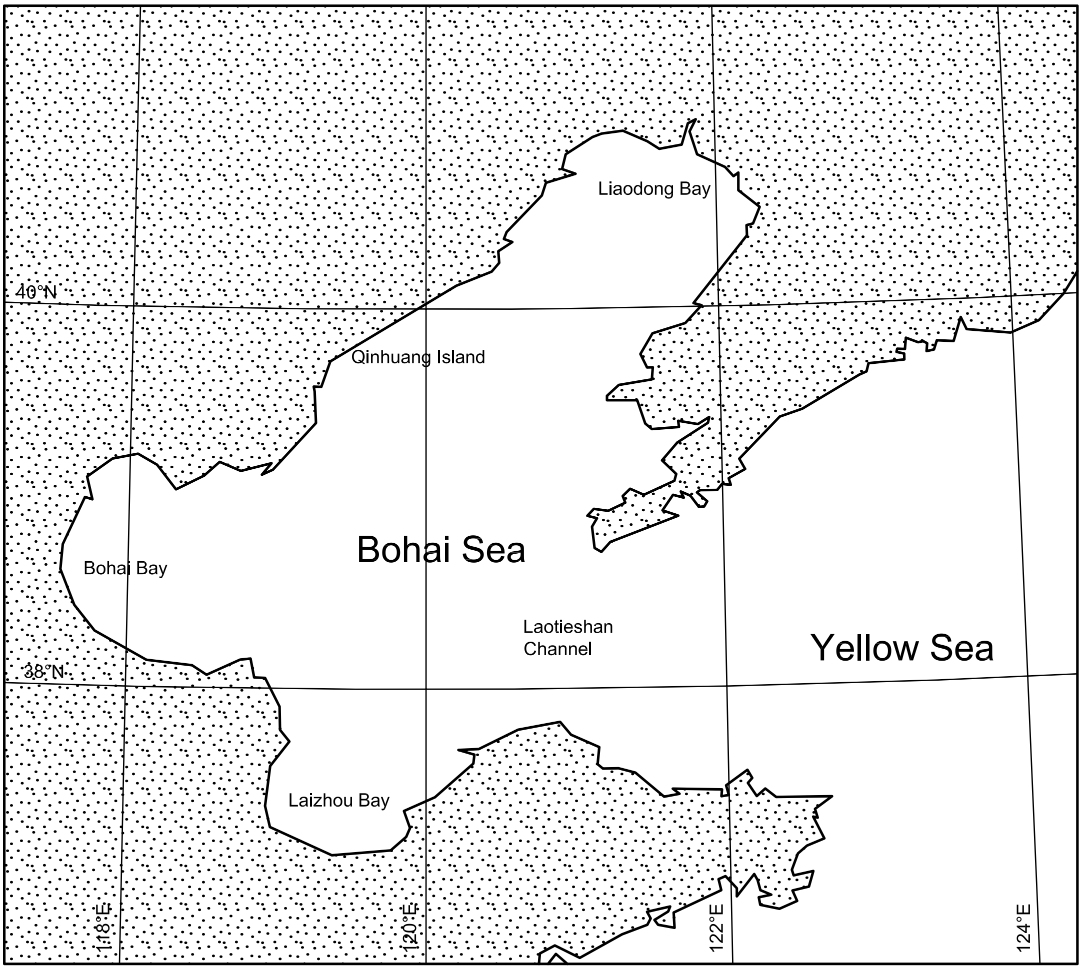


Figure B.13-1 — Map of the Bohai Sea

B.13.2 Bohai Sea technical information

B.13.2.1 Climatology

The climate is a monsoon type, with northerly winds in the winter and southerly in the summer. The low temperatures are found in January with average temperatures between –4 °C and –8 °C and an extreme low of –25 °C. Wind speeds during the winter months are between 5 m/s and 7 m/s, with maximum speeds in the range of 35 m/s to 40 m/s.

B.13.2.2 Hydrology

Currents in the region are mild, with stronger speeds of 20 cm/s found in the winter and lower speeds in the summer. Tidal elevation changes reach a maximum in the northern end of Liaodong Bay at 2,7 m and a minimum at Qinhuang Island at 0,8 m. Tidal currents are less than 1 m/s but can reach 2 m/s in the Laotieshan Channel.

Wave heights are most severe in winter, with an average wave height in the range of 1,1 m to 1,7 m and a maximum wave height in the 3,5 m to 6,0 m range.

Ice forms under the influence of cold air flowing south from Siberia. Due to the southerly position of the Bohai Sea, the ice found there consists of only first-year ice, mainly as floating pack ice. Ice conditions can vary significantly from north (more severe) to south (less severe). Average concentrations are 4/10 to 7/10.

First-year ice ridges are generally found in the shallow waters of the northern portion of Liaodong Bay in both normal and severe ice years. Surface ice temperatures are warm and are generally above −10 °C.

Ice drift is caused mainly by current but also by wind. A maximum ice drift of 190 cm/s has been observed.

Further details can be found in References [B.13-1] to [B.13-3].

Table B.13-2 — Bohai Sea meteorological conditions

Parameter		Average annual value	Range of annual values
Air temperature	Annual maximum, degrees Celsius	ND	ND
	Annual minimum, degrees Celsius	−10	ND
	Freezing degree days	ND	ND
Wind speed at 10 m elevation	10 min average, metres per second	ND	ND
Wind direction	Dominant winter (direction/ percentage occurrence)	ND	ND
	Dominant summer (direction/ percentage occurrence)	ND	ND
Precipitation	Annual rainfall, millimetres	ND	ND
	Annual snowfall, millimetres	ND	ND
Visibility (fog, snow, etc.)	Annual number days with visibility < 5 miles	ND	ND

Table B.13-3 — Bohai Sea oceanographic conditions

Parameter		Average annual value	Range of annual values
Waves	Significant wave height, metres	2,0 to 3,5	ND
	Range of zero-crossing periods, seconds	ND	ND
Current	Near-surface maximum speed, centimetres per second	ND	ND
	Bottom maximum speed, centimetres per second	ND	ND
Tidal current	Maximum surface speed, centimetres per second	100 to 200	ND
Tide	Tidal range (total), metres	0,8 to 2,7	ND
Wind-induced surge	Water depth increase range total, metres	1 to 2	ND
Water salinity	Average surface salinity, parts per thousand	28 to 31	ND
	Average mid-layer salinity, parts per thousand	< 31	ND
Water temperature	Summer surface maximum, degrees Celsius	ND	ND
	Summer surface average, degrees Celsius	ND	ND
Ice-induced gouge	Gouge depth, metres	ND	ND
	Water depth range, metres	ND	ND
Seismic	Magnitude	ND	ND

Table B.13-4 — Bohai Sea ice conditions

Parameter		Average annual value	Range of annual values
Sea ice occurrence	First ice	20 Nov.	14 Nov. to 16 Dec.
	Last ice	14 March	24 Feb. to 24 March
Level ice (first-year)	Landfast ice thickness, metres	0,4	0,1 to 0,6
	Floe thickness, metres	0,4	0,1 to 0,6
Rafted ice	Rafted ice thickness, metres	0,63	ND
Rubble fields	Sail height, metres	4,5	2,6 to 7,2
	Length, metres	ND	ND
Ridges (first-year)	Sail height, metres	2,7	ND
	Keel depth, metres	7,8	ND
Ice movement	Speed, metres per second	1,4	< 1,9

B.14 North Caspian

B.14.1 Description of region

The Caspian environment programme[B.14-1] gives a general overview of the Caspian Sea region. Reference [B.14-2] describes the metocean conditions encountered in the Caspian Sea and specifically refers to the ice conditions that can be expected in the North Caspian during the winter months.

Publicly available measured and modelled data are limited for the offshore areas of the Caspian Sea; most measured data are confined to land and coastal stations. Since the Second World War, the Astrakhan hydrometeorological observatory has routinely collected ice data. Data collection ceased in 1985 and ice reports are not available from this source after this date. Earth observing satellite data provide information on ice coverage post-1992. More extensive ice data have been collected since the start of offshore oil industry activity in the North Caspian in the late 1990s.

Table B.14-1 — General information for the North Caspian Sea

Area of coverage	44 °N to 47 °N, 47 °E to 53 °E
Length of winter season	November/mid-December to mid-March/late April
Length of summer season	Mid-March/late April to November/mid-December
Range of water depths, metres	0 to 10, averaging 5

A map of the Northern Caspian Sea is provided in Figure B.14-1.

B.14.2 North Caspian technical information

B.14.2.1 Climate

The Caspian Sea is approximately 1 200 km from north to south; this spans more than one climatic zone, so the meteorology differs significantly across the region. The North Caspian is influenced by a continental climate regime, with hot dry summers and cold winters, typically with relatively low snowfall. During the winter, the Siberian anticyclone creates east to southeasterly winds of cold, clear air that dominates the weather in the Northern Caspian. During the summer, the weather is influenced by the Azores high pressure, with the strongest and most persistent winds from between west and north.

The region is subject to extra-tropical cyclones at the rate of about ten strong events per year. These approach from the west, southwest or south, although a significant number are also generated locally. Cyclones most often appear in January, March and October. The largest number of stormy days occurs in the south in the region of the Apsheron Peninsula, where the number of days with winds higher than 15 m/s is between 60 days and 80 days. In the Northern Caspian, this is reduced to about half this value. In the Northern Caspian, the strongest winds occur between November and April, with typical annual maxima of around 25 m/s, rising to near 30 m/s for a 25 year return period storm. The summer months are more benign, with wind speeds only rarely exceeding 15 m/s. The strongest winds in the Northern Caspian tend to be from between southwest and west, although a more northwesterly component is apparent during the latter part of the year.

The weather conditions can be locally quite variable due to topographic effects, notably due to the Caucasus Mountains to the west and the localized topography to the north of Aktau.

Daily mean air temperatures vary significantly seasonally and from year to year, specifically during the winter period, when temperatures can fall to around –30 °C in some years, but only to around –10 °C in others. In the summer, air temperatures rise to between 25 °C and 30 °C.

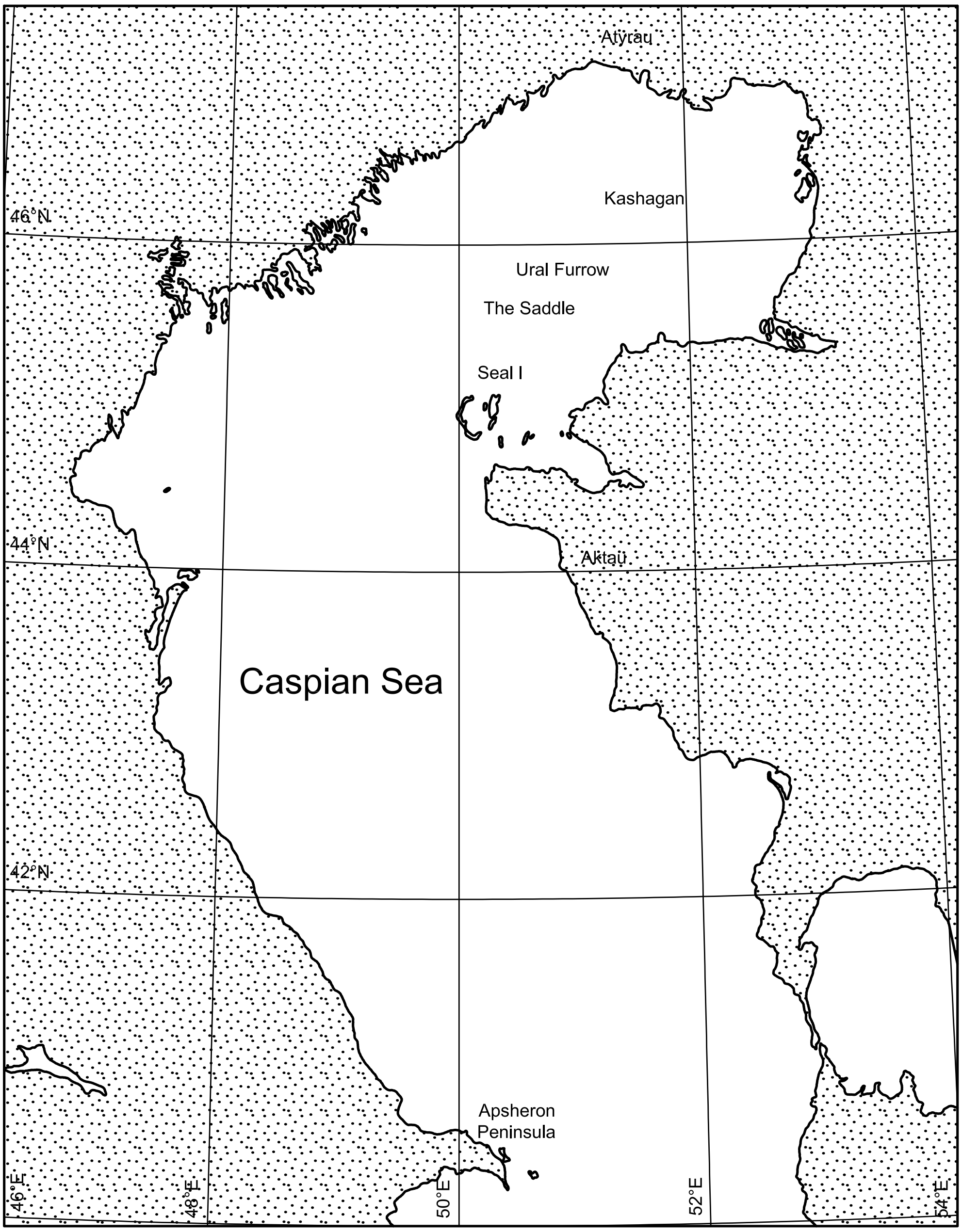


Figure B.14-1 — Map of the Northern Caspian Sea

B.14.2.2 Hydrology

The Caspian is a land-locked sea that consists of three distinct basins, with the deepest parts in the southern basin exceeding 1 000 m. The Northern Caspian is characterized by shallow water depths (typically on the order of 4 m to 9 m) and is affected by ice in winter and negative surges that can limit marine operations. The long-term level of the Caspian Sea is controlled by the relative magnitude of the water inputs (dominated by the Volga, which provides 85 % of the water input) and the evaporation from the sea surface. Changes in the climate or anthropogenic influences have a significant effect on the level. Water levels over the last 100 years have been up to 1,4 m higher and 2,2 m lower than the 2005 level of −27 m below Baltic Datum (1 m above Caspian Datum). Tides are minimal in the Northern Caspian, but there are significant seasonal fluctuations in sea level (−0,1 m to +0,15 m) and short-term wind-induced surges. The surges are not consistent across the Northern Caspian, with the magnitude (both positive and negative) increasing towards the east. Typical surges (one year return period) in the central part of the Northern Caspian are on the order of +0,6 m to −1,0 m, increasing to +1,0 m to −1,6 m in the extreme east.

The limited fetch and shallow water in the Northern Caspian means that the wave climate is almost exclusively locally generated and is consequently relatively benign. Virtually no long period swells are propagated into the area from the central basin due to the shallow water referred to as “The Saddle”, located to the east of the Seal Islands across the shallow water. Wave heights vary across the area, but maximum significant wave height values of around 2,5 m can be expected in the deeper waters of the Ural Furrow, decreasing to around 2 m in the western part of the Kashagan Field and down to 1,3 m in the shallow waters to the eastern limit of the sea. Wave periods are typically short, with maximum zero-crossing period values of between 3 s and 4 s, and peak period between 5 s and 6 s in the shallower water.

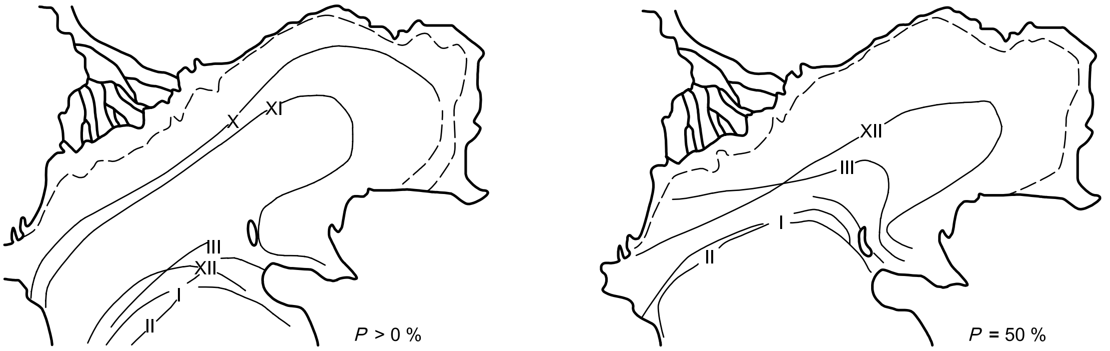
Water temperatures in the Northern Caspian closely match the air temperatures during the open water periods, with summer temperatures routinely reaching around 28 °C; temperatures fall during the winter to just below freezing. As a consequence of the climatic differences between the Northern and Southern Caspian, the non-summer water temperatures in the upper water column differ by several degrees Celsius among the major basins. As summer approaches, sea surface temperatures become more uniform across the entire Caspian.

Salinity in the southern and central basins of the Caspian is almost three times lower than that found in the ocean, averaging about 12,8 ‰. The Northern Caspian has considerably lower salinities due to the large inflow of freshwater from the Volga and Ural rivers; salinities vary from close to freshwater at the mouth of the rivers to generally less than 8 ‰ or 9 ‰ in the centre of the northern basin.

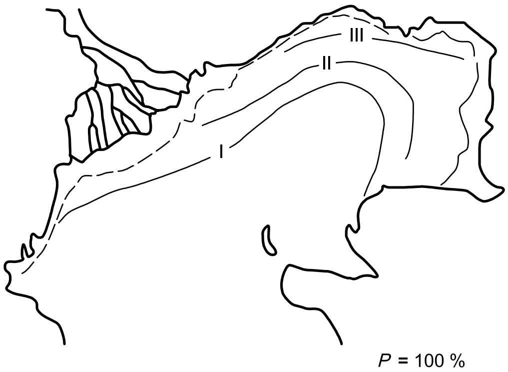
Currents are typically weak in the Northern Caspian, with no measurable tidal flow. Water movements are dominated by wind-driven flows and river discharges. Current speeds are typically less than 20 cm/s, but can increase significantly during storms. The general circulation in the Northern Caspian is not well understood, but mainly consists of an anti-cyclonic gyre in the eastern part and a general southerly movement along the western shore.

B.14.2.3 Ice

Ice forms in the northern portions of the Caspian in the winter, but there is considerable variability in both the onset and the duration of the ice cover. During severe winters, ice formation can begin as early as October, but has been delayed to as late as the end of December or early January. The ice formation starts along the northern and eastern coastlines and works southward, typically reaching its maximum southward extension by January or February, as indicated in Figure B.14-2.



a) Severe winters ($P > 0$, never exceeded) **b) Moderate winters ($P = 50$ %, exceeded 50 % of the time)**



c) Mild winters ($P = 100$ %, exceeded 100 % of the time)

Figure B.14-2— Ice boundaries for winters of different severities, by month (I to XII)[B.14.3]

Thermal ice growth is modest compared to arctic regions, but the lack of snow cover and of wind-induced ice movements during the freeze-up means that the ice can layer easily, resulting in thicker ice. Level ice thicknesses can reach 90 cm in severe winters, but are typically nearer 60 cm during an average year. Locally thicknesses can be considerably greater due to rafting or other factors. The low salinities also result in relatively strong ice.

The ice along the northern and eastern boundaries of the sea is typically landfast; in the central region, the stability of the ice is dependent on the severity of the winter, but pack ice can often be present for parts of the winter season. There are usually several significant movements during the course of a typical year, with recorded speeds of more than 0,5 m/s. The formation of ice piles (stamukhi) and ridges is common over much of the Northern Caspian; stamukhi can reach heights of more than 10 m, but are typically less than 8 m. These features are grounded and result in indentation of the seabed and form scours when they move. The ice typically tends to start receding in March, commencing in the Ural Furrow in the centre of the basin. The entire region is generally ice free by the middle to the end of April.

