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BSI Standards Publication

Marine energy — Wave, tidal and other water current converters

Part 2: Design requirements for marine energy systems

National foreword

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

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

MARINE ENERGY – WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS –

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FOREWORD

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- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or
- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical Specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 62600-2, which is a Technical Specification, has been prepared by IEC technical committee 114: Marine energy – Wave, tidal and other water current converters.

The text of this Technical Specification is based on the following documents:

Enquiry draft	Report on voting
114/168/DTS	114/176A/RVC

Full information on the voting for the approval of this Technical Specification can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62600 series, published under the general title *Marine energy – Wave, tidal and other water current converters*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- transformed into an International Standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

This part of IEC 62600 outlines minimum design requirements for marine energy converters and is not intended for use as a complete design specification or instruction manual.

Several different parties may be responsible for undertaking the various elements of the design, manufacture, assembly, installation, erection, commissioning, operation and maintenance of a marine energy system and for ensuring that the requirements of this document are met. The division of responsibility between these parties is a contractual matter and is outside the scope of this document.

Any of the requirements of this document may be altered if it can be suitably demonstrated that the safety of the system is not compromised. Compliance with this document does not relieve any person, organization, or corporation from the responsibility of observing other applicable regulations.

MARINE ENERGY – WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS –

Part 2: Design requirements for marine energy systems

1 Scope

1.1 General

This part of IEC 62600 provides the essential design requirements to ensure the engineering integrity of wave, tidal and other water current energy converters, referred to as marine energy converters (MECs), for a specified design life. Its purpose is to provide an appropriate level of protection against damage from all hazards that may lead to failure of the primary structure, defined as the collective system comprising the structural elements, foundation, mooring and anchors, piles, and device buoyancy designed to resist global loads.

This document includes requirements for subsystems of MECs such as control and protection mechanisms, internal electrical systems, mechanical systems and mooring systems as they pertain to the structural viability of the device under site-specific external environmental conditions. This document applies to wave, tidal and other water current converters and to structures that are either floating or fixed to the seafloor or shore. This document applies to structures that are unmanned during operational periods.

This document addresses site-specific conditions, safety factors for critical structures and structural interfaces, external load cases (including extreme load magnitude, duration, and frequency), failure probability and failure consequences for critical structures and structural interfaces (overall risk assessment), and failsafe design practices (demonstration of adequate redundancy). The effect of subsystem failure on the primary structure is also addressed.

This document does not address the effects of MECs on the physical or biological environment (unless noted by exception). This document is used in conjunction with the appropriate IEC and ISO standards, as well as regional regulations that have jurisdiction over the installation site.

1.2 Applications

This document is applicable to MEC systems designed to operate from ocean, tidal and river current energy sources, but not systems associated with hydroelectric impoundments or barrages. This document is also applicable to wave energy converters. It is not applicable to ocean thermal energy conversion (OTEC) systems or salinity gradient systems.

Although important to the overall objectives of the IEC 62600 series, this document does not address all aspects of the engineering process that are taken into account during the full system design of MEC systems. Specifically, this document does not address energy production, performance efficiency, environmental impacts, electric generation and transmission, ergonomics, or power quality.

This document, to the extent possible, adapts the principles of existing applicable standards already in use throughout the marine industry (structure, moorings, anchors, corrosion protection, etc.) and by reference, defers to the appropriate international documents. This document adheres to a Load Resistance Factor Design (LRFD) approach and the principles of limit state design as described in ISO 2394.

MECs designed to convert hydrokinetic energy from significant hydrodynamic forces into other forms of usable energy, such as electrical, hydraulic, or pneumatic may be different from other types of marine structures. Many MECs are designed to operate in resonance or conditions close to resonance. Furthermore, MECs are hybrids between machines and marine structures. The control forces imposed by the power takeoff (PTO) and possible forces from faults in the operation of the PTO distinguish MECs from other marine structures.

The goal of this document is to adequately address relevant design considerations for MECs that have progressed to an advanced prototype design stage or beyond. This refers to technology concepts that have been proven either through analysis, open water test data, scale model testing in tanks or dry land test facilities, and that are ready for commercialization. It is anticipated that this document will be used in certification schemes for design conformity.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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.