Freezing degree days (FDDs) in the Northern Caspian can vary significantly from year to year, with figures ranging from as high as 1 500 days in some years to as low as 300 days in others. The number of FDDs has been related to ice formation; see Reference [B.14-3].

Table B.14-2 — North Caspian meteorological conditions

Parameter		Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	37	35 to 42
	Minimum, degrees Celsius	−22	−18 to −29
	Freezing degree days	800	200 to 1 600
Wind speed at 10 m elevation	10 min average, metres per second	25	20 to 30
Wind direction	Dominant winter (direction/percentage occurrence)	E/30	E
	Dominant summer (direction/ percentage occurrence)	NW/20	NW
Precipitation	Annual rainfall, millimetres	230	170 to 300
	Annual snowfall, millimetres	300	ND
Visibility (fog, snow, etc.)	Annual number days with visibility < 5 miles	ND	ND

Table B.14-3 — North Caspian oceanographic conditions

Parameter		Average annual value	Range of annual values
Waves (water depth ~ 4 m)	Significant wave height, metres	1,3	1,1 to 1,7
	Range of zero-crossing periods, seconds	3,4	2,8 to 3,8
Current	Near-surface maximum speed, centimetres per second	50	40 to 80
Tidal current	Maximum surface speed, centimetres per second	ND	ND
Seasonal water level	Range, metres	+0,15 (positive) −0,10 (negative)	ND
Wind-induced surge	Water depth increase range in the central area (total), metres	+1,0 (positive) −1,0 (negative)	ND
Water salinity (N. Caspian)	Average surface salinity, parts per thousand	8	2 to 10
Water temperature	Summer surface maximum, degrees Celsius	28	26 to 31
	Summer surface average, degrees Celsius	25	ND
Seabed geotechnical – Ice-induced scour	Scour depth, metres	0 to 0,5	0 to 0,5
	Water depth range, metres	0 to 5	0 to 5
Seismic	Magnitude	ND	ND

Table B.14-4 — North Caspian sea ice conditions

Parameter		Average annual value	Range of annual values
Occurrence	First ice	Mid-Nov.	Oct. to mid-Dec.
	Last ice	End of March	Mid-March to late April
Level ice (first-year)	Landfast ice thickness, metres	0,8	ND
	Floe thickness, metres	0,8	ND
Rafted ice	Rafted ice thickness, metres	> 3	1 to > 3
Rubble fields	Sail height, metres	2 to 5	2 to 5
	Length, metres	up to 1 000	> 1 000
Ridges (first-year)	Sail height, metres	1 to 2	1 to 2
	Keel depth, metres	Limited by water depth	Limited by water depth
Stamukhi	Water depth range, metres	0 to 5	0 to 5
	Sail height, metres	up to 20	> 20
Ice movement	Speed nearshore, metres per second	0,5	0,5 to 1,0
	Speed offshore, metres per second	0,5	0, to 1,0

B.15 Baltic Sea

B.15.1 Description of region

The Baltic Sea area encompasses a number of regional sea areas, such as the Gulf of Bothnia, the Quark, the Bothnian Sea, the Gulf of Finland, the Gulf of Riga, the Baltic proper, the Kattegat, and the Belt Sea and Sound; see Figure B.15-1. The Baltic Sea is the largest brackish water basin in the world. Its water is a mixture of salty water from the ocean and freshwater supplied by numerous rivers. In the southern Baltic Sea salinity is as high as 20 ‰, but it is as low as 6 ‰ in the northern Baltic Sea. The water is almost fresh in river estuaries, for example near St Petersburg. More comprehensive information about the meteorological, hydrographical, and ice conditions in the Baltic Sea can be found in References [B.15-1] to [B.15-8].

Table B.15-1 — General information for the Baltic Sea

Parameter	Gulf of Bothnia	Gulfs of Finland and Riga	Baltic Sea proper	Danish Belts
Area of coverage	60 °N to 65 °N 12 °E to 14 °E	57 °N to 60 °N 20 °E to 30 °E	54 °N to 60 °N 13 °E to 22 °E	54 °N to 57 °N 10 °E to 13 °E
Length of winter season	November to June	December to April	January to April	January to March
Length of summer season	June to November	May to November	May to December	April to December
Water depth range, metres	0 to 130	0 to 120	0 to 80	0 to 50

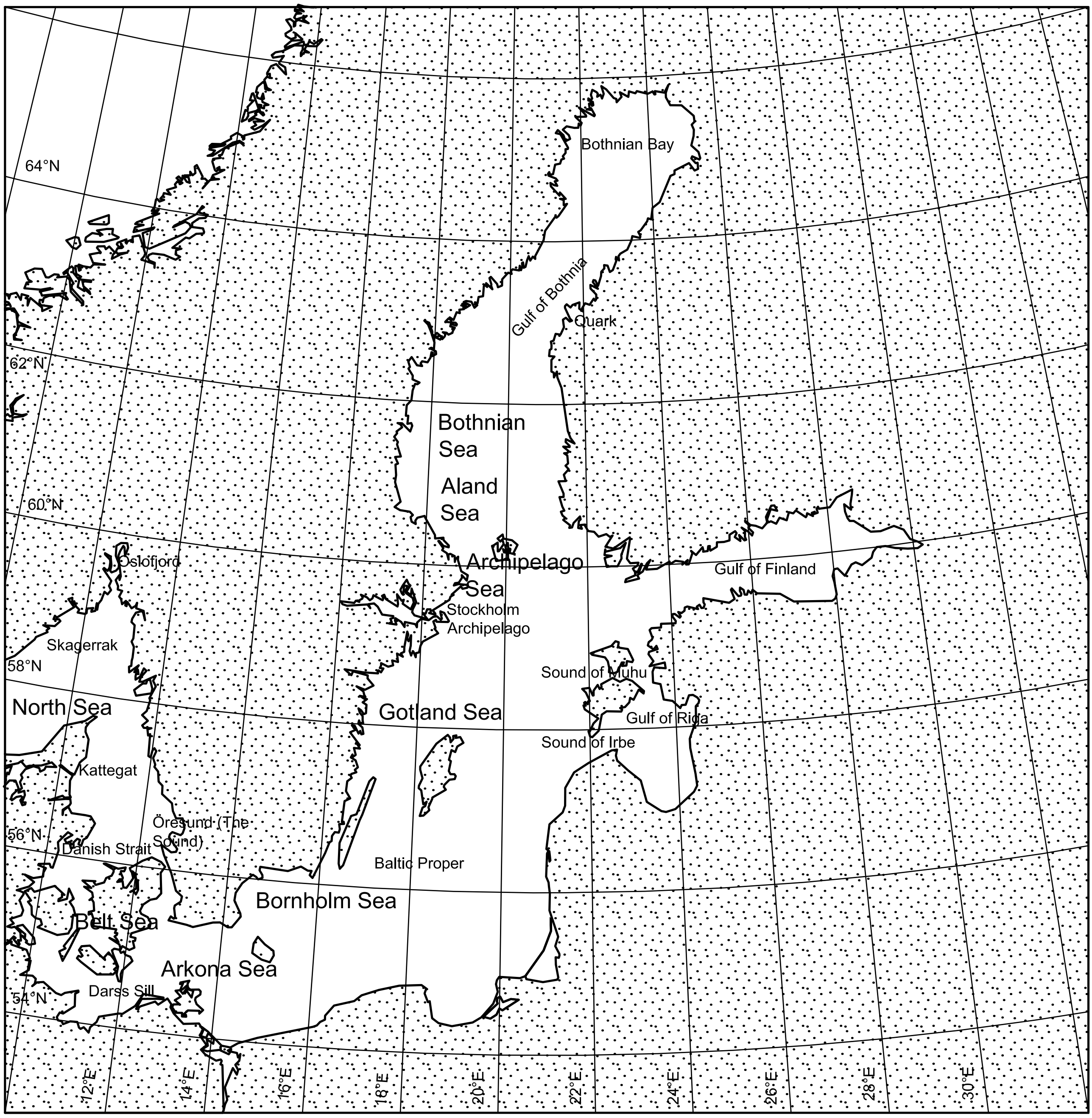


Figure B.15-1 — Map of the Baltic Sea area

B.15.1.1 Gulf of Bothnia

The Gulf of Bothnia is a brackish water body with two major basins, the Bothnian Sea and the Bothnian Bay, and a large archipelago area in the southeastern part. Due to the depression of the earth's surface by the glaciers of the last ice age, land uplift is still an ongoing process along coastal areas in the Gulf of Bothnia.

The sea area and the sea volume of the Gulf of Bothnia are 115 516 km^2 and 6 389 km^3, respectively. Due to the numerous rivers and precipitation, the northern basin, the Bothnian Bay, has a dominating estuarine character with surface salinity around 3,5 ‰ approaching river mouths. The average depth of the Bothnian Bay is 42 m. The Quark is a shallow sill 20 m deep that separates the Bothnian Bay and the Bothnian Sea. Most of the area consists of a shallow archipelago with a depth of less than 10 m. Slow but permanent land-uplift processes (8,5 mm/year) in the Quark area lead to the birth of the particular phenomenon: shallow fladas and glo-lakes.

The Bothnian Sea has an average depth of 68 m and a surface salinity around 6,5 ‰. The Gulf of Bothnia is separated from the Baltic proper by the Stockholm Archipelago, the Archipelago Sea and the Åland Sea between Sweden and Finland, areas which are characterized by an enormous topographic complexity, including more than 50 000 islands. The average water depth is only 23 m, but several trenches reach over 100 m. The mosaic structure and sharp environmental gradients (salinity, temperature, oxygen, exposure, etc.) create numerous biotopes.

B.15.1.2 Gulf of Finland

The Gulf of Finland is similar to a large delta area. The width of the Gulf of Finland is between 48 km and 135 km and its area is around 30 000 km^2. It is a very shallow water body with an average depth of 37 m and a maximum depth of 123 m. Due to the shallow water, its volume is only about 5 % of the total volume of the Baltic Sea. Islands, inlets and shallow bays are typical to the northern shore while the southern shore has a more open character.

B.15.1.3 Gulf of Riga

The Gulf of Riga is a relatively shallow water body with an average depth 26 m. The Gulf of Riga is connected to the sea through the Sound of Irbe with a sill depth of 35 m and the Sound of Muhu with a sill depth of 5 m. The area of the gulf is 16 330 km^2 and its volume 424 km^3. The water exchange with the Baltic proper averages about 360 km^3/year. The salinity varies between 4 ‰ and 7 ‰.

B.15.1.4 Baltic proper

The Baltic proper is the largest subdivision of the Baltic Sea, having a surface area of 211 069 km^2, around half of the total Baltic Sea area, and a volume of 13 045 km^3. The Baltic proper, which covers the area between the Darss Sill and the Gulf of Bothnia, Finland and Riga, is composed of the Arkona Sea, Bornholm Sea and Gotland Sea with its western and eastern sub-regions. The salinity varies from 6 ‰ in the north to about 20 ‰ in the south.

B.15.1.5 Kattegat, Belt Sea and Sound

The Kattegat and the Belt Sea and Sound, with an average depth of 19 m, constitute the transition area between the Baltic proper and the North Sea. This sea has an area of 42 408 km^2 and a volume of 802 km^3. The relatively shallow Kattegat, with a depth of less than 50 m, has an estuarine-like circulation. Surface water from the Baltic Sea has a salinity of 15 ‰ to 25 ‰ and overlays saltier water (with a salinity 30 ‰ to 35 ‰) from the southern North Sea. The Belt Sea is also usually strongly salinity stratified.

B.15.2 Baltic Sea technical information

B.15.2.1 Climatology

The absolute extreme air temperatures measured during the period 1961 to 1990 at coastal and island stations of the Baltic Sea are summarized in Reference [B.15-9].

B.15.2.2 Hydrology

Ocean water streaming in through the Danish Straits is very saline relative to Baltic Sea water and, therefore, heavy. About a quarter of the water exchange passes through the narrow and shallow Öresund Strait, while the main exchange occurs through the Belts. There is a high-frequency exchange of water going on all the time, but it has almost no effect on the Baltic Sea as the same water slops back and forth. Only during very exceptional conditions does the influx last long enough (over two weeks) to extend sufficiently into the Baltic Sea to result in a net exchange. During such a significant pulse, the Baltic Sea receives between 200 km^3 and 400 km^3 of salty ocean water within a few weeks. This saline water is slowly mixed with Baltic Sea water, and flows through the Arkona and Bornholm basins to the central basin of the Baltic Sea, the Gotland Deep, in about six months. It replaces old Baltic Sea water, often containing some hydrogen sulfide and little or no oxygen.

Without occasional pulses of seawater from the North Sea into the Baltic Sea, the latter would rapidly become salt-free. During the stagnation periods between the great pulses, the salinity level of the Baltic Sea decreases considerably.

Due to the heavy river discharge of freshwater and the low water exchange, the Baltic Sea is heavily stratified. The salinity of the surface water is low, while that of the deep water is high. Between these water masses, a halocline layer forms where the vertical salinity change is relatively steep. This prevents the vertical mixing of the water and the transport of oxygen from the surface to the bottom. Only when a sufficiently strong pulse of salty North Sea surface water enters into the Baltic Sea does new, oxygen-rich water reach into the deeps of the Baltic Sea proper.

B.15.2.3 Wave conditions

Annual maximum significant wave heights seldom exceed 5 m, regardless of region of the Baltic Sea. Annual wave periods are frequently less than 3 s for wind seas, while maximum wave periods up to 13 s prevail less than 0,1 % of the time. Typical wave periods for swell in the Baltic Sea are in the range of 4 s to 5 s, while maximum periods up to 15 s prevail less than 1 % of the time. In autumn and the open water periods of the winter, wave periods are, on average, longer than in the spring and summer. Further details are provided in Table B.15-3.

B.15.2.4 Sea ice

Figure B.15-2 shows examples of the ice coverage situation during winters of different severity (mild, moderate, severe).

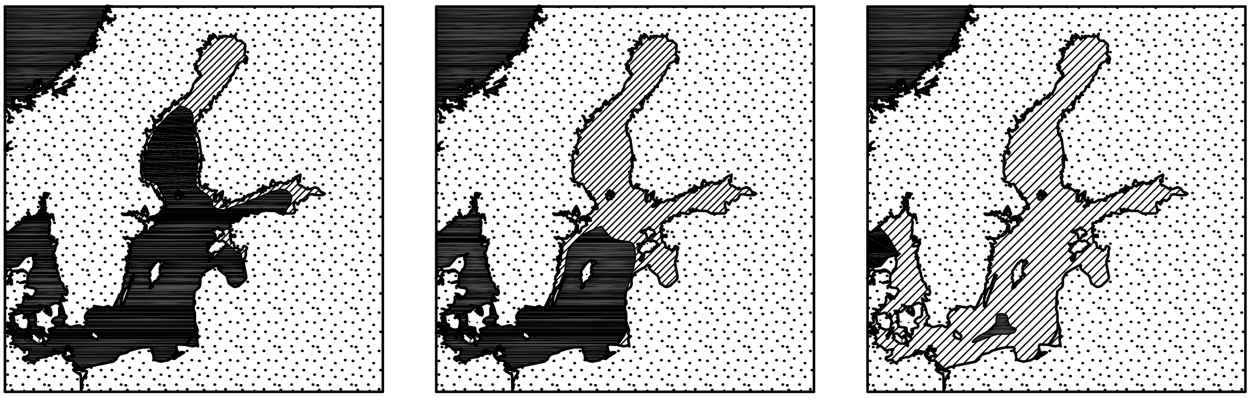
B.15.2.4.1 Ice formation

Ice formation begins in the northernmost parts of the Bothnian Bay and in the most eastern parts of the Gulf of Finland in the October to November time period. The Quark, the Bothnian Bay (totally) and the coastal areas of the Bothnian Sea freeze over slightly later. During average winters, the Bothnian Sea, the Archipelago Sea and the Gulf of Finland are totally frozen, along with the northern part of the Baltic Sea proper (partly).

In moderate winters, only shallow water areas in the Belts and Sounds are frozen. In cold winters, the surface layer of the Belts and Sounds is cooled down, which leads to ice formation in the open sea. During these periods, the ice thickness is about 10 cm to 15 cm and the ice coverage is less than 6/10. In severe winters, the sea can be completely covered with ice with a thickness in the range 30 cm to 70 cm.

In the Skagerrak and Kattegat along the Norwegian coast, ice is observed only in severe winters. More frequently, ice is observed in the Oslofjord, where broken ice (cake ice and brash ice) is pushed together due to onshore winds. In the harbours and fairways, ice starts to form, on average, in January and the last ice melts in the third decade of March.

In the Skagerrak along the Swedish coast, ice forms in moderate winters only in the inner part of the archipelagos, which does not affect navigation. Only in severe winters are significant amounts of ice observed in the fairways. Ice starts to form, on average, by the end of January and generally melts by the end of March.



a) Mild winter (1991 to 1992) — Maximum extent of ice cover 66 000 km^2

b) Average winter (1961 to 1990) — Maximum extent of ice cover 204 000 km^2

c) Extreme winter (1986 to 1987) — Maximum extent of ice cover 405 000 km^2

Figure B.15-2 — Baltic Sea ice cover

In severe winters, ice floes from the Kattegat can drift towards the north along the archipelagos. In the Kattegat, along the Swedish coast, ice forms in shallow bights in moderate winters. In the open sea, the occurrence of ice is infrequent. In severe winters, the low salinity surface water cools and 10 cm to 15 cm thick pancake ice starts to form. The ice coverage is on average less than 6/10.

In severe winters ice also occurs in the Danish Straits and the Baltic Sea proper. The sea area northeast of Bornholm is the last to cover with ice.

B.15.2.4.2 Ice break-up

In spring, with increased solar radiation, ice starts to melt from the southern regions towards the north. Normally by the beginning of April, the northern Baltic Sea proper is open. By early May, ice exists only in the Bothnian Bay, where it melts completely by early June.

On average, the duration of ice winter in the northern Baltic Sea proper is about 20 days. In the northern Bothnian Bay it can be more than six months. More detailed information on the duration of the ice period and average ice days for different areas of the Baltic can be found in Reference [B.15-9].

B.15.2.4.3 Ice morphology

The ice in the Baltic Sea exists mainly as landfast ice and drift ice. Landfast ice is situated in coastal and archipelago areas, where the water depth is less than 15 m. It develops early in the ice season and remains stationary until the melting period.

Drift ice has a dynamic nature, being forced mostly by winds and less by currents. Drift ice can be level, rafted or ridged, and its concentration ranges from 1/10 to 10/10. Drift ice movements are large: in stormy conditions, a thin drift ice field can move 20 km to 30 km in a single day. The motion results in an uneven and broken ice field, with distinct floes up to several kilometres in diameter, leads and cracks, slush and brash ice barriers, rafted ice and ridged ice.

Table B.15-2 — Baltic Sea meteorological conditions

Parameter		Gulf of Bothnia		Gulfs of Finland and Riga		Baltic Sea proper		Danish Belts	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	+24	+19 to +28	+25	+20 to +28	+24	+20 to +28	+23	+20 to +26
	Minimum, degrees Celsius	–25	–11 to –28	–18	–8 to –33	–20	–18 to –22	–18	–16 to –20
	Freezing degree days	1 200	800 to 1 600	800	400 to 1 200	700	400 to 1 000	600	400 to 800
Wind speed at 10 m elevation	10 min average, metres per second	6,4	0 to 22	6,3	0 to 25	ND	ND	ND	ND
Wind direction	Dominant winter (direction/ percentage occurrence)	220/23	220	220/18	220	240/20	240	240/20	240
	Dominant summer (direction/ percentage occurrence)	220/20	220	220/20	220	270/15	270	270/10	270
Precipitation	Annual rainfall, millimetres	480	300 to 680	560	310 to 740	600	500 to 700	600	500 to 700
	Annual snowfall, millimetres	160	ND	150	ND	ND	ND	ND	ND
Visibility (fog, snow, etc.)	Annual number days with visibility < 5 miles	150	102 to 186	185	110 to 240	ND	ND	ND	ND

Table B.15-3 — Baltic Sea oceanographic conditions

Parameter		Gulf of Bothnia		Gulfs of Finland and Riga		Baltic Sea proper		Danish Belts	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**
Waves, nearshore (< 100 m water depth)	Significant wave height, metres	4,5	3,0 to 6,0	3,5	3,0 to 5,2	3,0	1,5 to 3,0	3,0	1,5 to 4,0
	Range of zero-crossing periods, seconds	8	6,5 to 10	8	7 to 9	8	5 to 8	8	5 to 10
Waves, nearshore (> 100 m water depth)	Significant wave height, metres	ND	ND	ND	ND	4,0	3,0 to 5,5	ND	ND
	Range of zero-crossing periods, seconds	ND	ND	ND	ND	10	8 to 13	ND	ND
Current	Near-surface maximum speed, centimetres per second	ND	ND	ND	ND	75	25 to 130	125	50 to 200
	Bottom maximum speed, centimetres per second	ND	ND	ND	ND	ND	ND	ND	ND
Tidal current	Maximum surface speed, centimetres per second	ND	ND	ND	ND	ND	ND	ND	ND
Tide	Tidal range (total), metres	ND	ND	ND	ND	0,15	0,1 to 0,2	0,25	0,2 to 0,3
Wind-induced surge	Water depth range total, metres	0,9	0,4 to 2,0	0,85	0,4 to 2,0	1,3	1,0 to 1,7	1,4	1,2 to 1,7
Water salinity	Average surface salinity, parts per thousand	6	2 to 8	10	4 to 14	12	10 to 15	20	10 to 30
Water temperature	Summer surface maximum, degrees Celsius	ND	ND	ND	ND	18	17 to 19	17	16 to 18
	Summer surface average, degrees Celsius	ND	ND	ND	ND	ND	ND	ND	ND
Seabed geotechnical – Ice-induced gouge	Gouge depth, metres	ND	ND	ND	ND	ND	ND	ND	ND
	Water depth range, metres	ND	ND	ND	ND	ND	ND	ND	ND
Seismic	Magnitude	< 3	0 to 5	< 2	0 to 3	< 3	0 to 5	< 3	2 to 3,5

Table B.15-4 — Baltic Sea sea ice conditions

Parameter		Gulf of Bothnia		Gulfs of Finland and Riga		Baltic Sea proper		Danish Belts	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**
Occurrence	First ice	Dec.	Nov. to Dec.	Jan.	Dec. to Feb.	Jan.	Dec. to Feb.	Jan.	Dec. to March
	Last ice	May	May to June	April	March to May	April	March to April	March	April
Level ice (first-year)	Landfast ice thickness, metres	0,80	0,60 to 0,90	0,70	0,60 to 0,80	0,60	0,30 to 0,70	0,50	0,30 to 0,70
	Floe thickness, metres	0,60	0,40 to 0,90	0,50	0,40 to 0,80	0,40	0,30 to 0,70	0,40	0,30 to 0,70
Rafted ice	Rafted ice thickness, metres	1,0	0,20 to 1,50	0,80	0,30 to 1,20	0,60	0,30 to 0,90	0,70	0,30 to 1,00
Rubble fields	Sail height, metres	1,0	1,0 to 2,0	1,0	1,0 to 2,0	1,0	1,0 to 2,0	1	1,0 to 2,0
	Length, metres	200	100 to 1 000	200	100 to 1 000	200	100 to 1 000	200	100 to 1 000
Ridges (first-year)	Sail height, metres	2,0	1,0 to 3,0	2,0	1,0 to 3,0	1,5	1,0 to 2,0	1,5	1,0 to 3,0
	Keel depth, metres	12	3 to 25	12	3 to 15	10	3 to 12	10	5 to 15
Ice movement	Speed nearshore, metres per second	ND	ND	ND	ND	ND	ND	ND	ND
	Speed offshore, metres per second	ND	ND	ND	ND	ND	ND	ND	ND

B.16 Barents Sea

B.16.1 Description of region

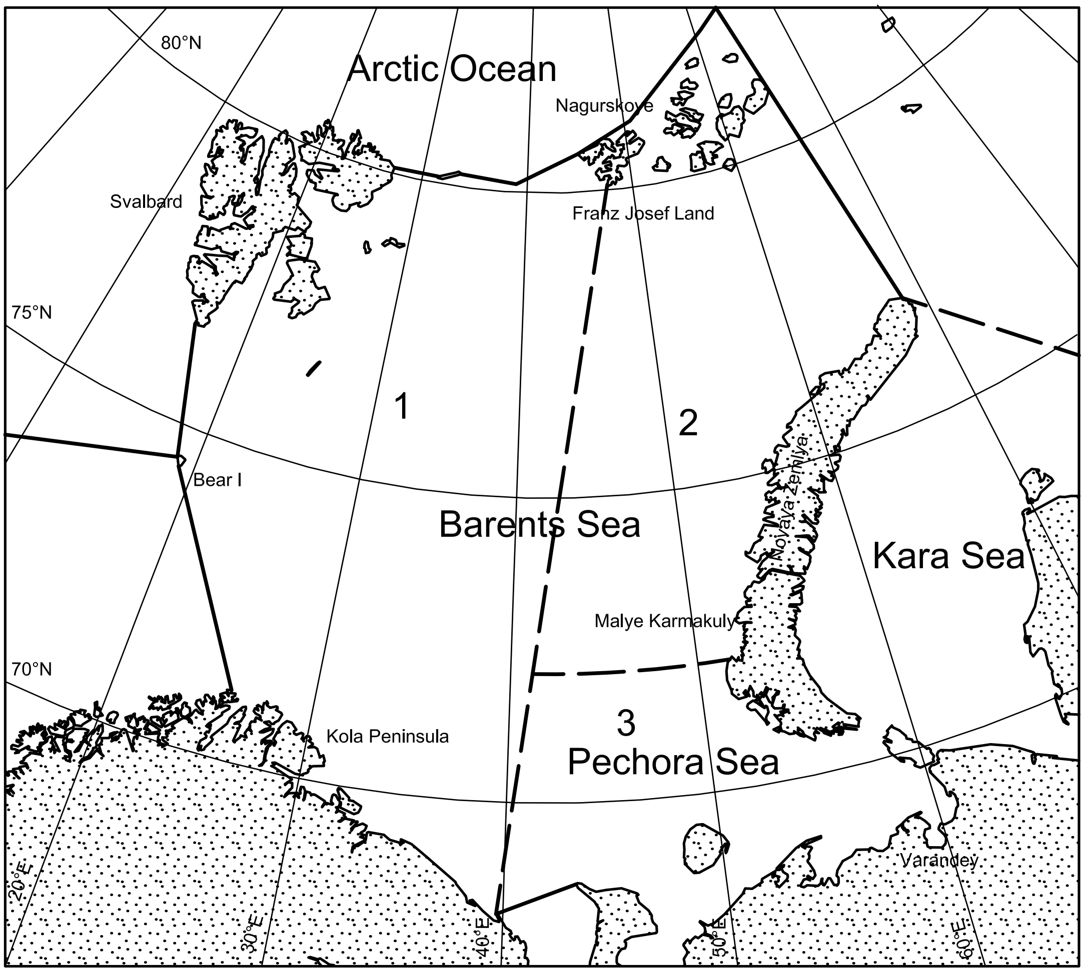
The Barents Sea is a marginal sea bordering on the Arctic Ocean in the north, the Greenland and the Norwegian Seas in the west, the Kara Sea in the east and the coast of the Kola Peninsula in the south (see Figure B.16-1).

The Barents Sea has its greatest depths, up to 600 m, in the central part and a vast shelf with depths of less than 100 m predominating in the southeast and near the coast of the Svalbard Archipelago. For the purposes of this International Standard, the Barents Sea is divided into the three parts shown in Figure B.16-1. This division takes into account the general physical-geographical features of the Barents Sea (seabed relief, atmospheric processes, system of currents, ice edge position, etc.).

NOTE The southeastern region encompasses the Pechora Sea and is, therefore, referred to as such in Tables B.16-2 to B.16-4.

Table B.16-1 — General information for the Barents Sea

Parameter	Western region	Northeastern region	Southeastern region (including the Pechora Sea)
Area of coverage	70 °N to 80 °N 18 °E to 42 °E	72 °N to 81 °N 40 °E to 67 °E	68 °N to 72 °N 38 °E to 60 °E
Length of winter season	12 months	12 months	October to July
Length of summer season	None	None	August and September



Key

1 western region
2 northeastern region
3 southeastern region (including the Pechora Sea)

Figure B.16-1 — Boundaries and regions of the Barents Sea

The major morphometric characteristics of the Barents Sea are as follows:

— area:	1 424 000 km^2;
— water volume:	316 000 km^3;

- average depth: 222 m;
- deepest depth: 600 m;

The hydrometeorological stations used to determine data are as follows:

a) western region: representative station, Bear Island;

b) northeastern region: Nagurskoye and Malye Karmakuly stations;

c) southeastern region: Varandey station.

B.16.2 Barents Sea technical information

B.16.2.1 Climate

The location and extent of the Icelandic Low determines the character of the atmospheric circulation in the autumn/winter period. Cyclones associated with storm winds have a high frequency of occurrence, between two per month and four per month, with trajectories usually passing from Iceland either into the central part of the Barents Sea or southward to the Kola Peninsula. In winter, northeasterly winds prevail in the northern part of the Barents Sea and southwesterly and southerly winds predominate in the southern area. The highest occurrence frequency of storm winds, with a speed greater than 16 m/s, is found in the southwestern Barents Sea.

In summer, cyclonic activity diminishes and a uniform higher pressure area forms over the Barents Sea. Cyclone trajectories move northwards, passing across the Franz Josef Land archipelago, and their occurrence frequency decreases, on average, to two cyclones per month. In most regions, winds are weak and their direction is variable. Storm winds occur infrequently during the summer period.

The lowest annual temperature differences, of 10 °C to 15 °C, are typical of the southern area of the Barents Sea, where sea ice is usually absent and southwesterly winds predominate. The largest annual temperature differences, between 25 °C and 30 °C, characterize the northern areas, where the winter ice cover contributes to intensive cooling of the lower air layers while dominating northeasterly winds advect Arctic Basin cold air masses into the region. The mean annual air temperature varies from +2 °C in the southern sea areas to −10 °C in the north of the sea.

B.16.2.2 Hydrology

The inter-annual and multi-year changes of the Barents Sea hydrological and ice regime are influenced by a system of stable warm and cold ocean currents.

The system of warm currents includes the South Spitsbergen, Nordkapp, Murmanskoye, Kaninskoye, Kolguyevo-Pechorskoye and Novozemelskoye Currents. The system of cold currents includes the coastal current of the Franz Josef Land, East Spitsbergen, Sudkapp, Bear Island, Perseus, Central and Litke Currents. The White Sea and the Pechora thermohaline currents, distinguished by a decreased salinity, comprise a special group of currents.

Four main water masses have been identified in the Barents Sea:

a) Atlantic water, with an increased temperature and salinity flowing from the west in the form of surface currents and transported from the north at depth from the Arctic Basin;

b) Arctic water, with below zero Celsius temperature and decreased salinity flowing from the north as a surface current;

c) coastal water, with a significant seasonal variation in temperature and low salinity, formed from continental runoff and coastal flow of freshened waters;

d) Barents Sea water, with a low temperature and high salinity, formed within the sea as a result of the mixing of different water masses.

Within the Barents, tides play a major role in sea level oscillations. In the western and southern areas, tides are regular and semi-diurnal (surface oscillations of 2,2 m to 3,7 m), whereas in the eastern area, tides have an irregular, semi-diurnal character (surface oscillations of up to 4,0 m). In the meridional direction, the tidal magnitude decreases from south to north, being only about 0,2 m in the vicinity of Franz Josef Land.

B.16.2.3 Sea ice and icebergs

An important distinguishing feature of the Barents Sea ice regime is that its surface area is never completely ice covered. During the period of the greatest ice cover, March to April, sea ice usually covers only 55 % to 60 % of the surface area, with open water occupying the remainder.

The ice cover can be a combination of multi-year ice up to about 3 m thick, first-year ice generally less than 1,5 m thick and icebergs. Multi-year ice spreads in a narrow zone along the eastern shores of the Svalbard Archipelago and Franz Josef Land, predominantly in spring, but it is not the prevailing ice type. In general, for the entire Barents Sea during the period of the maximum ice cover development, the fraction of multi-year ice averages 10 %, while the fraction of young ice is around 15 %.

The Barents Sea ice cover contains icebergs from the glaciers of Svalbard, Franz Josef Land and Novaya Zemlya. Icebergs drift from these glaciers under the influence of the prevailing winds and ocean currents. Entrained in the general ice drift, icebergs can move large distances during their life span. Information on icebergs and their drift is provided in References [B.16-1] to [B.16-4].

Landfast ice is established annually along most continental and island shores of the Barents Sea. The largest width and stability of landfast ice is noted in bays and inlets of the southern sea area and also among the islands of Franz Josef Land and Svalbard.

In the wintertime, strong ice pressure often occurs at sea and forms conglomerations such as hummocks, ridges and stamukhi. Stamukhi are generated in coastal areas in water depths up to 20 m. The maximum sail height for these features ranges from 3 m to 5 m and keel depths from 15 m to 20 m[B.16-5]. The greatest intensity of ridging is observed in the northwestern and southeastern sea areas due to the onshore drift of the ice.

Table B.16-2 — Barents Sea meteorological conditions

Parameter		Western region		Northeastern region		Pechora Sea	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Air temperature	Maximum, degrees Celsius	4,4	2,0 to 7,0	0,9	0,0 to 9,0	8,8	8,0 to 10,0
	Minimum, degrees Celsius	−7,7	−6,0 to −9,0	−24,0	−20,0 to −39,0	−19,0	−18,0 to −20,0
	Freezing degree days	2 000	1 150 to 2 300	3 500	3 500 to 3 600	2 500	2 300 to 2 800
Wind speed at 10 m elevation	10 min average, metres per second	26,6	25 to 28	23,4 to 31,9	20 to 35	22,3	20 to 25
Wind direction	Dominant winter (direction/percentage occurrence)	NE/26,8	NE	S/21 to SE/32	S to SE	SW/38,7	SW
	Dominant summer (direction/percentage occurrence)	W/19,0	W	S/24,8 to NW/34,1	S to NW	NE/24,7	NE
Precipitation	Annual rainfall, millimetres	560	500 to 620	320	300 to 340	510	500 to 520
	Annual snowfall, millimetres	ND	ND	ND	ND	ND	ND
Visibility (fog, snow, etc.)	Annual number days with visibility < 1 km (fogs)	76	50 to 80	66	50 to 80	64	50 to 80
	Annual number days with visibility < 2 km (snowstorms)	64	100 to 130	114	100 to 130	100	80 to 120

Table B.16-3 — Barents Sea oceanographic conditions

Parameter		Western region		Northeastern region		Pechora Sea	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**
Waves, nearshore (< 100 m water depth)	Significant wave height, metres	2,7	2,0 to 10,0	2,4 to 2,7	2,0 to 9,0	2,5	1,5 to 7,0
	Range of zero-crossing periods, seconds	11,0	10 to 13	11,0	10 to 13	9,0	8 to 10
Waves, nearshore (> 100 m water depth)	Significant wave height, metres	ND	ND	2,5	2,0 to 9,0	ND	ND
	Range of zero-crossing periods, seconds	ND	ND	9,5	8 to 10	ND	ND
Current	Near-surface maximum speed, centimetres per second	65,0	60,0 to 70,0	42,0	31,0 to 51,5	115,0	100 to 130
	Mid-layer maximum Speed, centimetres per second	ND	ND	ND	ND	30,0	20,0 to 50,0
	Bottom maximum speed, centimetres per second	ND	ND	ND	ND	ND	ND
Tidal current	Maximum surface speed, centimetres per second	35,0	30,0 to 40,0	15,0	10,3 to 20,6	35,0	30,0 to 40,0
Tide	Tidal range (total), metres	0,8	0,5 to 1,3	0,3	0,2 to 0,6	1,0	0,5 to 3,0
Wind-induced surge	Water depth range total, metres	ND	ND	1,8	1,7 to 1,9	1,5	1,0 to 3,5
Water salinity	Average surface salinity, parts per thousand	34,75	34,5 to 35,0	33,8	33,3 to 34,2	30,0	25,0 to 33,0
	Average mid-layer salinity, parts per thousand	35,0	34,0 to 36,0	34,5	33,0 to 35,0	ND	ND
Water temperature	Summer surface maximum, degrees Celsius	9,0	7 to 11	2,0	1,5 to 2,5	8,0	7 to 9
	Summer surface average, degrees Celsius	7,0	5 to 9	1,5	1,0 to 2,0	7,0	6 to 8
Seabed geotechnical — Ice-induced gouge	Gouge depth, metres	ND	ND	ND	ND	0,5	0,3 to 1,5
	Water depth range, metres	ND	ND	ND	ND	< 15	< 20
Seismic	Magnitude	ND	ND	ND	ND	ND	ND

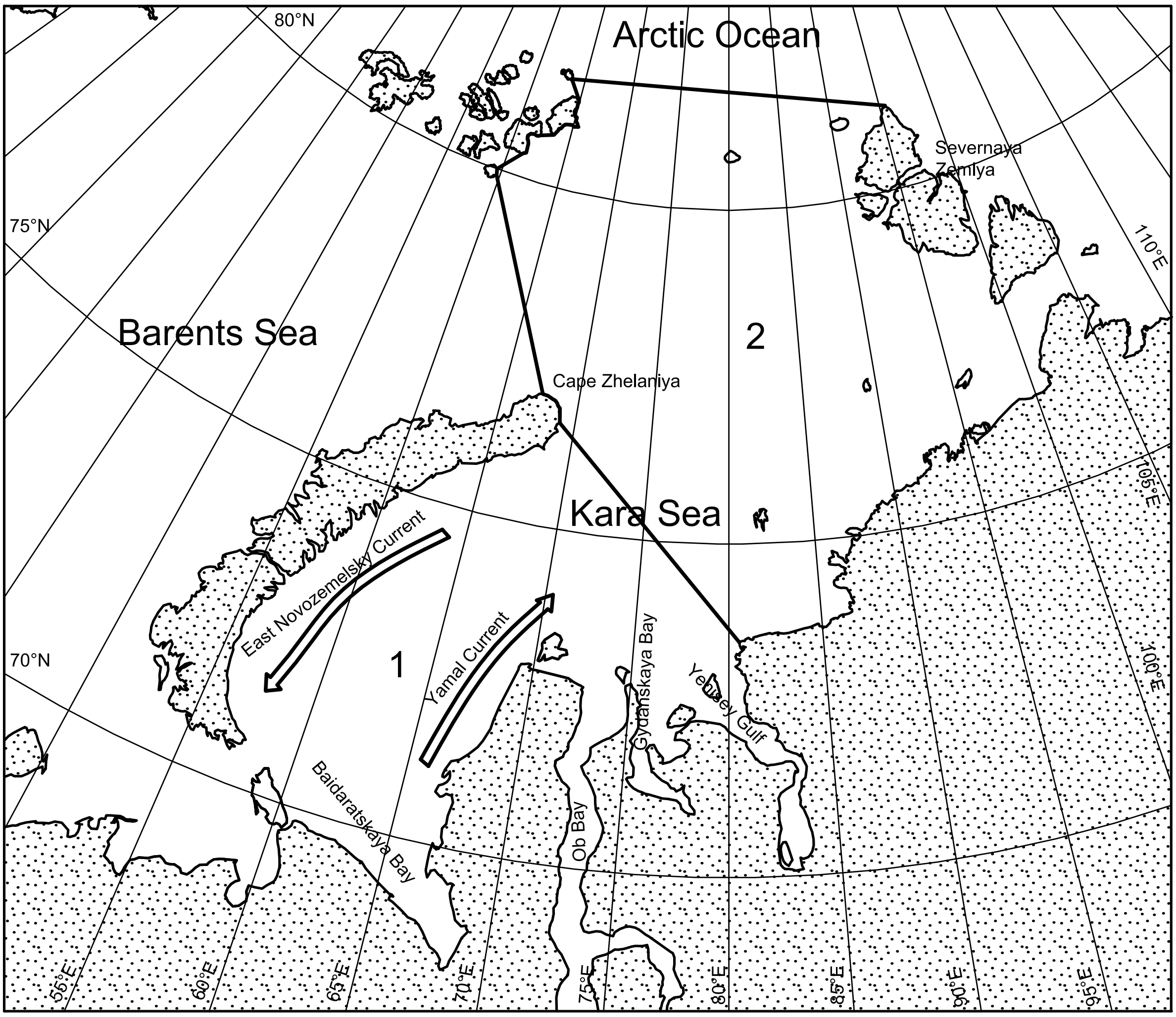
Table B.16-4 — Barents Sea sea ice conditions