IEC 60812, Analysis techniques for system reliability – Procedure for failure mode and effects analysis (FMEA)

IEC 61400-1, *Wind turbines – Part 1: Design requirements*

IEC 61643-11, *Low voltage surge protective devices – Part 11: Surge protective devices connected to low-voltage power systems – Requirements and test methods*

IEC 62305-3, *Protection against lightning – Part 3: Physical damage to structures and life hazard*

IEC TS 62600-1, *Marine energy – Wave, tidal and other water current converters – Part 1:* Terminology

IEC TS 62600-10, *Marine energy – Wave, tidal and other water current converters – Part 10: Assessment of mooring system for marine energy converters (MECs)*

ISO 527-1, *Plastics – Determination of tensile properties – Part 1: General principles*

ISO 2394, *General principles on reliability for structures*

ISO 12473, *General principles of cathodic protection in sea water*

ISO 13003, *Fibre-reinforced plastics – Determination of fatigue properties under cyclic loading conditions*

ISO 14125, *Fibre-reinforced plastic composites – Determination of flexural properties*

ISO 14126, *Fibre-reinforced plastic composites – Determination of compressive properties in the in-plane direction*

ISO 14129, *Fibre-reinforced plastic composites – Determination of the in-plane shear stress/shear strain response, including the in-plane shear modulus and strength, by the ±45° tension test method*

ISO 14130, *Fibre-reinforced plastic composites – Determination of apparent interlaminar shear strength by short-beam method*

ISO 15024, *Fibre-reinforced plastic composites – Determination of mode I interlaminar fracture toughness,* G_{IC}*, for unidirectionally reinforced materials*

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

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

ISO 19902:2007, *Petroleum and natural gas industries – Fixed steel offshore structures*

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

EN 12495, *Cathodic protection for fixed steel offshore structures*

EN 13173, *Cathodic protection for steel offshore floating structures*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 62600-1 as well as the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
normal wave height
NWH
significant wave height corresponding to a concurrent 10 min mean wind speed

3.2
primary structure
<marine energy converter> collective system comprising the structural elements, foundation, mooring and anchors, piles, and device buoyancy designed to resist global loads

4 Symbols and abbreviated terms

For the purposes of this document, the symbols and abbreviated terms given in IEC TS 62600-1 as well as the following apply.

d	water depth
f	wave spectrum frequency
f_{P}	wave spectrum peak frequency
f_{ck}	characteristic concrete compressive strength
f_{ckj}	characteristic cylinder strength
f_{e}	elastic buckling stress
f_{y}	specified minimum yield stress
F_{d}	load design value
F_{k}	load characteristic value
g	gravitational acceleration

h	ice thickness with a 50-year recurrence period
H_1	extreme wave height with a recurrence period of 1 year
H_5	extreme wave height with a recurrence period of 5 years
H_{50}	extreme wave height with a recurrence period of 50 years
H_{B}	breaking wave height
H_{EWH}	extreme wave height
H_{NWH}	normal wave height
H_{rated}	device rated wave height
H_{S}	significant wave height
$H_{\mathrm{S,NSS}}$	significant wave height of the normal sea state
H_{s1}	extreme stochastic wave height with a recurrence period of 1 year
H_{s5}	extreme stochastic wave height with a recurrence period of 5 years
H_{s50}	extreme stochastic wave height with a recurrence period of 50 years
$H_{\mathrm{s\ out}}$	extreme wave height exiting a device
$H_{\mathrm{s\ in}}$	extreme wave height into a device
H_{sT}	limiting value of $\mathrm{H_s}$ for transport, erection and/or maintenance
R	internal forces
R_{d}	design resistance
s	slope of beach floor
S	pseudo response spectrum
SWL	still water level
T	wave period
T_{P}	peak wave period
U_{bw}	breaking wave current velocity
U_{in}	current velocity into a device
U_{rated}	device rated current velocity
U_{out}	current velocity exiting a device
U_{ss}	sub-surface current velocity
U_{T}	limiting value of current velocity for transport, erection and/or maintenance
U_{w}	wind-generated current velocity
V	10 min mean wind speed
$V_{\mathrm{1\text{-}hour}}$	1 h mean value of wind speed at 10 m height above SWL
V_5	extreme wind speed with a recurrence period of 5 years
Φ	resistance factor
σ_{c}	ice crushing strength
σ_{U}	standard deviation of the current velocity
$\sigma_{\mathrm{U,c}}$	characteristic standard deviation of mean current velocity at a specified probability distribution
γ	damping ratio
γ_{F}	partial load safety factor
γ_{FM}	partial load effect and resistance factor
γ_{M}	material factor
γ_{Rd}	resistance model factor

γ_{S}	system effect factor
γ_{Sd}	load model factor
ω	angular frequency
λ	slenderness parameter; wave length

5 General considerations

5.1 General

There are a diversity of concepts and different approaches for MECs and there are broad and varied considerations for ensuring their structural integrity during lifecycle phases.

A common characteristic of all MEC structures that distinguishes them from other marine structures is the requirement to determine the loading and response of the structures due to their interaction with PTO and control systems. This affects strength, fatigue, and the capacity to survive operating and extreme meteorological and ocean conditions. In addition, failure of PTO, grid loss, and other conditions that may not be considered accidental shall be considered.

As part of the design process, the risks to structural integrity shall be assessed by means of a Failure, Modes and Effects Analysis (FMEA), a Failure, Modes, Effects and Criticality Analysis (FMECA), or similar method as per IEC 60812. This risk assessment shall be used to determine the possible structural failure modes associated with the fabrication, transportation, installation, service and removal of the MEC. It should consider the location of installation, the device characteristics, installation methodology, maintenance requirements, and activities of third parties in the area, including accidental scenarios.

5.2 Regulations

The requirements of regional regulations may be different from those given in this document. The designer shall ensure that the requirements of safety, reliability and durability of this document and regional regulations are met.

5.3 Suitability and/or relevance of standards

The use of a standard from other mature industries where nothing explicitly written for MECs is available carries a risk that important considerations for the marine energy application are given insufficient emphasis or ignored completely. This applies to standards written for offshore wind, oil and gas, and shipping.

It is expected that standards from other industries will be required to fill gaps in the design process. In many cases those standards are not identified by this document. Formal risk assessment techniques shall be used whenever a ‘non-marine-renewable-energy’ standard or guideline is used unless it can be demonstrated that the standard or guideline has been successfully adapted in previous designs with a similar application.

5.4 Quality assurance and quality control

The level of quality assurance and quality control shall be related to the consequences of the component, sub-system, system or assembly failing. Certification of quality systems of designers, manufacturers and operators by an accredited certifying body is desirable. Effective quality control through verification of design, testing, inspection and monitoring are essential for the success of the implementation of the technology. It is recommended that the quality system comply with the requirements of an internationally recognized quality management system.

5.5 Safety levels

In addition to the multitude of MEC concepts, there are several aspects to consider when defining the targets for safety and design life. Safety levels shall consider different expectation levels from different stakeholders and a balance among survivability, reputation, maintenance, repairs and production costs.

A safety level shall be clearly established covering all phases of MEC installation, operation, maintenance and decommissioning.

Safety levels shall be derived considering the following aspects and stakeholders:

- risk to life during installation, operation and removal of the MEC during in-service life;
- environmental impact, including for example: fluid releases, anti-fouling coatings, bilge water, and location of site relative to sensitive environments (protected species or sensitive sites and visual impacts);
- inspection and maintenance cost, risks during removal of equipment for inspection and maintenance;
- expected safety level by authorities where the MEC is designed to operate;
- financial risk (including loss of power generation); and
- public reputation and societal considerations.

When selecting the safety level, the consequences identified by a FMECA shall be referenced (see 5.1).

Three safety levels with reference to consequences for MECs have been identified and are defined in Table 1 along with target probabilities of failure. Reference should be made to Clause 7 for the use of these safety levels as part of the design process.

Table 1 – Safety levels

Safety level	Definition	Probability of failure
SL1	Operating conditions where failure implies high risk of human injury, significant environmental pollution or major economic or political consequences	$< 10^{-5}$ per year
SL2	For temporary or operating conditions where failure implies: some risk of human injury, some environmental pollution or significant economic or political consequences This level normally aims for a risk of less than 10^{-4} per year of a major single accident. It corresponds to a major incident happening on average less than once every 10,000 installation- years. This level equates to the experience level from major representative industries and activities.	$< 10^{-4}$ per year
SL3	Failure implies low risk of human injury and minor environmental and economic consequences	$< 10^{-3}$ per year

Guidance is given in this document to achieve a safety level of 2 based on reference to offshore wind and other offshore standards. Other safety levels may be appropriate based on project particulars. Partial load safety factors specified in Clause 7 of this document are based on target safety level 2. Partial load safety factors for any alternative target safety level can be adjusted accordingly, provided that the probability of failure of the target safety level is achieved.

Safety levels shall be considered while defining redundancy or safety features for the equipment and systems. Higher levels of safety might be required for critical sub-systems and components depending on their consequences of failure.

A higher safety level may be required due to the difficulty in access for maintenance and costs related to intervention offshore and the potential penalty of downtime to provide energy to the grid. The assessment of reliability, availability and survivability strategy for a particular device will directly influence the selection of an appropriate safety level.

Lower safety levels may be considered where there is a lower consequence of failure, which may be applicable to smaller unit sizes or to river current energy conversion systems.

5.6 Design principles – structure and foundations

Due consideration shall be given to aspects related to the relevant limit state: ultimate (ULS), serviceability (SLS), fatigue (FLS) and accidental (ALS). These limit states are normally associated with the limit state design methodology often referred to as Load and Resistance Factor Design (LRFD) or Partial Safety Factor Design (PSFD). Guidance is given in this specification based on LRFD methodology.

Allowable Stress Design (ASD) methods consider the same limit states through use of a single safety factor rather than separate load and resistance factors. This approach may be adopted provided the target safety levels in Table 1 are achieved.

An alternative design methodology, involving direct estimation of reliability of a MEC for a given limit state, may also be adopted to fulfill the safety levels as per Table 1. This approach requires:

- definition of different limit states for a design;
- definition of random variables entering in each limit state;
- consideration of probability distribution for each variable; and
- accepted method for estimating annual probability of failure in each limit state.