Parameter		Western region		Northeastern region		Pechora Sea	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**
Sea ice							
Occurrence	First ice	All year (north area)	All year (north area)	All year	All year	25 Oct.	20 Oct. to 5 Nov.
	Last ice	All year (north area)	All year (north area)	All year	All year	5 July	25 June to 15 July
Level ice (first-year)	Landfast ice thickness, metres	1,4	1,3 to 1,5	1,5	1,4 to 1,6	1,0	0,9 to 1,1
	Floe thickness, metres	1,3	1,2 to 1,4	1,4	1,3 to 1,5	0,8	0,7 to 0,9
Rafted ice	Rafted ice thickness, metres	0,4	0,3 to 0,5	0,4	0,3 to 0,5	0,4	0,8 to 1,0
Rubble fields	Sail height, metres	ND	ND	ND	ND	ND	ND
	Length, metres	ND	ND	ND	ND	ND	ND
Ridges (first-year)	Sail height, metres	4,7	4,5 to 5,0	4,2	4,0 to 4,5	3,5	3,0 to 4,0
	Keel depth, metres	17,5	15,0 to 20,0	15,0	14,0 to 16,0	16,0	15,0 to 18,0
Stamukhi	Water depth range, metres	< 20	< 20	< 20	< 20	< 15	< 20
	Sail height, metres	3 to 5	8 to 10	3 to 5	8 to 10	3 to 5	10 to 11
Level ice (second- and multi-year)	Landfast ice thickness, metres	2,5	2,2 to 2,8	2,5	2,2 to 2,8	None	None
	Floe thickness, metres	2,7	2,5 to 3,0	2,8	2,5 to 3,0	None	None
Ridges (second- and multi-year)	Sail height, metres	ND	ND	ND	ND	None	None
	Keel depth, metres	ND	ND	ND	ND	None	None
Rubble fields (second- and multi-year)	Average sail height, metres	ND	ND	ND	ND	None	None
	Length, metres	ND	ND	ND	ND	None	None
Ice movement	Speed nearshore, metres per second	0,5	0,4 to 0,6	ND	ND	0,7	0,6 to 0,8
	Speed offshore, metres per second	0,6	0,5 to 0,7	0,5	0,4 to 0,6	ND	ND
Icebergs							
Size	Mass, million tonnes	Up to 6	0 to 10	Up to 4	0 to 5	ND	ND
Frequency	Months present	Jan. to June	Jan. to June	All year	All year	Infrequent occurrence	Infrequent occurrence
	Number per year	10 to 40	10 to 40	ND	ND	ND	ND
	Maximum number per month	30	0 to 30	ND	ND	ND	ND

B.17 Kara Sea

B.17.1 Description of region

The Kara Sea is a marginal sea bordering on the Arctic Basin in the north, the Barents Sea in the west and the Laptev Sea in the east. The coastline is strongly irregular with large bays (Baidaratskaya, Gydanskaya and Ob Bays and the Yenisey Gulf) that deeply incise the mainland shoreline. The Kara Sea is usually subdivided by oceanographic conditions into two regions, southwestern and northeastern, with the boundary passing along the line from Cape Zhelaniya to Dikson Island (see Figure B.17-1).



Key

1 southwestern part

2 northeastern part

Figure B.17-1 — Boundaries and parts of the Kara Sea

The main morphometric characteristics of the Kara Sea are as follows:

— total area:	883 000 km^2;
— water volume:	98 000 km^3;
— mean depth:	111 m;
— maximum depth:	600 m.

Deep water regions (deeper than 500 m) occupy less than 1 % of the total area of the Kara Sea.

B.17.2 Kara Sea technical information

B.17.2.1 Climate

The prevailing air masses in the Kara Sea are the cold and dry arctic air, the relatively warm and moist sea air from the Atlantic and the continental air from the temperate latitudes, which is colder and drier in winter and comparatively warmer in summer.

The air temperature in the Kara Sea is consistently below 0 °C for eight months from October to May. The coldest period is from December to March, when the mean monthly air temperature is between −14 °C and −26 °C. The summer period lasts only for four months from June to September. The mean monthly summer air temperature is not more than 7 °C.

In winter, storms mostly produce westerly, southwesterly and southerly winds. In summer, storms result in northerly and northeasterly winds and are accompanied by a drop in air temperature.

B.17.2.2 Hydrology

In winter, the water masses in the shallow sea regions become almost uniform from the surface to the bottom and have a temperature of approximately −1,8 °C. The main mass of water (the heat sink of the Siberian Rivers) arrives at the sea in spring when it is still ice covered.

Usually beginning in July, the water temperature increases, first slowly and then with the sea becoming ice-cleared more rapidly, achieving its maximum by the end of August. In the coastal areas, the surface water temperature heats up to 6 °C to 8 °C. In the central part of the area, the water temperature at the sea surface is about 2 °C to 4 °C, while in the western sea area, the water temperature is about 2 °C. In September to October, the surface water temperature decreases to the freezing temperature.

In summer in the southwestern Kara Sea, the salinity in the surface layer decreases as a result of ice melting and the inflow of flood water, achieving its minimum in August/September. The surface water salinity is usually 30 ‰ to 32 ‰. The most brackish water is in the south near the mouths of the large rivers, where the surface water salinity decreases to 10 ‰.

In the shallow Kara Sea area, wind-driven currents prevail but have variable directions and speeds. In general, the gradients and tidal currents are weak. The summer period is characterized by more or less stable water flows that form a cyclonic gyre in the southwestern sea area composed of a relatively warm Yamal Current flowing northeastward from the Kara Gate Strait and a relatively cold East Novozemelsky Current flowing southward along the east shores of Novaya Zemlya.

The tidal sea level oscillations are not greater than 0,5 m, while the wind-driven surge water rise in the coastal areas can be 2 m to 3 m.

B.17.2.3 Sea ice and icebergs

The Kara Sea area is covered by 7/10 to 9/10 ice concentration for eight months to 10 months per year. In summer, complete ice clearance usually occurs in the southwestern area and in the coastal northeastern areas of the sea.

The ice cover is composed of multi-year ice with a thickness of about 2,5 m in the north of the sea, first-year ice with a thickness up to 1,8 m and young ice up to 0,3 m covering fractures and flaw polynyas.

Landfast ice is established annually along all mainland and island shores of the Kara Sea. During the maximum development period of the landfast ice, its boundary passes within the 10 m to 20 m isobaths. Second-year ice or multi-year landfast ice is possible near the shores of the Severnaya Zemlya archipelago.

In winter, strong ice pressures lead to the formation of hummocks, ice ridges and stamukhi. Stamukhi are spread along the coastal areas, both among drifting ice and in landfast ice in depths up to 20 m. The observed maximum values of stamukha geometry comprise are a sail height of 10 m to 15 m and the keel depth of 20 m to 25 m.

Icebergs are mainly centred near the northeast coast of Novaya Zemlya and the west coast of the Severnaya Zemlya archipelago. Icebergs have not been sighted in the southern coastal areas.

Table B.17-1 — Kara Sea meteorological conditions

Parameter		Amderma		Bely Island		Dikson		Vize Island	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**
Air temperature	Annual month maximum, degrees Celsius	6,9	ND	5,0	ND	5,1	ND	0,5	ND
	Absolute maximum, degrees Celsius	31	32	27	27	27	27	8	9
	Annual month minimum, degrees Celsius	–19,3	ND	–24,9	ND	–26,0	ND	–25,8	ND
	Absolute minimum, degrees Celsius	–44	–45	–48	–48	–48	–48	–47	–48
	Freezing degree days	2 946	ND	4 107	ND	4 497	ND	4 975	ND
Wind speed at 10 m elevation	Maximum observed, metres per second	40	ND	40	ND	40	ND	34	ND
	3 s gust, metres per second	ND	55	ND	50	ND	62	ND	44

Table B.17-1 (*continued*)

Parameter		**Amderma**		**Bely Island**		**Dikson**		**Vize Island**	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**
Wind direction	Dominant winter (direction/ percentage occurrence)	N/6 NE/8 E/9 SE/9 S/27 SW/25 W/8 NW/5 Calm/3	ND	N/11 NE/10 E/10 SE/17 S/19 SW/12 W/9 NW/7 Calm/5	ND	N/6 NE/9 E/8 SE/11 S/37 SW/11 W/4 NW/6 Calm/8	ND	N/13 NE/14 E/15 SE/20 S/13 SW/7 W/5 NW/9 Calm 4	ND
	Dominant summer (direction/ percentage occurrence)	N/12 NE/16 E/17 SE/5 S/8 SW/10 W/12 NW/17 Calm/3	ND	N/17 NE/18 E/12 SE/9 S/6 SW/14 W/10 NW/11 Calm/3	ND	N/24 NE/26 E/5 SE/4 S/10 SW/10 W/8 NW/10 Calm/3	ND	N/15 NE/11 E/10 SE/11 S/10 SW/12 W/15 NW/14 Calm/2	ND
Precipitation	Annual rainfall, millimetres	400	—	300	—	360	—	260	—
	Largest month rainfall (month/amount)	Sept./60	ND	Sept./47	ND	Sept./69	ND	Aug./34	ND
	Rainfall — maximum within 24 hours, millimetres	ND	ND	ND	ND	ND	ND	ND	ND
	Annual snowfall, millimetres	ND	ND	ND	ND	ND	ND	ND	ND
Visibility (fog, snow, etc.)	Annual number days with visibility < 1 km (fogs)	86	ND	93	ND	91	ND	89	ND
	Annual number days with visibility < 2 km (snowstorms)	106	ND	91	ND	112	ND	86	ND
	Month with greatest visibility < 1 km (month and percentage occurrence)	July/12	ND	July/20	ND	July/20	ND	July/30	ND

Table B.17-2 — Kara Sea oceanographic conditions

Parameter		Southwestern part		Northeastern part	
		Average annual value	Range of annual values	Average annual value	Range of annual values
Waves	Significant wave height 50 %, metres	0,9	0,5 to 1,0	0,7	0,5 to 0,9
	Associated periods, seconds	5	54 to 6	4	3 to 5
	Maximum wave height 1 %, metres	7	8 to 10	10	14 to 16
	Associated periods, seconds	7	ND	9	ND
Current	Near-surface maximum speed, centimetres per second	80 to 100	ND	100 to 120	ND
	Near-surface average speed, centimetres per second	5 to 10	ND	5 to 10	ND
	Bottom maximum speed, centimetres per second	ND	ND	ND	ND
	Bottom average speed, centimetres per second	ND	ND	ND	ND
Water temperature	Summer surface maximum, degrees Celsius	4,5 to 5,5	4,5 to 5,5	2,5 to 3,5	2,5 to 3,5
	Summer surface average, degrees Celsius	2,5 to 3,5	2,5 to 3,5	0,5 to 2,0	0,5 to 2,0
Water salinity	Average surface salinity (July), parts per thousand	20 to 25	20 to 25	25 to 30	25 to 30
Tide	Tidal range, metres	0,6 to 0,8	0,6 to 0,8	0,4 to 0,6	0,4 to 0,6
Wind-induced surge	Water level range, metres	2,3 to 2,6	3,0	1,6 to 2,6	3,0
	Water depth positive increase, metres	1,3 to 1,4	1,5	1,0 to 1,4	1,5
	Water depth negative decrease, metres	−0,9 to −1,2	−1,5	−0,7 to −1,1	−1,5

Table B.17-3 — Kara Sea sea ice conditions

Parameter		Southwestern part		Northeastern part	
		Average annual value	Range of annual values	Average annual value	Range of annual values
Sea ice occurrence	First ice	10 to 20 Oct.	ND	10 to 20 Sept.	ND
	First landfast ice	25 Oct. to 10 Nov.	ND	20 to 30 Sept.	ND
	Last landfast ice	10 July to 20 July	ND	25 to 30 July	ND
	Last ice	20 July to 20 Aug.	ND	All year	ND
	Continuous ice period (days)	280 to 300	ND	365	ND

Table B.17-3 (*continued*)

Parameter		Southwestern part		Northeastern part	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**
Level ice (first-year)	Landfast ice thickness, metres	1,6	ND	1,8	ND
	Floe length, metres	3 000 to 6 000	ND	4 000 to 6 000	ND
	Floe thickness, metres	1,4 to 1,8	ND	1,6 to 1,8	ND
Surface deformation	Amount, percentage	50	ND	60	ND
	Month of maximum deformation	April to May	ND	April to May	ND
Rafted ice	Rafted ice thickness, metres	0,4	ND	0,4	ND
	Rafted ice floe thickness, metres	ND	ND	ND	ND
Ridges (first-year)	Average sail height, metres	1,3 to 1,5	ND	1,5 to 1,8	ND
	Maximum sail height, metres	4,0 to 6,0	ND	5,0 to 6,0	ND
	Average keel depth, metres	ND	ND	ND	ND
	Ice block thickness, metres	30 to 40	ND	50 to 60	ND
	Width, metres	5,0	ND	5,0	ND
	Number per kilometre	3	ND	3 to 4	ND
Level ice (second- and multi-year)	Landfast ice thickness, metres	ND	ND	1,8 to 2,0	ND
	Floe thickness, metres	ND	ND	1,8 to 2,2	ND
Ridges (second- and multi-year)	Sail height, metres	ND	ND	3,0 to 5,0	ND
	Keel depth, metres	ND	ND	13,0 to 18,0	ND
	Number per kilometre	ND	ND	ND	ND
Ridged ice zones (rubble fields)	Average sail height, metres	ND	ND	ND	ND
	Average keel depth, metres	ND	ND	ND	ND
Stamukhi	Water depth, metres	10 to 15	ND	10 to 15	ND
	Sail height, metres	5 to 10	ND	5 to 10	ND
Ice movement	Speed nearshore, metres per second	0,4	ND	0,3	ND
	Speed offshore, metres per second	0,3	ND	0,2	ND
	Prevailing direction	NE	ND	N, NW in winter S, SE in summer	ND

Table B.17-3 (*continued*)

Parameter		Southwestern part		Northeastern part	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**
Iceberg size	Sail height, metres	ND	ND	ND	ND
	Length, metres	ND	ND	ND	ND
	Mass, tonnes	ND	ND	ND	ND
Iceberg frequency	Month present	ND	ND	ND	ND
	Number per year	ND	ND	ND	ND
Ice-induced scour	Average/maximum scour depth, metres	ND	ND	ND	ND
	Scour frequency, number per kilometre	ND	ND	ND	ND
	Water depth range, metres	ND	ND	ND	ND

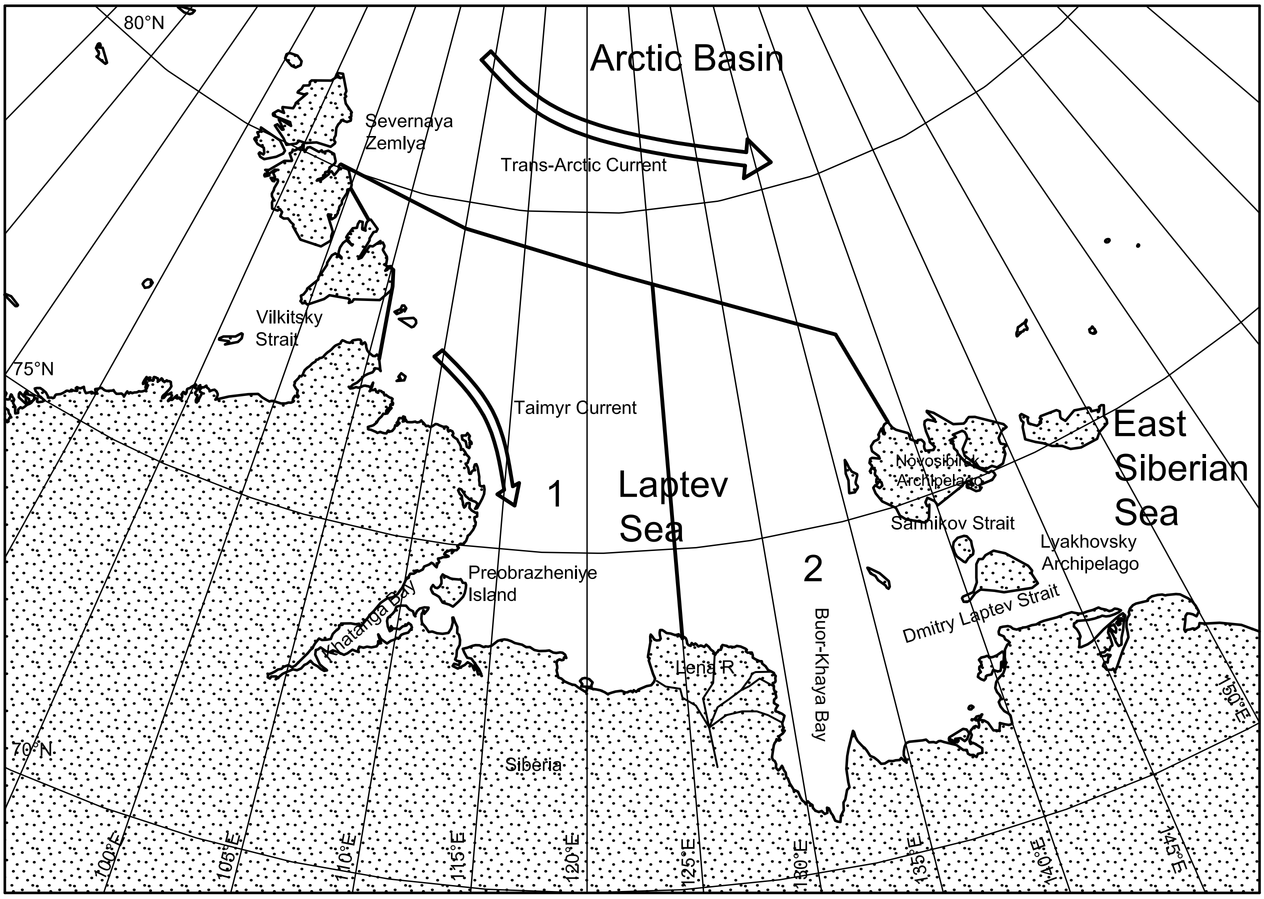
B.18 Laptev Sea

B.18.1 Description of region

The Laptev Sea (see Figure B.18-1) has free communication with the Arctic Basin.

When active studies of the Arctic began in the 1930s, ice observations were carried out within the smaller area shown as key item 1 in Figure B.18-1. The Laptev Sea is now considered to include the areas shown as key items 1 and 2 combined. The total area of the Laptev Sea is approximately 540 000 km^2.

Great depth contrasts are observed in the Laptev Sea. In the southern part, average depths do not exceed 15 m to 25 m, while the northern border of the sea passes through the deep (more than 2 000 m) ocean seabed. A sharp increase in water depth to 3 000 m divides the sea along the Vilkitsky Strait latitude. Depths less than 50 m occupy about 54 % of the sea area.



Key

1	western part
2	eastern part

Figure B.18-1 — Boundaries and parts of the Laptev Sea

B.18.2 Laptev Sea technical information

B.18.2.1 Climate

The rather severe climate of the Laptev Sea is due to its high latitude position (71 °N to 81 °N) and the peculiarities of the atmospheric circulation. The polar night lasts 70 days to 80 days in the southern part of the sea and 100 days to 120 days in the northern area. Duration of solar radiance in the northern part is about 1 100 h per year and increases in the near-coastal area to 1 200 h to 1 250 h. The sunniest month is April (250 h per month to 350 h per month). During the major part of a year (from September to April), the radiance balance is negative, but due to the summer months when its value reaches 300 month-MJ/m^2 to 400 month-MJ/m^2 per month, the total annual radiance balance is positive.

The atmospheric circulation over the sea has a seasonal character. From October to March, the major part of the sea is under the effect of the Iceland Low while, at the same time, the weather of the southeastern part of the sea is formed by a spur of the strong Siberian High. Depressions travel from the west two times per month to three times per month. In winter, air flow with a southerly component (from continent to the sea) predominates.

The transformation of the atmospheric circulation begins in April; by May, a low pressure system has developed over Siberia while an area of high pressure develops over the Laptev Sea. In summer, the air flow over the sea is usually directed from the sea to the coast and has a significant easterly component. In summer, the number of depressions over the sea increases and reaches three to four (in the western part) and four to five (in the eastern part). These depressions lead to sharp fluctuations of air temperature, strong winds, cloudiness and precipitation.

Throughout the year, weak winds (less than 5 m/s) prevail over the sea. Their frequency of occurrence almost never decreases below 50 % and, in the central and northern regions, it reaches 60 % to 70 %. In September and October, the frequency of occurrence of weak winds decreases to 40 % to 45 %. The number of days with stormy winds ($\geqslant$ 15 m/s) is about 40 days per year to 50 days per year in the coastal zone, but is significantly less (about 20 days per year) in the open sea.

In the southwestern part of the Laptev Sea, the maximum wind speed can reach 38 m/s to 40 m/s in the inter-seasonal periods and in winter, and 24 m/s to 28 m/s in summer. In the eastern part, the maximum wind speed does not exceed 34 m/s in all seasons.

In the summer months, the climate of the Laptev Sea is significantly affected by sea currents. The cold East Taimyr Current flows from north to south along the eastern coast of the Taimyr Peninsula. The warm Lena Current (in the eastern part of the sea) is caused by the Lena River run-off and moves towards the north and northeast. As a result, the summer is colder in the western part of the Laptev Sea. In addition, the ice edge position during summer greatly influences the weather conditions.

The length of the warm period varies from 58 days (near the Vilkitsky Strait) to 108 days (in the Buor-Khaya Bay).

A peculiarity of the thermal regime of the Laptev Sea is the inverse character of the air temperature distribution during the winter months: the northern part of the sea is warmer, while the southern part is colder. During the winter months (January to February), the air temperature in the coastal zone is –30 °C to –32 °C, while in the northern part it is about –29 °C. From April, due to the radiance effect, the air temperature increases from north to south from –21 °C to –22 °C to –19 °C to –20 °C.

In summer, the air temperature over a large portion of the sea is close to 0 °C. In the south, just near the coastline, the air temperature in July to August reaches 8 °C, but in the wider coastal zone of the sea, it decreases rapidly to 2 °C. In summer, the highest values of the air temperature do not exceed 12 °C to 15 °C (in the northern part) and 26 °C to 28 °C (in the southern part).

B.18.2.2 Hydrology

Cyclonic circulation of seawater is typical for the Laptev Sea. Near the northern edge of the Severnaya Zemlya Archipelago, the East Taimyr Current branches off from the Trans-Arctic Current and goes southward along the eastern coast of the Severnaya Zemlya Archipelago and Taimyr Peninsula. Then the water moving eastward along the continent coast is strengthened by the Lena Current. The major part of this flow turns north and northeast (the Novosibirskoye Current), then goes beyond the Laptev Sea to join the Trans-Arctic Current moving to northwest. A minor branch penetrates to the East Siberian Sea through the Sannikov Strait.

The upper layer of the Laptev Sea is Arctic surface water, which is permanently replenished by river and melted water. The total volume of river run-off is about 767 km^3. The major part of river run-off is formed by the Lena River. River water is mixed intensively with cold and saline arctic water. Water of the western part of the sea is more saline than that of the east due to contributions of cold, saline water coming from the north. Surface water salinity reaches 29 ‰ to 30 ‰ in the northwestern part and decreases to 25 ‰ to 10 ‰ in the eastern part. In the north, relatively warm water of Atlantic origin penetrates below the surface arctic water along the deep bottom troughs.

In years with favourable ice conditions, the water temperature in the western part can reach 7 °C to 8 °C in the south; then it steadily decreases to about –1 °C near the ice edge. In the eastern part, water temperature varies from 10 °C to 11 °C near the Lena delta to 5 °C to 6 °C in the Dmitry Laptev Strait and to 2 °C in the Sannikov Strait. In unfavourable ice conditions, the surface water temperature in August is about –1 °C throughout the major part of the sea area.

The general character of tides in the Laptev Sea is semi-diurnal. The tidal wave reaches the sea from the north, steadily attenuating and changing its form as it propagates to the coasts. The tidal amplitude is generally about 0,5 m and exceeds 2,0 m in Khatanga Bay. Wind-induced surges are especially significant in the summer and autumn periods, with heights reaching 2,5 m at times.

Wave development in the Laptev Sea depends on the area of ice free water. The length of the wave fetch varies from 90 km to 100 km in July to 550 km to 650 km in September (on average). Maximum fetch can reach 850 km to 1 000 km. The highest waves are observed near the western coast and in the central part where, in summer, maximum waves caused by easterly storm winds can reach 5 m. In the southeastern part of the sea, maximum waves do not exceed 4 m. The stormiest period is autumn (September to October), when wave heights can reach about 6 m.

B.18.2.3 Sea ice

For almost nine months (October to June), ice covers the entire area of the Laptev Sea. Due to the peculiarities of the atmospheric circulation, ice moves northward to the Arctic Basin during most of this period. In winter (October to March), about 280 000 km^2 of ice (on average) is transported from the Laptev Sea to the Arctic Basin. Due to almost constant transport of ice out of the sea, polynyas with open water or young ice are continually formed beyond the landfast ice. The most stable polynyas are the Anabar-Lena polynya (in the southern part of the sea), the Western Novosibirsk polynya (in the eastern part) and the Northern Novosibirsk polynya (to the north of the Novosibirsk Archipelago). These polynyas have lengths of several hundred kilometres and widths of 30 km to 40 km on average (sometimes more than 100 km). The long-term average value of the total area of all polynyas in March is 34 000 km^2.

Landfast ice is especially wide in the eastern part of the Laptev Sea, where it occupies more than half of the total area of this region. The width of landfast ice to the west of the Lyakhovsky Archipelago is about 300 km on average, and it steadily decreases to 50 km to the north of the Lena River delta. Landfast ice thickness in the eastern part of the sea reaches 2 m and more.

Just before melting starts, thick first-year ice (thickness is more than 120 cm) prevails in the sea and occupies about 85 % of the sea area. The relative area occupied by young ice (less than 30 cm) and thin first-year ice (30 cm to 70 cm) is about 10 %. Ice ridge concentration in the sea varies from 1 point to 3 points (according to the 5 point scale).

Ice melting begins, on average, between 5 June and 10 June in the southern part of the sea. By this time, ice formation in the polynyas stops, and they become heat absorbers and play the role of epicentres of ice disappearance. On average, the final break-up of landfast ice takes place between 15 July and 20 July. Landfast ice in the southeastern part of the sea forms the Yana ice massif situated near the Sannikov Strait and the Dmitry Laptev Strait. Concentrated ice (70 % to 100 %) in the western part of the Laptev Sea forms the Taimyr ice massif. In summer, it is enhanced by ice coming from the Arctic Basin and this massif becomes an obstacle for navigation from the Vilkitsky Strait to the Laptev Sea. The Taimyr ice massif rarely disappears completely by the end of the melting period. By contrast, the Yana ice massif disappears completely in 80 % of the cases. On average, just before new ice formation at the end of September, 50 % of the western part of the Laptev Sea and 80 % of the eastern part are ice free.

According to expedition data, at the end of September on the navigation routes, the thickness of ice with 90 % to 100 % concentration is on average 105 cm in the western part and 85 cm in the eastern part.

In summer, stamukhi are observed near the coastline or on the banks in the open sea, where the depth is not more than 10 m. These are the remainder of landfast ice or strongly ridged, drifting ice floes sunk on the sea bottom. The stamukha draughts vary from 1,5 m to 22 m. Usually, stamukhi are destroyed by the end of August.

Small icebergs slowly drift down to the Laptev Sea from the islands of the Severnaya Zemlya Archipelago; the maximum quantity of icebergs is observed near the northern island of this archipelago. Under the effect of wind and the East Taimyr Current, icebergs drift southward along the Taimyr coast. In some cases, icebergs are observed near Preobrazheniye Island. Icebergs occur mainly in the western part of the Laptev Sea, while in the eastern part, only small icebergs are observed on occasion.

Stable ice formation in the Laptev Sea begins near its northern boundary between 5 September and 10 September on average, and propagates steadily southward. The sea becomes completely covered with young ice by around the first week of October.

Table B.18-1 — Laptev Sea meteorological conditions

Parameter		Andrey Island		Tiksi		Kotelny	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**
Air temperature	Annual month maximum, degrees Celsius	3,2	ND	7,7	ND	2,6	ND
	Absolute maximum, degrees Celsius	25	28	33	33	22	21
	Annual month minimum, degrees Celsius	–31,3	ND	–31,4	ND	–30,4	ND
	Absolute minimum, degrees Celsius	–52,1	–53	–50,3	–52	–46,8	–48
	Freezing degree days	5 805	ND	5 342	ND	5 498	ND
Wind speed at 10 m elevation	Maximum observed, metres per second	40	ND	51	ND	34	ND
	3 s gust, metres per second	56	ND	69	ND	42	ND
Wind direction	Winter (direction/ percentage occurrence)	N/1 NE/2 E/13 SE/21 S/10 SW/32 W/18 NW/3 Calm/8	ND	N/5 NE/3 E/1 SE/1 S/18 SW/52 W/16 NW/4 Calm/27	ND	N/3 NE/6 E/10 SE/21 S/19 SW/27 W/9 NW/5 Calm/12	ND
	Summer (direction/ percentage occurrence)	N/7 NE/11 E/21 SE/14 S/2 SW/7 W/24 NW/14 Calm/7	ND	N/18 NE/33 E/13 SE/5 S/5 SW/7 W/8 NW/11 Calm/11	ND	N/15 NE/112 E/11 SE/14 S/6 SW/11 W/16 NW/15 Calm/3	ND
Precipitation	Annual rainfall, millimetres	300	ND	400	ND	210	ND
	Largest month rainfall (month/amount)	August/52	ND	August/62	ND	August/38	ND
	Rainfall — maximum within 24 hours, millimetres	ND	ND	ND	ND	39	ND
	Annual snowfall, millimetres	ND	ND	ND	ND	ND	ND

Table B.18-1 (*continued*)

Parameter		Andrey Island		Tiksi		Kotelny	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**
Visibility (fog, snow, etc.)	Annual number days with visibility < 1 km (fogs)	60	ND	40	ND	68	ND
	Annual number days with visibility < 2 km (snowstorms)	82	ND	71	ND	75	ND
	Month with greatest visibility < 1 km (month and percentage occurrence)	July/14	ND	July/12	ND	August/20	ND

Table B.18-2 — Laptev Sea oceanographic conditions

Parameter		Western part		Eastern part	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**
Waves	Significant wave height 50 %, metres	0,3 to 0,4	ND	0,3 to 0,4	ND
	Associated periods, seconds	2,5	ND	3	ND
	Maximum wave height 1 %, metres	4,0 to 5,0	4,0 to 6,0	5,5	6,0 to 10,0
	Associated periods, seconds	6	ND	6	ND
Current	Near-surface maximum speed, metres per second	1,1	ND	0,7	ND
	Near-surface average speed, metres per second	0,05 to 0,10	ND	0,05 to 0,10	ND
	Bottom maximum speed, metres per second	ND	ND	ND	ND
	Bottom average speed, metres per second	ND	ND	ND	ND
Water temperature	Summer surface maximum, degrees Celsius	4	ND	3	ND
	Summer surface average, degrees Celsius	1 to 2	ND	0 to 1	ND
Water salinity	Average surface salinity (July), parts per thousand	20 to 28 (offshore) 15 to 16 (nearshore)	ND	25 to 29,5 (offshore)	ND
Tide	Tidal range, metres	0,2 to 0,4	ND	0,1 to 0,4	ND
Wind-induced surge	Water depth increase range, metres	1,3 to 1,6	1,4 to 1,7	1,8 to 2,0	1,7 to 2,2
	Water depth decrease range, metres	–1,1 to –1,4	–1,2 to –1,6	–1,1 to –1,3	–1,4 to –1,6
	Water level range, metres	1,8 to 3,1	2,2 to 3,2	2,9 to 3,2	3,2 to 3,8

Table B.18-3 — Laptev Sea sea ice conditions

Parameter		Southwestern part		Northeastern part	
		Average annual value	Range of annual values	Average annual value	Range of annual values
Sea ice occurrence	First ice	All year 1 to 3 Oct. (nearshore)	ND	All year 3 to 5 Oct. (nearshore)	ND
	First landfast ice	15 to 25 Oct.	ND	25 to 30 Oct.	ND
	Last landfast ice	20 July to 25 July	ND	10 July to 15 July	ND
Level ice (first-year)	Landfast ice thickness, metres	1,9 to 2,1	ND	2,0 to 2,2	ND
	Floe length, metres	10 000 to 15 000	ND	5 000 to 10 000	ND
	Floe thickness, metres	1,4 to 1,6	ND	2,0 to 2,4 (north area) 1,6 to 1,8	ND
Surface deformation	Amount, percentage	60	ND	50	ND
	Month of maximum deformation	April to May	ND	April to May	ND
Rafted ice	Rafted ice thickness, metres	ND	ND	ND	ND
	Rafted ice floe thickness, metres	ND	ND	ND	ND
Ridges (first-year)	Average sail height, metres	1,0 to 1,5	ND	1,5 to 2,0	ND
	Maximum sail height, metres	1,5 to 2,0	ND	2,5	ND
	Average keel depth, metres	ND	ND	ND	ND
	Maximum keel depth, metres	ND	ND	ND	ND
	Ice block thickness, metres	0,3 to 0,4	ND	0,3 to 0,4	ND
	Consolidated layer, metres	ND	ND	ND	ND
	Width, metres	5,0 to 7,5	ND	7,5 to 10,0	ND
	Length, metres	ND	ND	ND	ND
	Number per kilometre	2 to 5	ND	4 to 5	ND
Level ice (second- and multi-year)	Floe thickness, metres	2,4 to 2,8	ND	2,8 to 3,2	ND
Ridges (second- and multi-year)	Sail height, metres	ND	ND	ND	ND
	Keel depth, metres	ND	ND	ND	ND
Ridged ice zones (rubble fields)	Average sail height, metres	ND	ND	ND	ND
	Average keel depth, metres	ND	ND	ND	ND
Stamukhi[a]	Water depth, metres	ND	ND	1,6 to 22,0	ND
	Sail height, metres	ND	ND	ND	ND
	Length, metres	ND	ND	5 000	ND

Table B.18-3 (*continued*)

Parameter		Southwestern part		Northeastern part	
		Average annual value	Range of annual values	Average annual value	Range of annual values
Ice movement	Speed nearshore, metres per second	ND	ND	ND	ND
	Speed offshore, metres per second	0,08 to 0,13	ND	0,10 to 0,15	ND
	Prevailing direction	NW	ND	WNW	ND
Iceberg size	Sail height, metres	ND	ND	ND	ND
	Keel depth, metres	ND	ND	ND	ND
	Length, metres	ND	ND	ND	ND
	Width, metres	ND	ND	ND	ND
	Mass, tonnes	ND	ND	ND	ND
Iceberg frequency	Month present	All year	ND	Sometimes	ND
	Number per year	ND	ND	ND	ND
Ice-induced scour	Average/maximum scour depth, metres	ND	ND	ND	ND
	Average/maximum scour width, metres	ND	ND	ND	ND
	Average/maximum scour length, metres	ND	ND	ND	ND
	Scour frequency, number per kilometre	ND	ND	ND	ND
	Water depth range, metres	ND	ND	ND	ND

[a] The mean length of stamukhi is presented; the length varies between 400 m and 7 300 m.

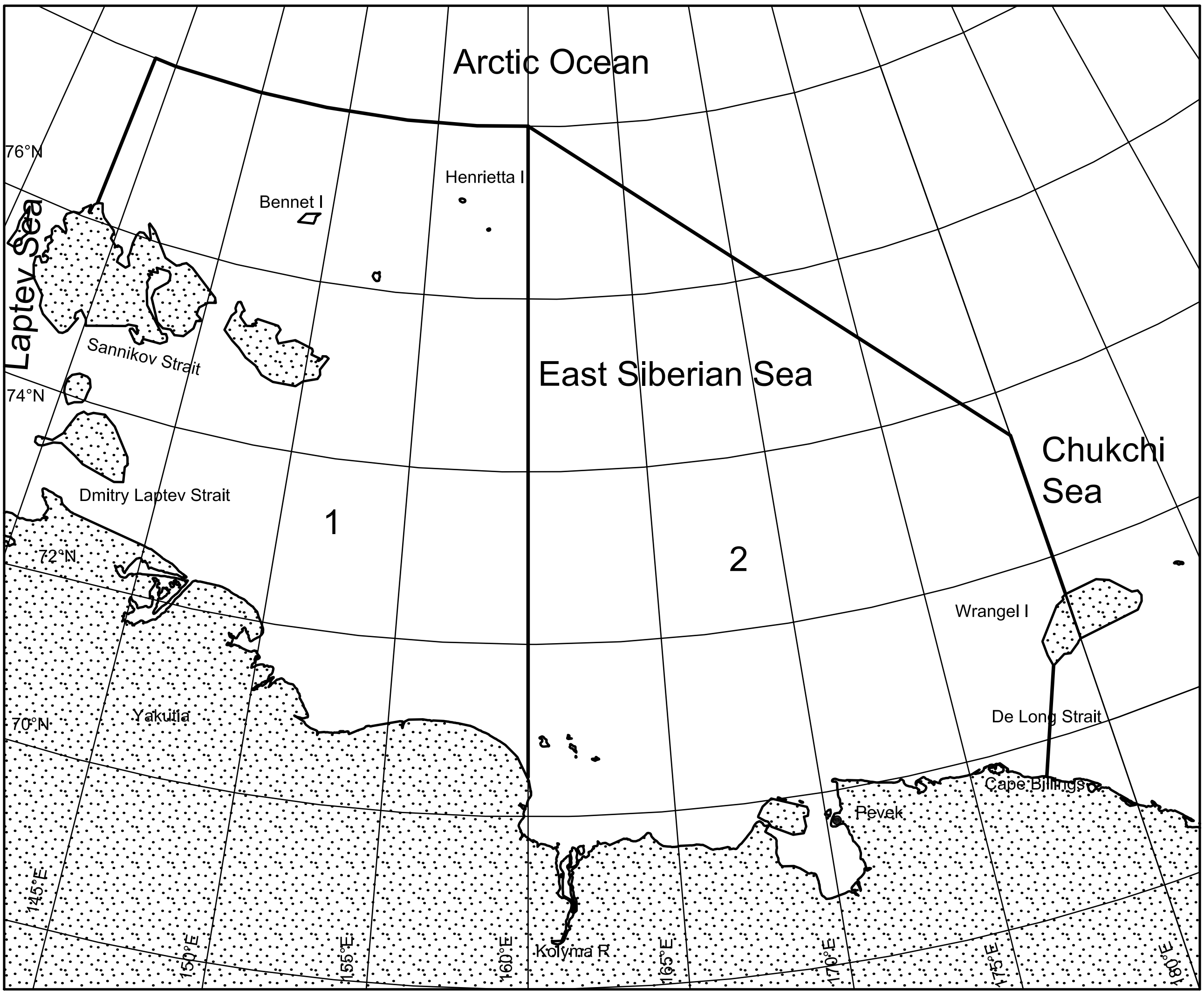
B.19 East Siberian Sea

B.19.1 Description of region

The East Siberian Sea is one of the seas of the Siberian shelf. In the north the sea has an open border with the Arctic Basin, in the west it adjoins the Laptev Sea, and in the east in adjoins the Chukchi Sea. In general, the East Siberian Sea is a very shallow water basin with an extremely flat bottom sloping to the northeast; the flat and gently sloping coastal plains gradually grade into the sea floor. The prevailing depths range from 10 m to 20 m in the western part of the sea and from 30 m to 40 m in the eastern part.