A particular design approach shall be used throughout the entire design process of a MEC to ensure a coherent execution that is acceptable to the client, regulators and certification authority.

5.7 Load definition and load combinations

The FMEA/FMECA shall be used to identify limit states where the structure would no longer meet the prescribed safety level requirements. Clauses 6 to 9 further detail methodologies to ensure that adequate consideration shall be given to the following:

- overall device stability against translation or overturning forces;
- integrity of any sub-components, where relevant;
- performance of ground anchorage, including consideration of ground fatigue;
- structural capacity and fatigue performance of structural components; and
- operational limits on mechanical equipment, seals and bearings.

Based on identified limit states, all load cases where these limit states could be exceeded shall be identified to enable design assessment (refer to Clause 7). For all identified load cases, consideration shall be given to device fault and failure conditions that could affect the device loading. It is important that the level of uncertainty surrounding the behavior of the MEC at an early stage of development is considered when defining the basic load cases.

For all load cases identified, sufficient analysis based on the underlying physical principles shall be undertaken to establish that the probability of exceeding any of the identified limit states falls within the limits set out in Table 1.

5.8 Other considerations

5.8.1 Stability and watertight integrity

The designer shall consider scenarios that could cause flooded or partly flooded compartments or inadvertent shift of permanent ballast. Permanent ballast shall be adequately restrained to avoid excessive movement and shifting due to device movements. The designer shall consider how to restore adequate stability after flooding by connecting or alternatively starting onboard bilge and/or ballast pumps. Provision of emergency supply to pumps, or provisions for piping for external connection of such pumps shall be considered. Free surface conditions for all floodable compartments shall be considered.

Subclause 7.3.7.11 deals with stability and watertight integrity.

5.8.2 Electrical, mechanical, instrumentation and control systems

Reference should be made to Clause 10 for detailed guidance on electrical and mechanical systems and how they can impact structural integrity.

5.8.3 Reliability issues

A MEC consists of structural, mechanical, electrical and control systems that are interdependent. Thus, it is essential to check not only the reliability of each of the systems separately but their impact on the device as a whole. The planned inspection and maintenance of the device shall be considered during the design stage as discussed in Clause 12. Guidance on considering reliability for various components and systems is provided in Annex B.

5.8.4 Corrosion protection

Due consideration shall be given to the adequate durability and performance of the structure and components in corrosive environments. See Clause 8 and Annex C for additional information.

5.8.5 Design for operation, inspection, maintenance and decommissioning

The manner in which the MEC is operated and maintained will have a significant impact on the structural integrity and functionality throughout the service life of the device. In order for any maintenance methodology to be effective, it shall be considered in a holistic manner throughout the design, construction and operation process. In particular, the planned inspection and maintenance shall be considered during the design stages to ensure that it is practical, economic and safe. The designer shall also consider removal and decommissioning during the design phase. See Clause 13 for life cycle considerations.

5.9 Operational and structural resonance

The designer shall take into account the harmonic response of both structural and mechanical elements. Structural damping can be expected to be quite low. Hydrodynamic damping can be quite significant and shall be estimated.

There are two types of MECs: ones that exploit a resonant response, in order to maximize the power captured, and those that do not. Operational resonance refers to devices that exploit a resonant response in order to maximize the power captured. For these MECs, the designer shall pay close attention to the fatigue stresses and the fatigue life. The dynamic behavior of the device may also require special considerations for stability beyond the normal margins provided by the stability curves and requirements for ships or floating offshore installations.

For devices that do not exploit a resonant response, environmental loads may induce structural resonance. The designer shall either ensure the natural frequencies of the structural and mechanical elements are sufficiently separated from the exciting frequency or ensure that there is sufficient damping in the design so fatigue stresses induced are not significant. Structural resonance can also occur in modes not associated with energy conversion. It should be noted that avoiding natural frequencies will not completely eliminate fatigue stresses. All MEC designs shall have adequate strength and safety factors to accommodate fatigue stresses.

Guidance on the approach to consider operational and structural resonance and the assessment of natural and exciting frequencies for MECs is provided in Annex D.

5.10 Basis of design

The basis of design describes the technical approach and design parameters planned for the project. The basis of design summarizes all baseline data, loadings, material characteristics, design methodology, and applicable design standards that are to be considered during the design process.

The basis of design shall be applicable to all stages of development from the prototype design stage of an MEC (after the initial concept has been proven to work) up to the final detailed design. The key objective of the basis of design is to act as an overarching document that promotes consistency during all design work. Further guidance on the typical contents of a basis of design is provided in Annex E.

6 External conditions

6.1 General

The external conditions described in Clause 6 shall be considered in the modeling, analysis and prediction of environmental conditions for calculating environmental loads on MECs. The most important environmental phenomena for MECs are waves and currents, but consideration shall also be given to wind, ice, earthquake, soil conditions, temperature, fouling and other external conditions.

The marine conditions for load and safety considerations are divided into the normal marine conditions, which will occur more frequently than once per year during normal operation of the MEC, and the extreme marine conditions, which are defined as having a 1-year and 50-year recurrence period. The normal and extreme conditions to be considered in design are prescribed in Clause 7.

6.2 Waves

6.2.1 Normal sea state (NSS)

The Normal Sea State (NSS) is characterized by a significant wave height, a peak period and a wave direction. The designer shall follow ISO 19902 when developing fatigue and ultimate load calculations based on the NSS. Where available, regional or site specific data shall be used to specify spectral shape and directional distributions

6.2.2 Normal wave height (NWH)

The Normal Wave Height (NWH), H_{NWH} shall be assumed equal to the expected value of the significant wave height based on the concurrent 10 min mean wind speed, $H_{\mathrm{S,NSS}}$ or derived from analysis of appropriate measurements and/or hindcast data for the site of deployment of the MEC. Consideration shall be given to the range of wave periods T appropriate to the normal wave height. Design calculations shall be based on values of the wave period within this range that result in the highest loads on the MEC.

The wave periods T in combination with the normal wave heights, H_{NWH} may be assumed to be within the range given by IEC 61400-3:

$$11{,}1\sqrt{H_{\mathrm{S,NSS}}(V)/g} \leq T \leq 14{,}3\sqrt{H_{\mathrm{S,NSS}}(V)/g} \qquad (1)$$

where:

$H_{\mathrm{S,NSS}}$ is the significant wave height of the normal sea state in metres;

V is the 10 min mean wind speed in metres per second;

T is the wave period in seconds.

Short-term stationary irregular sea states may be described by a wave spectrum that represents the power spectral density function of the vertical sea surface displacement. Different combinations of wave periods, wave heights and directions at the same probability level (e.g., 10^{-2} or 10^{-4}) shall be considered to arrive at the most unfavorable values for the different action effects.

The most frequently used spectra for wind-generated seas are Pierson-Moskowitz (PM) spectrum for a fully developed sea, and the JONSWAP spectrum for a developing sea. Standard wave spectrum formulations are given in Annex F. The Ochi-Hubble spectrum based on superposition of two modified Pierson-Moskowitz spectra or the Torsethaugen double peak spectral model based on sea state and swell may also be appropriate. Information on swell spectra can be found in ISO 19901-1.

6.2.3 Extreme sea state (ESS)

The designer shall consider the extreme stochastic sea state model for the extreme significant wave height, H_{s50}, with a recurrence period of 50 years; the extreme significant wave height, H_{s5}, with a recurrence period of 5 years; and the extreme significant wave height, H_{s1}, with a recurrence period of 1 year. The values of H_{s50}, H_{s5} and H_{s1} shall be determined from analysis of appropriate measurements and/or hindcast data for the site of MEC deployment. The extreme significant wave height, H_{s50} estimated from hindcast data may underestimate the recurrence conditions. The designer shall take into account the range of peak spectral period, T_p appropriate to H_{s50}, H_{s5} and H_{s1} respectively. Design calculations shall be based on values of peak spectral period that result in the highest loads acting on the MEC.

In the absence of information defining the long-term joint probability distribution of extreme wind and waves, it shall be assumed that the extreme 10-min mean wind speed with 50-year recurrence period occurs during the extreme 3 h sea state with 50-year recurrence period. The same assumption shall apply with regard to the combination of the extreme 10 min wind speed and the extreme 3 h sea state, each with a 1-year recurrence period.

6.2.4 Extreme wave height (EWH)

The extreme wave height is the largest significant wave height for a given recurrence value. The extreme deterministic design wave shall be considered for the extreme wave height H_{50} with a recurrence period of 50 years; extreme wave height H_5 with a recurrence period of 5 years; and the extreme wave height H_1 with a recurrence period of 1 year. The values of H_{50}, H_5, H_1 and the associated wave periods may be determined from analysis of appropriate measurements at the MEC deployment site. Alternatively, the designer may assume the following based on the Rayleigh distribution of wave heights:

$$H_{50} = 1{,}86\ H_{s50} \qquad (2)$$

$$H_5 = 1{,}86\ H_{s5} \qquad (3)$$

and

$$H_1 = 1{,}86\ H_{s1} \qquad (4)$$

where the significant wave heights H_{s50}, H_{s5} and H_{s1} are values for a 3 h reference period.

A recurrence period of 50 years corresponds to SL2. This shall be adjusted for sites where extreme events with higher recurrence periods than 50 years are relevant (e.g. Gulf of Mexico or North Atlantic).

The range of wave periods T appropriate to the severe wave height shall be considered in the design calculations. The computations shall be based on values of the wave period within this range that result in the highest loads on the MEC.

In deep waters, the wave periods T to be used with H_{EWH} may be assumed to be within the range given by Formula (1).