The borders of the East Siberian Sea are shown in Figure B.19-1.

The total area of the East Siberian Sea is approximately 770 000 km^2.



Key

1 western part

2 eastern part

Figure B.19-1 — Boundaries and parts of the East Siberian Sea

B.19.2 East Siberian Sea technical information

B.19.2.1 Climate

The peculiarities of the East Siberian Sea climate are due to its high latitude, the influence of the cold Arctic Basin and the proximity of the Asian continent. The polar night lasts 50 days to 60 days in the southern part of the sea and 80 days to 120 days in the northern part. The duration of solar radiance everywhere exceeds 1 200 h per year. The largest duration of solar radiance, about 250 h to 300 h, is observed in April.

In winter, from November to March, the atmospheric circulation over the sea is caused by shallow gradients of atmospheric pressure that are formed between the Siberian and Canadian anticyclones and the Aleutian Low located east of the area. The winds are unstable during this period, but winds with a westerly component slightly predominate in the western part of the sea. In winter, the number of depressions crossing the sea is two per month to four per month. All depressions are of Pacific origin; some of them go through Yakutia and the Kolyma River area. These depressions lead to a brief warming (sometimes almost up to a thaw). Depressions arriving from the east through the Bering Strait are rarer.

In spring, April to May, the atmospheric circulation changes as the Siberian and Canadian anticyclones disappear and the Aleutian depression weakens. Simultaneously, the Arctic anticyclone is formed to the north of the Beaufort Sea; the spur of this anticyclone determines the circulation regime over the East Siberian Sea. In May the number of cyclones decreases to one to two, easterly atmospheric flow predominates and, moving further from the coast, these flows acquire a northerly component. The same atmospheric flow is typical for the summer period.

In summer, the circulation regime is influenced by the low pressure trough, which is connected with the Siberian depression and stretches along the Arctic coast. In July, the number of cyclones increases up to four to five.

In September, the atmospheric circulation is transformed to a winter type. At this time, the southerly winds slightly predominate in the western part of the sea and a northerly wind predominates in the east.

Annually, weak winds (less than 5 m/s) are typical. In all months, their frequency of occurrence never decreases below 50 % and, in the central and northern parts, it reaches 60 % to 70 %. Storms (mean wind speeds $\geqslant$15 m/s) at the coast are observed between 15 days per year and 50 days per year. Their frequency of occurrence depends on the local topography and, in general, it increases from west to east.

In summer, the maximum wind speed usually does not exceed 22 m/s to 24 m/s in the western region and 28 m/s to 30 m/s in the east. Considering local storms, extremely strong southern winds (the so-called “yuzhak”) are observed in Pevek village. They can arise quite suddenly and the wind speed reaches hurricane values of up to 40 m/s to 45 m/s.

During a major part of the year, air temperatures below 0 °C are observed over the sea. The duration of the period having a positive daily temperature is less than two months in the north and three to three-and-a-half months in the south. During July and August in the northern part of the sea, a stable air temperature close to 0 °C is observed; near the coast, the temperature is about 4 °C to 5 °C and in the bays and gulfs that deeply incise the shoreline, it reaches 7 °C to 8 °C. In summer months, the highest temperature does not exceed 15 °C in the northern half of the sea and 25 °C to 30 °C near the coast.

The monthly mean temperature of the coldest months (January to February) varies from −24 °C near Wrangel Island to −30 °C near the New Siberia Archipelago and to −32 °C to −34 °C in the estuary areas of the Indigirka and Kolyma rivers. In spring (April to May), an air temperature field with low gradients is formed over the sea. The mean temperature varies from −18 °C in the eastern part to −21 °C in the western part.

B.19.2.2 Hydrology

Sea level fluctuations and currents of the East Siberian Sea are formed mainly by hydrometeorological factors, e.g. wind, atmospheric pressure, water exchange with the Arctic Basin and neighbouring seas, and river run-off. The tide in the western part of the sea is a result of the tidal wave from the Arctic Basin, while in the south-eastern part, it is a result of the tidal wave entering from the Chukchi Sea through the De Long Strait. The value of the tidal variation in sea level for a large part of the sea does not exceed 0,3 m, while the wind-induced fluctuations can reach 2 m to 3 m or more.

In the northern part of the East Siberian Sea, the permanent current coinciding with the main Trans-Arctic Drift is directed towards the west-northwest. The current direction is predominantly along the west-east axis. In the eastern part of the East Siberian Sea, an easterly coastal current is observed, which has a permanent character as far as Cape Billings and further through the De Long Strait. Maximum current speeds are observed in the straits and shallow water zones.

Waves in the East Siberian Sea are relatively low due to significant ice cover and the shallowness of the sea. In July to October, as the ice edge moves northward, the frequency of occurrence of high waves increases, reaching its maximum in September.

The salinity in the western part of the East Siberian Sea is 16 ‰ to 20 ‰ due to the influence of coastal water coming from the Laptev Sea through the Sannikov and Dmitry Laptev Straits and river run-off to the East Siberian Sea. In the eastern part of the sea in the De Long Strait, salinity increases to 29,5 ‰.

In summer, in the western part of the sea, the surface water layer in the ice free area is warmed to 2 °C, while in the coastal zone the temperature can reach 4 °C. As for the eastern part of the sea, where the ice edge is located closer to the coastline, the water temperature in summer varies on average within the range 0 °C to 1 °C.

B.19.2.3 Sea ice

From October to May/June, the East Siberian Sea is entirely covered by sea ice. Ice growth lasts until the end of May. Under the effect of radiance heat, puddles appear in the coastal zone, on average, during the first five days of June. By the middle of June, they propagate to the northern part of the sea. The ice cover (both landfast and drifting) at the beginning of melting consists of thick (more than 120 cm) first-year ice and occupies about 80 % of the sea surface in the western part and about 65 % in the eastern one. From historical databases, on average, old ice (multi-year and second-year) from the Arctic Basin occupies 12 % of the sea surface in the western part of the sea and 30 % in the eastern part. A minor part of the ice cover consists of younger ice: thin first-year ice (30 cm to 70 cm thick) and medium first-year ice (70 cm to 120 cm thick).

The area of landfast ice of the East Siberian Sea is on average 274 000 km^2. About two-thirds of the landfast ice area is situated in the western part of the sea. The development of landfast ice is, to a great extent, promoted by the shallowness of this region; water depths of less than 25 m occupy about half of the entire region. The maximum development of landfast ice is observed in April, or sometimes in May. Its seaward boundary is often delineated by stamukhi formed during the periods of strong coastward winds. Stamukhi can occur in the entire landfast ice zone at depths less than 20 m to 30 m.

During the major part of the year, ice drift is predominantly from the Arctic Basin to the East Siberian Sea. Due to this, the ice ridge concentration in the sea is about 4/10 and, closer to the landfast ice boundary, it reaches 6/10.

Sometimes small icebergs, floebergs and ice islands occur in the East Siberian Sea. A few small icebergs drift down to the sea from Henrietta and Bennet islands, and can drift from other regions as well. Sometimes floebergs and ice islands can be falsely identified as icebergs.

During the July to September period, under the influence of thermal and dynamic factors, the ice cover melts and the sea becomes ice-free. On average, the landfast ice is steadily broken up during the period from 5 to 25 July. The highest concentration of ice is localized in two ice massifs: the Novosibirsky ice massif (western part of the sea) and the Ayonsky ice massif (eastern part of the sea). The Novosibirsky ice massif is less stable: in 50 % of cases it disappears completely by the end of September.

The Ayonsky ice massif is a periphery of the oceanic ice massif, which is a source of multi-year ice for the East Siberian Sea. The ice of the Ayonsky ice massif rarely disappears completely; usually half of this massif remains frozen until the beginning of the new ice season. On average, at the beginning of a new ice season, the residual ice occupies 50 % of the western part and 75 % of the eastern part of the East Siberian Sea. The mean thickness of the residual ice is about 70 cm to 80 cm. The most favourable navigation conditions occur from the middle of August to the middle of September.

Stable ice formation begins in the last week of August at the northern boundary of the East Siberian Sea among the concentrated ice. During September, the “wave” of ice formation moves southward and, by the first week of October, young ice appears in the coastal zone.

As young ice thickness reaches 10 cm to 30 cm, landfast ice is formed. The mean date of landfast ice formation falls during the second half of October. As a rule, landfast ice in the sea is formed in the open water. If residual ice remains in the sea, landfast ice is formed, on average, almost two weeks earlier.

Table B.19-1 — East Siberian Sea meteorological conditions

Parameter		Cape Shalaurov		Chetyrekhstolbovoy Island		Cape Billings	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**
Air temperature	Annual month maximum, degrees Celsius	2,5	ND	2,2	ND	2,9	ND
	Absolute maximum, degrees Celsius	23,0	28,5	23,0	23,0	28,0	29,5
	Annual month minimum, degrees Celsius	–31,3	ND	–29,2	ND	–28,3	ND
	Absolute minimum, degrees Celsius	–48,4	–51,0	–47,6	–50,0	–50,0	–51,0
	Freezing degree days	5 370	ND	4 960	ND	4 710	ND
Wind speed at 10 m elevation	Maximum observed, metres per second	38	ND	40	ND	40	ND
	3 s gust, metres per second	50	ND	42	ND	62	ND
Wind direction	Dominant winter (direction/percentage occurrence)	N/8 NE/25 E/17 SE/4 S/2 SW/8 W/26 NW/10 Calm/17	ND	N/9 NE/20 E/17 SE/2 S/2 SW/23 W/17 NW/10 Calm/13	ND	N/2 NE/5 E/25 SE/7 S/8 SW/18 W/26 NW/9 Calm/8	ND
	Dominant summer (direction/percentage occurrence)	N/8 NE/20 E/33 SE/4 S/1 SW/5 W/21 NW/8 Calm/6	ND	N/12 NE/23 E/25 SE/9 S/4 SW/5 W/7 NW/15 Calm/7	ND	N/6 NE/16 E/35 SE/5 S/3 SW/3 W/14 NW/17 Calm/5	ND
Precipitation	Annual rainfall, millimetres	250	ND	220	ND	320	ND
	Largest month rainfall (month/amount, millimetres)	August/37	ND	August/34	ND	August/54	ND
	Rainfall: maximum within 24 h, millimetres	ND	ND	ND	ND	ND	ND
	Annual snowfall, millimetres	ND	ND	ND	ND	ND	ND
Visibility (fog, snow, etc.)	Annual number days with visibility < 1 km (fogs)	78	ND	80	ND	84	ND
	Annual number days with visibility < 2 km (snowstorms)	65	ND	61	ND	71	ND
	Month with greatest visibility < 1 km (month and percentage occurrence)	August/20	ND	July/20	ND	July/15	ND

Table B.19-2 — East Siberian Sea oceanographic conditions

Parameter		Western part		Eastern part	
		Average annual value	Range of annual values	Average annual value	Range of annual values
Waves	Significant wave height 50 %, metres	0,3 to 0,4	ND	0,3 to 0,4	ND
	Associated periods, seconds	2,5	ND	3	ND
	Maximum wave height 1 %, metres	4,0 to 5,0 (offshore) 2,5 (nearshore)	4,0 to 6,0	5,5 (offshore) 3,0 to 4,0 (nearshore)	6,0 to 10,0
	Associated periods, seconds	6,0 (offshore) 5,5 (nearshore)	ND	6,0 (offshore) 4,5 to 5,5 (nearshore)	ND
Current	Near-surface maximum speed, centimetres per second	110	ND	70	ND
	Near-surface average speed, centimetres per second	5 to 10	ND	5 to 10	ND
	Bottom maximum speed, centimetres per second	ND	ND	ND	ND
	Bottom average speed, centimetres per second	ND	ND	ND	ND
Water temperature	Summer surface maximum, degrees Celsius	4	ND	3	ND
	Summer surface average, degrees Celsius	1 to 2	ND	0 to 1	ND
Water salinity	Average surface salinity (July), parts per thousand	20 to 28 (offshore) 15 to 16 (nearshore)	ND	25 to 29,5 (offshore)	ND
	Average mid-layer salinity, parts per thousand	ND	ND	ND	ND
Tide	Tidal range, metres	0,2 to 0,4	ND	0,1 to 0,4	ND
Wind induced surge	Water depth increase range, metres	1,3 to 1,6	1,4 to 1,7	1,8 to 2,0	1,7 to 2,2
	Water depth decrease range, metres	−1,1 to −1,4	−1,2 to −1,6	−1,1 to −1,3	−1,4 to −1,6
	Water level range, metres	1,8 to 3,1	2,2 to 3,2	2,9 to 3,2	3,2 to 3,8

Table B.19-3 — East Siberian Sea sea ice conditions

Parameter		Western part		Eastern part	
		Average annual value	Range of annual values	Average annual value	Range of annual values
Sea ice occurrence	First ice	All year (offshore) 1 to 3 Oct. (nearshore)	ND	All year (offshore) 3 to 5 Oct. (nearshore)	ND
	First landfast ice	15 to 25 Oct.	ND	25 to 30 Oct.	ND
	Last landfast ice	20 to 25 July	ND	10 to 15 July	ND
	Last ice	All year	ND	All year	ND
	Continuous ice period, days	365	ND	365	ND
Level ice (first-year)	Landfast ice thickness, metres	1,9 to 2,1	ND	1,5 to 1,9	ND
	Floe length, metres	10 000 to 15 000	ND	5 000 to 10 000	ND
	Floe thickness, metres	1,4 to 1,6	ND	2,0 to 2,4 (north area) 1,6 to 1,8	ND
Surface deformation	Amount, percentage	60	ND	50	ND
	Month of maximum deformation	April to May	ND	April to May	ND
Rafted ice	Rafted ice thickness, metres	ND	ND	ND	ND
	Rafted Ice floe thickness, metres	ND	ND	ND	ND
Ridges (first-year)	Average sail height, metres	1,0 to 1,5	ND	1,5 to 2,0	ND
	Maximum sail height, metres	1,5 to 2,0	ND	2,5	ND
	Average keel depth, metres	ND	ND	ND	ND
	Maximum keel depth, metres	ND	ND	ND	ND
	Ice block thickness, metres	0,3 to 0,4	ND	0,3 to 0,4	ND
	Consolidated layer, metres	ND	ND	ND	ND
	Width, metres	5,0 to 7,5	ND	7,5 to 10,0	ND
	Length, metres	—	ND	—	ND
	Number per kilometre	2 to 5	ND	4 to 5	ND
Level ice (second- and multi-year)	Floe thickness, metres	2,4 to 2,8	ND	2,8 to 3,2	ND
Ridges (second- and multi-year)	Sail height, metres	ND	ND	ND	ND
	Keel depth, metres	ND	ND	ND	ND
Ridged ice zones (rubble fields)	Average sail height, metres	ND	ND	ND	ND
	Average keel depth, metres	ND	ND	ND	ND
Stamukhi[a]	Water depth, metres	ND	ND	ND	ND
	Sail height, metres	ND	ND	ND	ND

Table B.19-3 (*continued*)

Parameter		Western part		Eastern part	
		Average annual value	**Range of annual values**	**Average annual value**	**Range of annual values**
Ice movement	Speed nearshore, metres per second	ND	ND	ND	ND
	Speed offshore, metres per second	0,08 to 0,13	ND	0,10 to 0,15	ND
	Prevailing direction	NW	ND	WNW	ND
Iceberg size	Length, metres	ND	ND	ND	ND
	Mass, tonnes	ND	ND	ND	ND
Iceberg frequency	Month present	Sometimes	ND	Sometimes	ND
	Number per year	ND	ND	ND	ND
Ice-induced scour	Average/maximum scour depth, metres	ND	ND	ND	ND
	Water depth range, metres	ND	ND	ND	ND

[a] According to air-borne and satellite observations, the stamukhi both within the landfast ice area and at its boundary are present every year, but special measurements of their parameters were not carried out.

B.20 Black Sea

B.20.1 Description of region

The Black Sea is situated between 27° 21′ E and 41° 47′ E, and 46° 38′ N and 40° 54′ N (see Figure B.20-1). The maximum distance from west to east is 1 160 km, and from north to south is 600 km. The distance between the southern edge of the Crimea Peninsula and the Turkish coast (in the narrowest place) is 263 km. The area of the sea is 422 000 km^2, its mean depth is 1 315 m, maximum depth 2 210 m, and water volume 555 000 km^3.

The shelf, continental slope and deep abyss are clearly seen in the Black Sea. The coasts are very steep, even including the northwestern part, where the shelf has its maximum width (more than 200 km) and prevailing depths of 50 m to 70 m; the 20 m isobath is almost everywhere located not more than several nautical miles far from the coast.

The continental slope is very steep and strongly incised by submarine valleys and canyons. The abyssal plain is flat; its depth steadily increases to 2 000 m towards the centre.

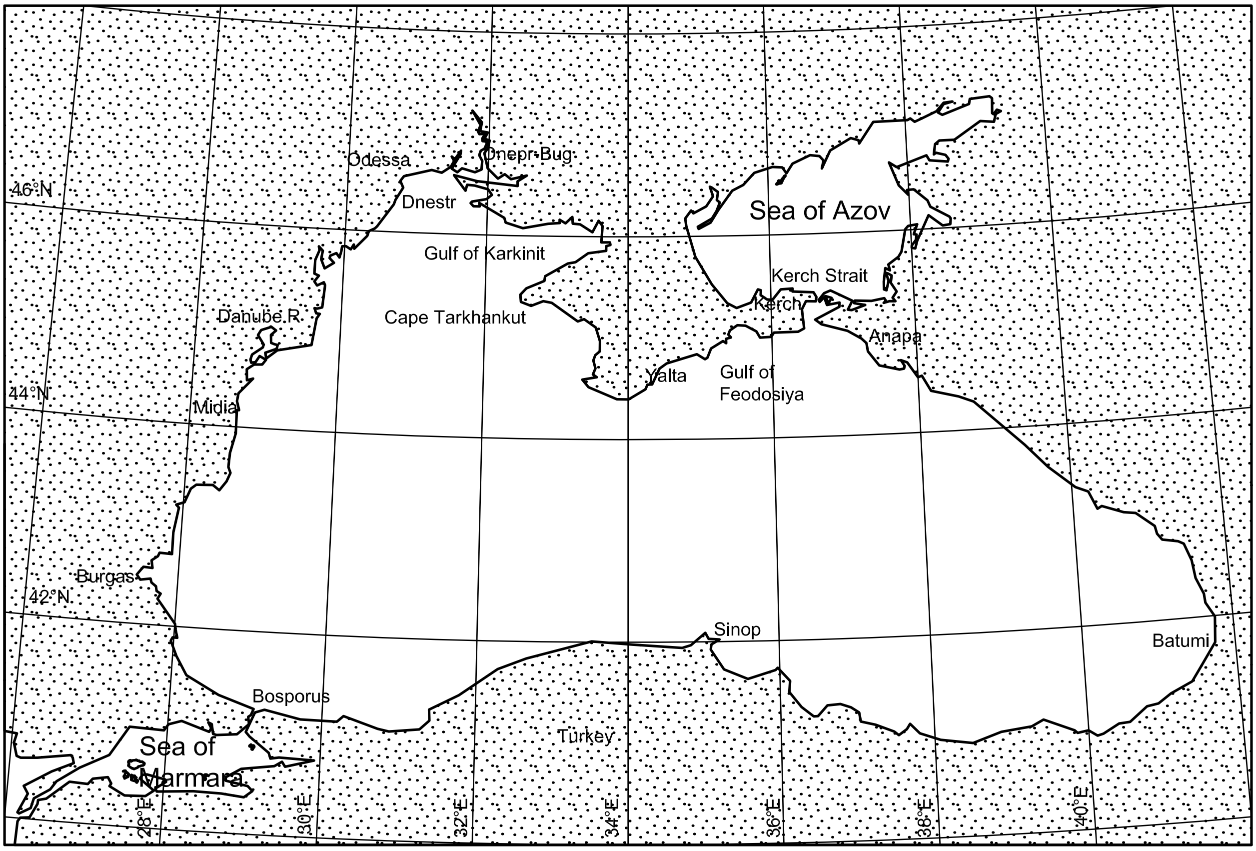


Figure B.20-1 — Map of the Black Sea and the Sea of Azov

B.20.2 Black Sea technical information

B.20.2.1 Climate

Due to its small size and insularity, the climate of the sea is significantly exposed to the influence of the surrounding land and characterized by the continental climate, which is clearly seen in the large seasonal fluctuations of air temperature and the irregular distribution of precipitation.