NOTE Water is considered 'deep' for a wave, if its depth is greater than one-half of the wavelength of the wave. Otherwise, it is considered 'shallow.'

The extreme wave heights H_{50}, H_5, H_1 and the associated wave periods for shallow water sites shall be determined from analysis of appropriate site-specific measurements. In the absence of measurements, H_{50}, H_5 and H_1 shall be assumed equal to the breaking wave height if the breaking wave height is less than the values of H_{50}, H_5 and H_1 determined from the Rayleigh distribution given by Formulae (1) and (3).

6.2.5 Breaking waves

A breaking wave is a wave whose amplitude reaches a critical level that causes large amounts of wave energy to be transformed into turbulent kinetic energy when the crest of the wave overturns. The effect of breaking waves shall be assessed, if necessary, for a given site during the design of the MEC. Depending on the wave steepness and the slope of the seabed, breaking waves are classified as spilling, plunging or surging.

Annex G provides guidance for determination of the nature and dimensions of breaking waves based on site conditions and presents an empirical model of the distribution of wave heights for shallow water.

6.2.6 Wave run-up

The designer shall consider hydrodynamic loads arising from the maximum vertical extent of wave travel on a beach or structure above the still water level.

6.3 Sea currents

6.3.1 General

The most common categories of ocean currents are: wind generated currents, tidal currents, circulational currents, loop and eddy currents, soliton currents, and longshore currents. The total current velocity is the vector sum of all components at a given position in the water column. The designer shall determine whether sea currents may be neglected for calculation of fatigue loads on the components of the supporting structure considering the site characteristics and MEC's geometry.

6.3.2 Sub-surface currents

The sub-surface current velocity $U_{ss}(z)$ profile may be characterized by a simple power law over the water depth d, as a function of height z above SWL:

$$U_{ss}(z) = U_{ss}(0)\,\{(z+d)/d\}^{1/7} \qquad (5)$$

The 1-year, 5-year and 50-year recurrence values of the sea surface velocity $U_{ss}(0)$ may be determined from analysis of measurements of tidal, storm surge, wind generated and wave induced surf. If the current velocity is of significant importance to the design, current velocity measurements shall be carried out at the MEC deployment site.

Currents through the depth shall be combined vectorially with the design wave conditions.

6.3.3 Wind-generated near-surface currents

The wind-generated current may be characterized as a linear distribution of velocity $U_{\mathrm{w}}(z)$ reducing from the surface velocity $U_{\mathrm{w}}(z)$ to zero at a depth of 20 metres (m) below the static water level SWL:

$$U_{\mathrm{w}}(z) = U_{\mathrm{w}}(0)\ \{(1+z)/\ 20\} \tag{6}$$

The wind generated current velocity at the sea floor will be non-zero at sites where the water depth is less than 20 m.

The wind generated sea surface current velocity may be assumed to be aligned with the wind direction and may be determined from

$$U_{\mathrm{w}}(0) = 0{,}01\ V_{\text{1-hour}}\ (z = 10\ \mathrm{m}) \tag{7}$$

where $V_{\text{1-hour}}\ (z = 10\ \mathrm{m})$ is defined as the 1 h mean value of wind speed at 10 m height above SWL.

The 1-year, 5-year and 50-year recurrence values of $V_{\text{1-hour}}\ (z = 10\ \mathrm{m})$ may be determined from analysis of site measurements.

6.3.4 Tidal currents

Tidal currents are often magnified by topographical features, such as headlands, inlets and straights, or by the shape of the seabed when water is forced through narrow channels. Strong tidal currents may exist in inlets and straits in coastal regions (IEC TS 62600-201).

Marine tidal current turbulence generated by sea bed material, ripples, bed forms, changes in bathymetry, waves and swell, ambient environment, and vortices shed from the blades and support structure shall be considered in determining frictional drag, flow separation, transition from laminar to turbulent flow, thickness of boundary layers, extent of secondary flows, and the spreading of jets and wakes

6.3.5 Breaking wave-induced surf currents

The surf currents generated by the shear forces of breaking waves along the coast shall be considered when the MEC is to be sited near a breaking wave zone.

Numerical methods (e.g. a Boussinesq model considering fully coupled wave and current motions) can be used for the estimation of the breaking wave induced surf currents. The near-shore surf currents that have a direction parallel to the shoreline (longshore currents) may be estimated based on the current velocity U_{bw} at the location of breaking waves as:

$$U_{\mathrm{bw}} = 2s\sqrt{gH_{\mathrm{B}}} \tag{8}$$

where:

H_{B} is the breaking wave height;

g is the gravity acceleration;

s is the beach floor slope.

The breaking wave height may be estimated based on the site characteristics presented in Annex G.

6.3.6 Normal current model (NCM)

The normal current model includes the appropriate site-specific combination of wind-generated currents and breaking wave surf induced currents, if any, associated with normal wave conditions.

For ultimate load cases involving normal and severe wave conditions the normal current model shall be used with the velocity of the wind generated currents estimated from the relevant mean wind speed (refer to Clause 7).

6.3.7 Extreme current model (ECM)

The extreme current model is defined as the appropriate site-specific combination of sub-surface currents; wind generated currents and breaking wave surf induced currents, if any, associated with recurrence periods of 1, 5 and 50 years, respectively.

For ultimate load cases involving extreme wave conditions, the extreme current model shall be assumed together with sea currents using the same recurrence period as the waves.

6.3.8 Normal turbulence model (NTM)

The level of turbulence in a tidal flow depends on the roughness of the bed, the shape and length of the channel and the flow mean velocity. Turbulence is generally described by the spectrum of velocity fluctuations in the mean flow direction.

The NTM represents turbulent current velocity in terms of a characteristic standard deviation of mean current velocity, $\sigma_{\mathrm{U,c}}$. The characteristic standard deviation $\sigma_{\mathrm{U,c}}$ is defined as the 90 % quantile in the probability distribution of the standard deviation σ_{U} of the current velocity conditioned on the 10 min mean current velocity at a specific point in the water column. Guidance on calculating characteristic standard deviation $\sigma_{\mathrm{U,c}}$ based on wind turbulence is provided in IEC 61400-1. When modelling the NTM, a frequency spectrum shall be used with suitable length scales. This frequency spectrum will be a function of standard deviation of mean current. The NTM shall also take account of spatial coherence. It has been shown in a number of references that measured tidal turbulence seems to fit wind turbulence models.

NOTE See example in the NREL TurbSim user guide (TurbSim User's Guide Version 1.06.00) that has the relevant formulae for a tidal NTM. This model is similar to the turbulence model used (in TurbSim) for non-complex wind sites. Also Milne et al. (2013) reported that the Von Karman spectrum model, a wind turbulence spectrum model, seemed to have a reasonable fit to measurements of tidal turbulence if suitable length scales were used.

6.3.9 Extreme turbulence model (ETM)

The extreme turbulence model describes dynamic loads produced by tidal or estuarial flows in extreme conditions. The Extreme Turbulence Model (ETM) represents turbulent current velocity in terms of a characteristic standard deviation of current velocity, $\sigma_{\mathrm{U,c}}$. The characteristic standard deviation $\sigma_{\mathrm{U,c}}$ is defined as the 98 % quantile in the probability distribution of the standard deviation σ_{U} of the current velocity conditioned on the 10 min mean current velocity at a specific point in the water column. For guidance on the frequency spectrum, spatial coherence, etc. see the guidance given for the NTM.

Guidance on the turbulence models can be taken from IEC 61400-1 but the models shall be calibrated with the (partial) factors of safety to ensure the governing safety level is achieved. In both cases the standard deviation is defined in terms of a reference turbulence intensity (and velocity at the turbine hub and other factors). But, for tidal streams turbulence intensity seems to vary with mean tidal speed (Milne et al. 2013, Osalusi, 2010), with turbulence intensity increasing as mean tidal speed decreases. The NTM and ETM shall therefore be related to a specific point in the tidal cycle, i.e. there shall be NTM and ETM for each point at the tidal cycle where the loading is calculated. In addition the turbulence shall be measured in all three orthogonal directions and then the standard deviation derived for each direction.

Tidal site measurements for turbulence shall take account of the influence of waves on fluctuating tidal speed. When deriving the loading from the tidal current, the influence of waves and turbulence shall be dealt with separately as the influence of the wave loading will have more variability than the turbulence.

6.4 Wind conditions

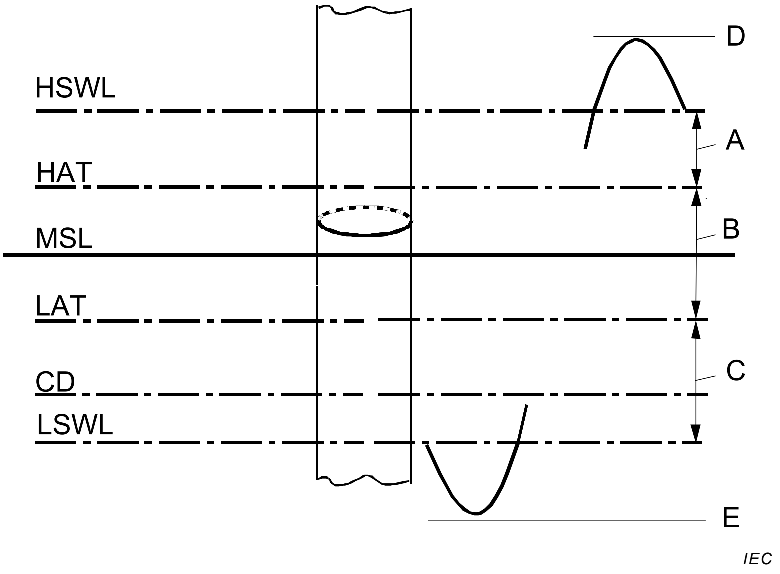
The MEC shall be designed to safely withstand the wind conditions adopted as the basis for design. The normal wind conditions and the design wind conditions shall be taken in accordance with IEC 61400-1. The wind conditions may be ignored if freeboard is insignificant.