Winter is characterized by non-stable cloudy weather with strong winds and significant fluctuations in temperature. Intrusions of cold, dry air from moderate latitudes caused by the spur of the Siberian High are accompanied by northeasterly (often stormy) winds, a rapid decrease of air temperature, and frequent and abundant precipitation. Under the effect of these winds, the western part of the sea is significantly cooled, while the eastern part, being protected by Caucasian Mountains, remains relatively warm.

As the Siberian High spur weakens, the Mediterranean winter cyclone brings warm (sometimes strong) southwesterly winds. The northwestern part of the sea, which is open to winds blowing from the continent, is characterized by a colder climate. The mean temperature of January is −1 °C to −5 °C in the northwestern part, about 8 °C in the central area, and 6 °C to 9 °C in the eastern and southern parts.

In summer, the Black Sea is influenced by a spur of the Azores High. The weather is stable, bright and hot, and the winds are weak. From the middle of June to the middle of September, the air temperature over the sea is practically homogeneous. The mean temperature in July and August is 23 °C in the west and 24 °C in the east.

The spatial distribution of precipitation over the sea is very non-homogeneous. The maximum precipitation is observed in the southeastern area: 1 800 mm per year near Sukhumi and 2 744 mm per year near Batumi. In the northwest the amount of precipitation is 500 mm per year, in the south up to 800 mm per year. In summer, the precipitation is caused by short cloud burst rains. There have been cases when the amount of precipitation was 261 mm per day (in Batumi) and 150 mm per day (in Odessa). In winter, the precipitation has a persistent character.

B.20.2.2 Hydrology

The hydrological regime is governed by climatic factors, water exchange with neighbouring seas and continental run-off.

Every year, numerous rivers flowing into the Black Sea bring, on average, 338 km^3 of freshwater. The run-off is characterized by significant interannual variability due primarily to fluctuations in the Danube river run-off.

The lower Bosporus Current brings about 200 km^3 per year of heavier, more saline water from the Sea of Marmara. Double this volume of Black Sea water flows from the Black Sea to the Sea of Marmara as the upper Bosporus Current. About 50 km^3 of water per year flows to the Black Sea from the Sea of Azov through the Kerch Strait and 34 km^3 per year is brought from the Black Sea to the Sea of Azov.

The Black Sea differs sharply from other seas due to its permanent fresh upper layer, which is less dense than the underlying layers. Such a stable stratification of the water layers prevents convection. As a result, all significant changes of physical properties of water caused by atmospheric processes, waves, currents and other hydrometeorological factors take place in the upper 150 m to 200 m of the water column.

The water temperature regime of the Black Sea is formed predominantly as a result of the effects of solar radiance and water-atmosphere heat exchange. The mean annual water surface temperature is 11 °C in the northwest, 13 °C in the northeast and 16 °C in the southeast.

The mean salinity of the Black Sea is 21,9 ‰. As the amount of run-off and precipitation exceeds the evaporation, the upper layer remains fresh. The multi-year mean salinity of almost the entire area of the sea surface is about 17 ‰ to 18 ‰.

In the deep part of the sea, the vertical change in salinity is from 17 ‰ to 18 ‰ at the surface to 22,5 ‰ at the sea floor. The maximum gradients are observed within the upper layer (100 m to 150 m), where the role of freshwater is important.

The fluctuations of river run-off, external water exchange, evaporation and precipitation, and the effect of wind and atmospheric pressure result in seasonal and interannual changes of the sea level. According to historical data, the difference between the sea level in summer and autumn is 14,8 cm (in general, autumn is the period with the lowest level).

Fluctuations in sea level caused by storm winds are significant. Storms are especially active from October to February in the west and northwestern parts of the sea.

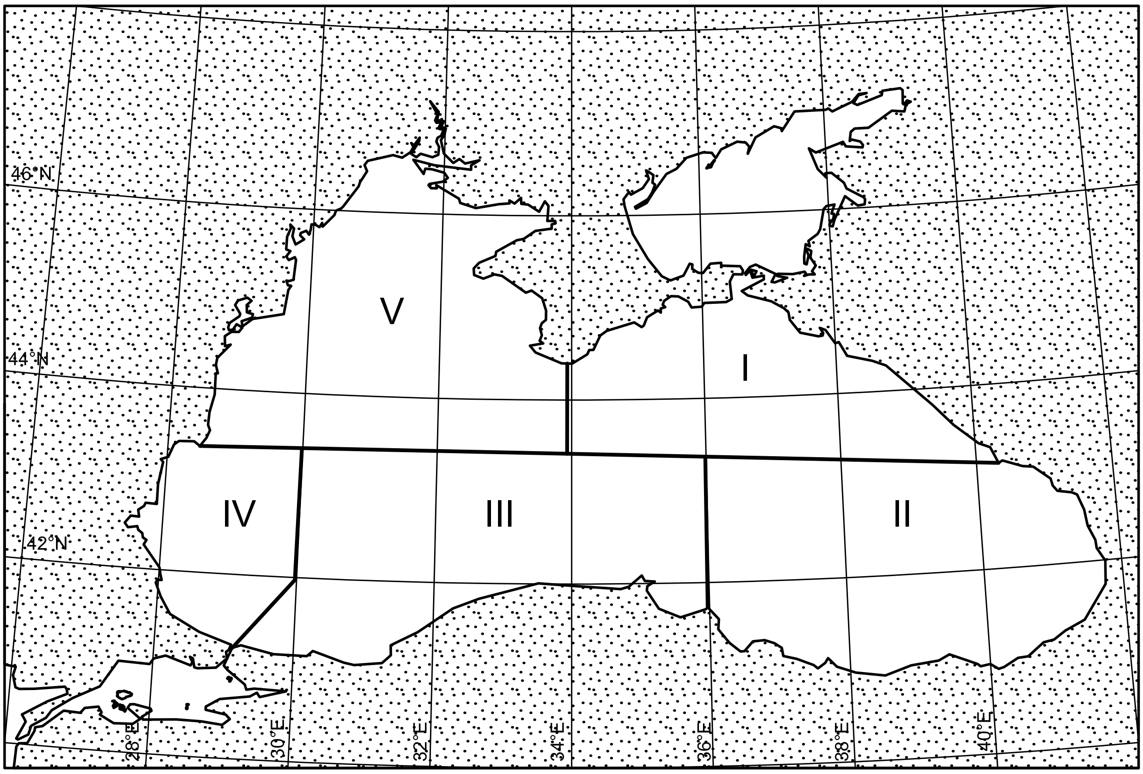
The tidal oscillations in the Black Sea have an irregular, semi-diurnal character and do not exceed 14 cm.

The character of the atmospheric circulation over the Black Sea and river run-off determine the surface circulation: water moves anti-clockwise along the coasts. The speed of the surface current is usually about 10 cm/s to 30 cm/s, but during periods of strong winds it can become significantly stronger. Strong winds blowing over the Black Sea, mainly in autumn and winter, lead to high wave conditions.

The Black Sea is traditionally divided into five regions reflecting the spatial variability of wind and wave regimes, see Figure B.20-2.

Regions I, IV and V are characterized by a predominance of northerly and easterly winds. This zone is also characterized by higher wave heights, which increase from east to west. This can be explained by a greater fetch of the stronger and more stable northeasterly and easterly winds in the western part.

For the remaining regions, the prevailing wind direction is difficult to determine.



Key

I	northeastern
II	southeastern
III	southwestern
IV	western
V	northwestern

Figure B.20-2 — Parts of the Black Sea

B.20.2.3 Sea ice

Every year only a small part of the Black Sea is covered by ice and, even in severe winters, ice cover occupies less than 5 % of the total sea area. The northwestern region has a relatively greater ice cover extent (see Figure B.20-3).

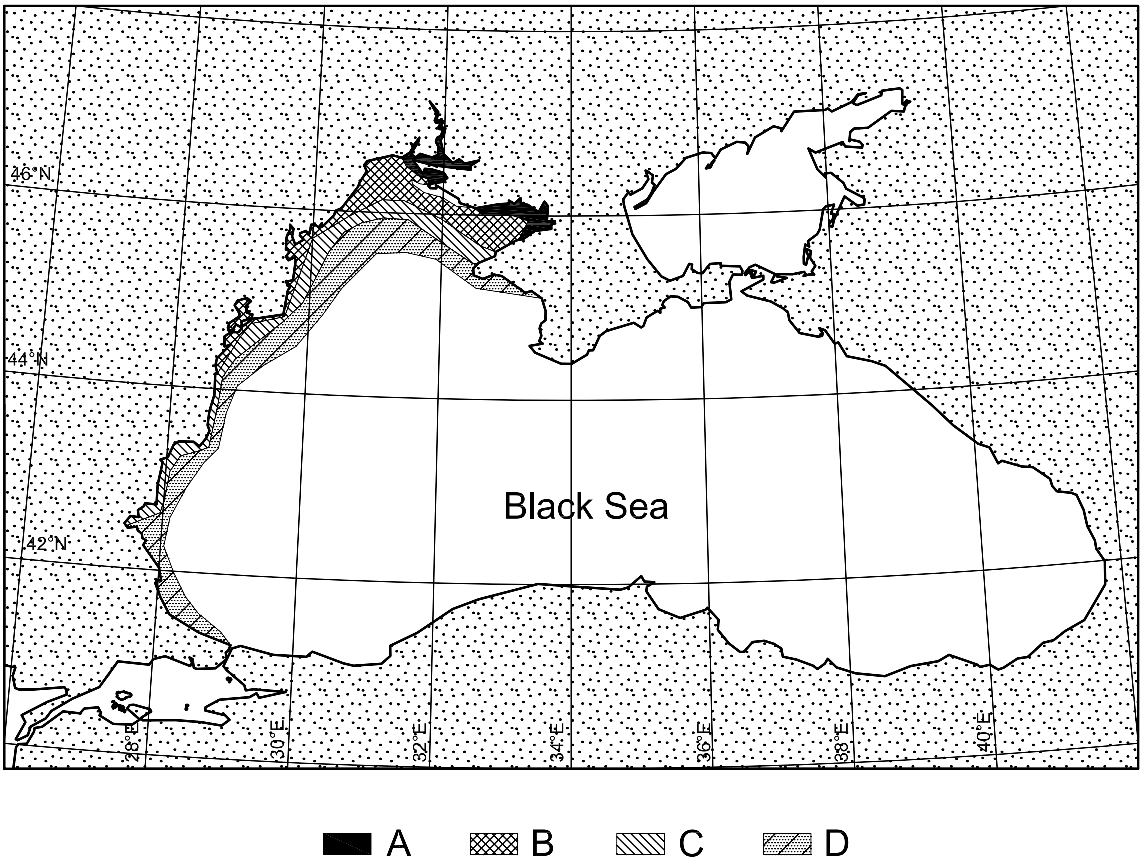
Ice formation usually begins in the middle of December. The date of the first appearance of ice varies significantly depending on weather conditions and geographical position. The Dnepr-Bug and Dnestr firths freeze completely every year, but the ice cover can break up and drift away into the sea during the course of the winter.

The Gulf of Karkinit is covered by motionless ice up to Cape Tarkhankut (the western edge of the Crimea Peninsula); during a short period, ice cover exists near Sevastopol and the southern point of Crimea. The ice carried out from the Sea of Azov through the Kerch Strait reaches the Gulf of Feodosiya (in the west) and town of Anapa (in the east).

The landfast ice boundary in moderate winters lies from the Dnepr firth along the coast at a distance of 2 nautical miles to 5 nautical miles and crosses part of the Gulf of Karkinit. The drifting ice edge encircles a wider area between the Capes of Midia (Romania) and Tarkhankut.

In extremely severe winters, the ice season lasts about 130 days in the northwest and 85 days in the northeast. In mild winters, the ice season duration does not exceed 40 days.

Ice usually disappears in the northwest in March. Depending on the date of arrival of the warm weather, the ice disappears at the beginning of March or, at the latest, at the beginning of April.



Key

A in mild winters

B in moderate winters

C in severe winters

D in extremely severe winters

Figure B.20-3 — The boundaries of ice cover propagation in winters of various severity

Table B.20-1 — Black Sea meteorological conditions

Parameter		**Yalta**	**Batumi**	**Sinop**	**Burgas**	**Odessa**
		Average annual value	**Average annual value**	**Average annual value**	**Average annual value**	**Average annual value**
Air temperature	Annual month maximum, degrees Celsius	23,5	23,0	22,7	22,7	22,3
	Absolute maximum, degrees Celsius	39	40	34	34	37
	Annual month minimum, degrees Celsius	3,9	6,8	6,2	2,4	−1,7
	Absolute minimum, degrees Celsius	−25	−8	−5	−16	−27
	Freezing degree days	ND	ND	ND	ND	270
Wind speed at 10 m elevation	Maximum observed, metres per second	40	40	23[a]	25[a]	40
	3 s gust, metres per second	ND	ND	ND	ND	ND
Wind direction	Winter[b] (direction/ percentage occurrence)	N/12,4 NE/7,2 E/15,7 SE/7,7 S/8,8 SW/6,9 W/14,9 NW/19,8 Calm/6,6	N/8,1 NE/6,4 E/7,6 SE/13,1 S/11,9 SW/16,9 W/13,5 NW/5,9 Calm/16,6	ND	ND	N/16 NE/13 E/10 SE/9 S/10 SW/7 W/11 NW/19 Calm/5
	Summer (direction/ percentage occurrence)	ND	ND	ND	ND	N/12 NE/5 E/3 SE/14 S/12 SW/7 W/12 NW/28 Calm/7
Precipitation	Annual rainfall, millimetres	665	2 744	796	579	500
	Largest month rainfall (month/amount, millimetres)	Dec./102	Oct./331	Dec./114	June/81	Dec./58
	Rainfall — maximum within 24 hours, millimetres	154	261	ND	ND	150
	Annual snowfall, millimetres	ND	ND	ND	ND	ND
Visibility (fog, snow, etc.)	Annual number days with visibility < 1 km (fogs)	12	8	ND	ND	42
	Annual number days with visibility < 2 km (snowstorms)	0,7	0,16	ND	ND	9
	Month with greatest visibility < 1 km (month and percentage occurrence)	Feb./4	April/2,5	ND	ND	Feb./10

NOTE There are no data for the range of annual values.

[a] The data for Sinop and Burgas are obtained from synoptic charts for 1971 to 1980.

[b] For Yalta and Batumi, the frequency of occurrence of wind direction is represented by annual data.

Table B.20-2 — Black Sea oceanographic conditions

Parameter		Average annual value[a,b]				
		Region I	Region II	Region III	Region IV	Region V
Waves	Significant wave height 50 %, metres	0,5	0,2	0,4	0,3	0,4
	Associated periods, seconds	3,1	2,2	2,9	2,8	2,9
	Maximum wave height 1 %, metres	1,8[c] [3,9][d]	1,7[c] [4,4][d]	2,3[c] [4,9][d]	2,2[c] [5,6][d]	2,6[c] [6,8][d]
	Associated periods, seconds	6,1 [9,4][d]	7,0 [13,0][d]	7,3 [11,0][d]	6,6 [10,2][d]	7,6 [12,0][d]
Current	Near-surface maximum speed, centimetres per second	35 to 82	ND	ND	36 to 90	36 to 99
	Near-surface average speed, centimetres per second	ND	ND	ND	ND	15 to 40
	Bottom maximum speed, centimetres per second	ND	300[e]	ND	ND	(20 to 30)[f]
	Bottom average speed, centimetres per second	ND	3 to 16	ND	ND	ND
Water temperature	Summer surface maximum, degrees Celsius	25,1 to 27,1 (nearshore)	23,0 to 28,6 (nearshore)	ND	25,9 (nearshore)	23,6 to 27,3 (nearshore)
	Summer surface average, degrees Celsius	22,2 to 25,0 (nearshore)	24,5 to 25,7 (nearshore)	ND	23,3 (nearshore)	20,6 to 24,6 (nearshore)
Water salinity	Average surface salinity (July), parts per thousand	16,52 to 19,06 (nearshore)	14,03 to 16,48 (nearshore)	ND	16,47 (nearshore)	13,66 to 19,51 (nearshore)
Tide	Quadrature, centimetres	0,2 to 1,8	2 to 2,4	ND	0,2 to 3	2,8 to 4,6
	Syzygy, centimetres	3,5 to 4,9	9,6 to 10	ND	3,6 to 8,2	11,6 to 14
Wind-induced surge	Water depth increase range, metres	0,39 to 0,78	0,62 to 0,98	ND	ND	0,52 to 1,46
	Water depth decrease range, metres	–0,38 to –0,60	–0,52 to –0,6	ND	ND	–0,44 to –1,95
	Water level range, metres	0,78 to 1,22	1,22 to 1,5	ND	ND	0,96 to 2,89

[a] Regions correspond to those in Figure B.20-2.

[b] There are no data for the range of annual values (except as indicated).

[c] Mean wave height of 1 % probability.

[d] Numbers relate to range of annual values.

[e] Unique values obtained from isolated measurements.

[f] Speeds at northeastern wind near the western coast of the region.

Table B.20-3 — Black Sea sea ice conditions

Parameter[a]		Region I[b]		Region IV[b]		Region V[b]	
		Average annual value	Range of annual values	Average annual value	Range of annual values	Average annual value	Range of annual values
Sea ice occurrence	First ice	3 to 28 Jan.	ND	8 Jan.	ND	6 Dec. to 22 Jan.	ND
	First landfast ice	3 Jan. to 14 Feb.	ND	ND	ND	15 Dec. to 7 Feb.	ND
	Last landfast ice	24 Jan. to 20 Feb.	ND	5 Nov.	ND	19 Jan. to 8 March	ND
	Last ice	24 Jan. to 23 Feb.	ND	7 Feb.	ND	12 Feb. to 18 March	ND
	Continuous ice period, days	8 to 40	ND	30	ND	19 to 102	ND
Level ice (first-year)	Landfast ice thickness, metres	ND	ND	ND	ND	[0,13 to 0,34][c]	ND
Surface deformation	Amount, percentage	ND	ND	ND	ND	ND	ND
Rafted ice	Rafted ice thickness, metres	ND	ND	ND	ND	ND	ND
Ridges (first-year)	Average sail height, metres	ND	ND	ND	ND	ND	ND
	Average keel depth, metres	ND	ND	ND	ND	ND	ND
Ridged ice zones (rubble fields)	Average sail height, metres	ND	ND	ND	ND	ND	ND
	Average keel depth, metres	ND	ND	ND	ND	ND	ND
Stamukhi	Water depth, metres	ND	ND	ND	ND	ND	ND
	Sail height, metres	ND	ND	ND	ND	ND	ND
Ice movement	Speed nearshore, metres per second	ND	ND	ND	ND	ND	ND
	Speed offshore, metres per second	ND	ND	ND	ND	ND	ND
	Prevailing direction	ND	ND	ND	ND	ND	ND

[a] The data refer to the spatial variations of ice regime.

[b] Regions correspond to Figure B.20-2; Regions II and III are not included because ice has never been observed there.

[c] The values of maximum ice thickness for moderate winter.

B.21 Sea of Azov

B.21.1 Description of region

The Sea of Azov is situated between 45° 17′ N and 47° 17′ N, and 34° 49′ E and 39° 18′ E (see Figure B.21-1). It is connected with the Black Sea through the shallow Kerch Strait. The maximum length of the sea is 360 km and maximum width is 176 km. The area of the sea is 39 000 km^2, the mean depth is 7 m and the maximum is 13 m. The volume of water is 290 km^3.

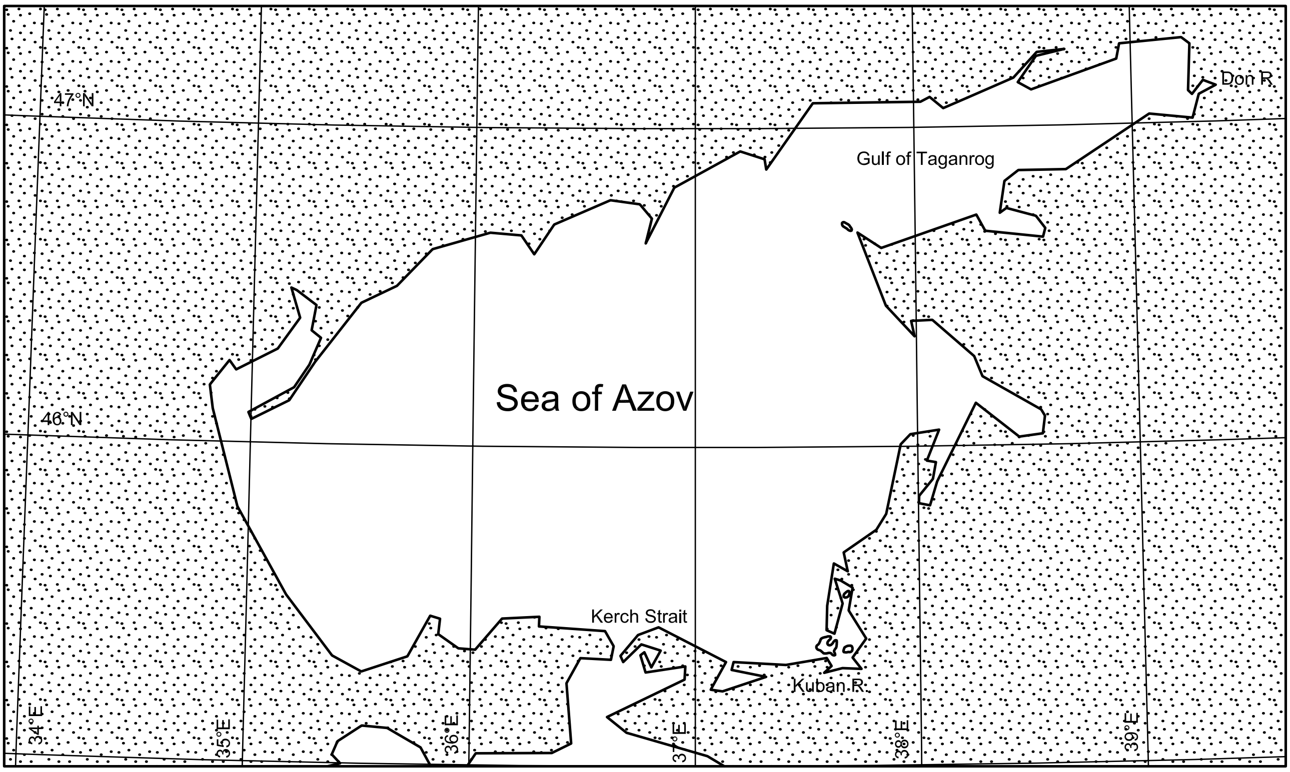


Figure B.21-1 — Map of the Sea of Azov

B.21.2 Sea of Azov technical information

B.21.2.1 Climate

Due to its small size and insularity, the Sea of Azov climate is significantly affected by the surrounding land and has features similar to those of the surrounding continent (e.g. a large difference between summer and winter temperatures). In winter, the weather is temperately cold, unstable, windy and generally unpleasant. The summer weather is warm and bright. The annual mean temperature is 9 °C in the northern part of the sea and 11 °C in the southern.

The winter intrusions of cold air from temperate latitudes, caused by the spur of the Siberian High, are accompanied by northeasterly and easterly winds (often with mean wind speeds of 15 m/s or more), sometimes with a hard frost. The periods of low temperature alternate with thaws when the sea is exposed to the effect of the winter Mediterranean cyclone that brings warm (sometimes strong) southwesterly winds.

In the coldest months (January and February), the air temperature can reach –22 °C in the south and –33 °C in the north. The mean air temperature in January and February is –4 °C to –6 °C along the northern coast and –1 °C along the southern coast.

In summer, the Sea of Azov is exposed to the effect of the Azores High. The weather is very warm and bright. In June, the air temperature in various parts of the sea reaches 20 °C to 24 °C, and in the warmest months (July to August) it reaches 23 °C to 25 °C. The maximum temperature in these months is 33 °C to 43 °C and the minimum is 9 °C to 13 °C.

Weak, temperate winds prevail over the sea during all seasons. The frequency of occurrence of winds weaker than 6 m/s is 70 %, and that of calms is 3 % in winter and 5 % in other seasons. Winds stronger than 14 m/s have a frequency of occurrence of less than 1 %, and that of winds stronger than 20 m/s is about 0,1 %.

Precipitation over the sea area is distributed inhomogeneously. The total amount of precipitation is about 500 mm per year along the eastern coast and 330 mm per year in the west.

Fog has a clear seasonal character. The maximum frequency of occurrence is observed from October to March (an average of 4 days per month to 10 days per month having fog). In summer, fogs are rare.

B.21.2.2 Hydrology

The regional climate plays a significant role in forming the hydrological regime of the Sea of Azov. In addition, the hydrology is influenced by the water exchange with the Black Sea and continental run-off, as well as by its shallow water and small size.

Two large rivers, the Don and the Kuban, contribute 90 % of the total annual run-off, which averages about 28 km^3. Every year, an average of about 50 km^3 of water flows out of the Sea of Azov into the Black Sea, and an average of about 34 km^3 flows back from the Black Sea to the Sea of Azov.

While fluctuations in the run-off, external water exchange, evaporation and precipitation, and the influence of wind result in sea level fluctuations on various temporal scales, the sea level changes caused by storm winds are the most significant. The largest values of the storm-surge sea level fluctuations of wind origin are observed in the Gulf of Taganrog.

The main generator of sea currents in the Sea of Azov is wind. The role of the Don and the Kuban is seen only in the zones close to their respective estuaries. Sea currents are generally weaker than 10 cm/s but winds of 15 m/s to 20 m/s can lead to current speeds reaching 60 cm/s to 70 cm/s in some regions.

Waves in the Sea of Azov grow quickly but also quickly decay when the wind drops. The shallow waters and small area restrict wave development. Even during strong storms, the maximum wave height is only about 4 m. In all seasons, waves lower than 2 m predominate. Sometimes short steep waves, which are dangerous for small vessels, can be encountered.

The annual mean seawater temperature is 11,5 °C. Due to its shallow depth, the water is significantly cooled in winter and warmed in summer. During July and August, the water temperature is about 24 °C to 25 °C, and in the coastal zone, it can reach 32 °C.

The shallow water promotes rapid cooling and warming within the whole water column, which leads to vertical homogeneity of the water temperature. The difference between water temperatures at the sea surface and at the sea floor does not exceed 1 °C, on average.

Significant freshwater run-off along with the small size of the Sea of Azov results in low salinity: 11 ‰ to 13 ‰. The salinity spatial distribution in the central part is homogeneous. Maximum values (13 ‰ to 15 ‰) are observed in the zone close to the Kerch Strait. Significant salinity spatial variability is observed in the Gulf of Taganrog: from values close to average at the gulf entrance to 5 ‰ and less at the head of the gulf. Also, the salinity of the Gulf of Taganrog can vary significantly due to wind-induced level fluctuations.

The deeper water layers have somewhat greater salinity, which increases the vertical stability of the water column.

B.21.2.3 Sea ice

Sea ice in the Sea of Azov is formed every year. In severe winters, ice covers the major part and sometimes the entire sea surface area. In mild winters, ice occurs in the firths, bays and gulfs protected from waves and along the coast as well. Ice conditions in the Sea of Azov are not stable. Ice can appear and disappear several times per season, and can be transformed from drifting to landfast and vice versa.

In temperate winters, the first ice appears between the end of November and the beginning of December in the Gulf of Taganrog. Three to four weeks later, this gulf is covered by motionless ice (see Figure B.21-2). Simultaneously, landfast ice is formed along the northern coast, and a large amount of drifting ice accumulates near its boundary. At the same time, drifting ice appears in the southwest; this ice moves to the Black Sea through the Kerch Strait. Later, landfast ice forms along the entire coastline. At the end of January, the Kerch Strait, which is considered an ice poor region, is covered by relatively stable ice. As for the central part of the sea, drifting ice usually appears between the end of January and the beginning of February. The probability of landfast ice propagation to the open sea in January and February in temperate winters is 10 % to 20 %.

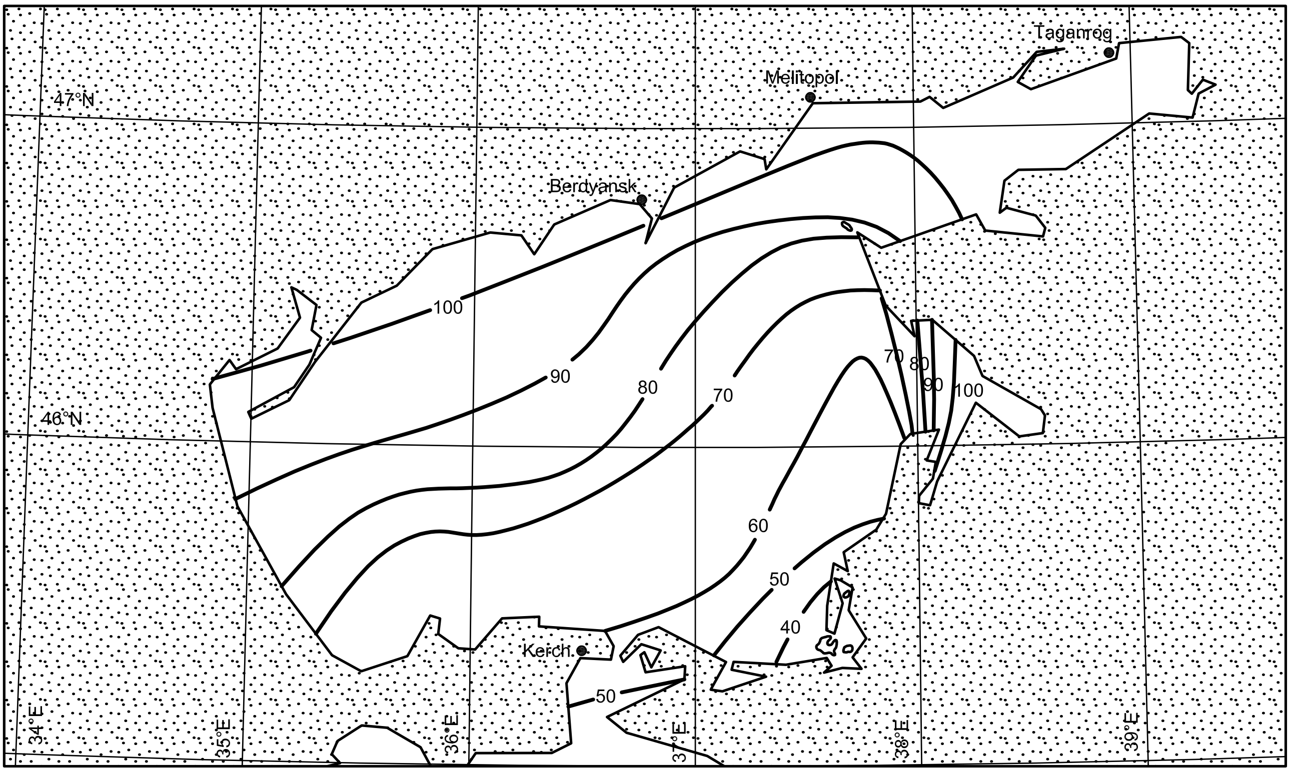


Figure B.21-2 — Frequency of occurrence of ice in temperate winter (February)

In mild winters, the central part of the Sea of Azov is, as a rule, ice free, although sometimes small amounts of drifting ice appear here.

Ice cover in the Sea of Azov reaches its maximum in the first half of February. Ice thickness at this time is about 30 cm to 40 cm. Ice ridge heights in the open sea do not exceed 1 m.

According to historical data, ice cover occupies about 30 % of the sea area (in temperate winters, up to 80 %). Its distribution within the sea depends significantly on prevailing winds and currents.

Ice growth stops during the second half of February. Break-up of ice takes place in March to April, first in the southern part and river estuaries, then in the north, and finally in the Gulf of Taganrog. The mean duration of the ice season is four-and-a-half months.

Table B.21-1 — Sea of Azov meteorological conditions

Parameter		Melitopol		Berdyansk		Kerch	
		Average annual value	**Range of annual values**	**Range of annual value**	**Range of annual values**	**Average annual value**	**Range of annual values**
Air temperature	Annual month maximum, degrees Celsius	23,2	ND	23,4	ND	23,6	ND
	Absolute maximum, degrees Celsius	40,0	ND	39,0	ND	37,0	ND
	Annual month minimum, degrees Celsius	–4,6	ND	–3,8	ND	–0,7	ND
	Absolute minimum, degrees Celsius	–30,0	ND	–29,0	ND	–26,0	ND
	Freezing degree days	ND	ND	390	ND	ND	ND
Wind speed at 10 m elevation	Maximum observed, metres per second	21[a]	26	18[a]	22	18[a]	22
	3 s gust, metres per second	35[b]	45	30[b]	39	30[b]	39
Wind direction	Winter (direction/ percentage occurrence)	N/8,9 NE/18,3 E/27,5 SE/5,9 S/5,3 SW/9,9 W/13,3 NW/10,8	ND	N/8,1 NE/29,4 E/24,1 SE/4,3 S/5,1 SW/7,6 W/12,8 NW/8,6	ND	N/14,6 NE/20,9 E/10,9 SE/6,3 S/12,2 SW/6,8 W/11,0 NW/17,2	ND
	Summer (direction/ percentage occurrence)	N/20,3 NE/11,7 E/9,3 SE/7,1 S/9,5 SW/13,5 W/11,6 NW/16,9	ND	N/15,4 NE/19,9 E/10,4 SE/4,3 S/7,7 SW/19,3 W/11,8 NW/11,0	ND	N/19,2 NE/15,4 E/5,0 SE/5,4 S/9,1 SW/8,7 W/18,5 NW/18,5	ND
Precipitation	Annual rainfall, millimetres	491	728	461	632	484	660
	Largest month rainfall (month/amount, millimetres	Jan./57,5	August/ 167	Jan./55	June/136	Jan./46	July/176
	Rainfall — maximum within 24 hours, millimetres	112	ND	101	ND	117	ND
	Annual snowfall, millimetres	ND	ND	ND	ND	ND	ND
Visibility (fog, snow, etc.)	Annual number days with visibility < 1 km (fogs)	54	ND	44	ND	42	ND
	Annual number days with visibility < 2 km (snowstorms)	8	ND	9	ND	2	ND
	Month with greatest visibility < 1 km (month and percentage occurrence)	Nov./30	ND	Jan./26	ND	Jan./26	ND

[a] Maximum wind speed at 10 min averaging with a frequency of occurrence of once per year.

[b] Wind gust speed with a frequency of occurrence of once per year.

Table B.21-2 — Sea of Azov oceanographic conditions

Parameter		Average annual value	Range of annual values
Waves	Significant 50 % wave height, metres	0,2 to 0,5	ND
	Associated periods, seconds	2,5 to 3,0	ND
	Maximum wave height 1 %, metres	3,0	4,3
	Associated periods, seconds	5	ND
Current	Near-surface maximum speed, centimetres per second	18 to 90	ND
	Near-surface average speed, centimetres per second	⩽ 10	ND
	Bottom maximum speed, centimetres per second	9 to 45	ND
	Bottom average speed, centimetres per second	⩽ 5	ND
Water temperature	Summer surface maximum, degrees Celsius	27,0 to 28,6 (offshore) 29,0 to 32,8 (nearshore)	ND
	Summer surface average, degrees Celsius	23,3 to 24,7 (offshore) 24,2 to 24,9 (nearshore)	ND
Water salinity	Average surface salinity (summer), parts per thousand	12,2 (offshore) 8,05 (nearshore)	ND
Tide	Tidal range, metres	ND	ND
Wind-induced surge	Water depth increase range, metres	0,62 to 3,21	1,32 to 3,34
	Water depth decrease range, metres	−0,91 to −3,57	−1,12 to −4,30
	Water level range, metres	1,99 to 6,09	2,44 to 7,64

Table B.21-3 — Sea of Azov sea ice conditions

Parameter		Average annual value	Range of annual values
Occurrence	First ice	23 Nov. to 20 Jan.	ND
	First landfast ice	31 Dec. to 1 Feb.	ND
	Last landfast ice	18 Feb. to 13 March	ND
	Last ice	25 Feb. to 1 April	ND
	Continuous ice period, days	[37 to 106][a]	ND
Level ice (first-year)	Landfast ice thickness, metres	0,2 to 0,4	ND
	Floe length, metres	ND	ND
	Floe thickness, metres	[0,26 to 0,39][b]	ND
Surface deformation	Amount, percentage	20 to 60	ND
	Month of maximum deformation	March	ND
Rafted ice	Rafted ice thickness, metres	[0,46 to 0,99][b]	ND
	Rafted ice floe length, metres	ND	ND
	Rafted Ice floe thickness, metres	ND	ND

Table B.21-3 (*continued*)

Parameter		Average annual value	Range of annual values
Ridges (first-year)	Average sail height, metres	[0,46 to 0,82][b]	ND
	Maximum sail height, metres	[1,04 to 1,33][b]	ND
	Average keel depth, metres	[1,66 to 2,15][b]	ND
	Maximum keel depth, metres	[3,39 to 3,75][b]	ND
	Ice block thickness, metres	[0,03 to 0,2][b]	ND
	Consolidated layer, metres	[0,85 to 0,9][b]	ND
	Width, metres	[8 to 10][b]	ND
	Length, metres	[180 to 200][b]	ND
	Number per kilometre	ND	ND
Ridged ice zones (rubble fields)	Average sail height, metres	ND	ND
	Average keel depth, metres	ND	ND
	Thickness of the consolidated layer, metres	ND	ND
	Length, metres	ND	ND
	Width, metres	ND	ND
Stamukhi	Water depth, metres	ND	ND
	Sail height, metres	ND	ND
	Width, metres	ND	ND
	Length, metres	ND	ND
Ice movement	Speed nearshore, metres per second	[0,8 to 1,9][c]	ND
	Speed offshore, metres per second	ND	ND
	Prevailing direction	W, SW	ND
Ice-induced scour	Average/maximum scour depth, metres	ND	ND
	Average/maximum scour width, metres	ND	ND
	Average/maximum scour length, metres	ND	ND
	Scour frequency, number per kilometre	ND	ND
	Water depth range, metres	ND	ND

[a] Number of days with ice per year.

[b] Ice parameter values are obtained from isolated measurements in severe winter.

[c] Maximum values of ice drift.

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