The wind regime for load and safety considerations is divided into the normal wind conditions that occur more frequently than once per year during normal operation of the MEC and the extreme marine conditions, which are defined as having 1-year, 5-year, and 50-year recurrence periods.

6.5 Water level

6.5.1 General

The variation in water level at the site shall be taken into account in the calculation of the hydrodynamic loading of MECs. The designer may assume a constant water level equal to the mean sea level (MSL) for ultimate load cases involving normal wave conditions (NSS and NWH). Different water levels are illustrated in Figure 1.



HSWL	highest still water level
HAT	highest astronomical tide
MSL	mean sea level
LAT	lowest astronomical tide
CD	chart datum (often equal to LAT)
LSWL	lowest still water level
A	positive storm surge
B	tidal range
C	negative storm surge
D	maximum crest elevation
E	minimum trough elevation

Figure 1 – Definition of water levels (see IEC 61400-3)

6.5.2 Normal water level range (NWLR)

The normal water level shall be assumed equal to the variation in water level with a recurrence period of 1 year. The normal water level range may be assumed to be equal to the variation between highest astronomical tide (HAT) and lowest astronomical tide (LAT) in the absence of site-specific data to characterize the long-term probability distribution of water levels.

The NWLR shall be assumed for those fatigue and ultimate load cases involving the normal sea state model (NSS) based on the joint probability distribution of sea state conditions, wind speed and current speed (H_s , T_p , U_ss).

6.5.3 Extreme water level range (EWLR)

The extreme water level range shall be used for ultimate load computations on the MEC due to the wave conditions with a recurrence period of 50 years. Determination of loads shall be based on the water levels that result in the highest loads acting on the MEC. The relevant governing design water levels shall be determined for computing the hydrodynamic loading, ice loading, and buoyancy of the support structure.

The design calculations shall include the following water levels if the long-term joint probability distribution of water level is not available:

- highest still water level with a recurrence period of 50 years, based on an appropriate combination of highest astronomical tide and positive storm surge;
- lowest still water level with a recurrence period of 50 years, based on an appropriate combination of lowest astronomical tide and negative storm surge; and
- water level associated with the highest breaking wave load.

6.6 Sea and river ice

Loading on the component/support structure of a MEC due to sea or river ice can be critical in some areas. Ice may form in areas where subfreezing temperatures can prevail a major portion of the year. Ice may exist in these areas as first-year ice, multi-year floes, first-year and multi-year pressure ridges, and/or ice islands. Ice features will influence the design and construction of MECs. Global ice forces vary depending on factors such as location, size and configuration of the MEC, mode of ice failure, temperature, salinity, speed of load application, and ice composition.

Ice forces may cause static loading from a fast ice cover, or dynamic loading caused by wind and current induced motion of ice floes. Moving ice floes impacting the MEC over an extended period of time may result in significant fatigue loading. River MECs need to consider the spring freshet 'wall of ice'. A site-specific assessment of the occurrence and properties of the ice shall be undertaken prior to the design of the support structure. The following parameters shall be determined from the assessment:

- ice thickness, h, with a 50-year recurrence period;
- ice crushing strength, σ_c;
- risk of current or wind induced ice floe;
- risk of forces induced by fluctuating water level; and
- frequency of ice concentration.

NOTE Ice capable of disrupting the harvest of tidal power currently occurs in the Bay of Fundy, Nova Scotia. Recommendation has been made for deployment of tidal current harvesting devices in the headwaters of the Bay of Fundy to be designed for 30 % cover by 15 cm thick ocean ice in 100 m floes.

6.7 Earthquakes

Seismic forces shall be considered for sites that are determined to be seismically active. The designer shall define the pseudo response spectra for the design of the MEC primary and support structures. For a given damping ratio γ and angular frequency ω, the pseudo response spectrum S gives the maximum value of the response over the duration of the response. The designer shall consider non-linear effects that may require site-specific time history analysis for specified ground motions.

6.8 Marine growth

Marine growth influences the dynamic and hydrodynamic characteristics of structural members through the added mass of the growth, increased outer dimensions and increased roughness of the surface. The thickness of marine growth is site-specific and depends on location, member orientation, water depth and structure age (or time since removal of growth). Site-specific data shall be used to establish the extent of marine growth, likely thickness and depth dependence of the growth for a given location.

A strategy for inspection and possible removal of marine growth shall be planned as part of the support structure design. Inspection frequency, inspection method and growth removal criteria shall be based on the impact of marine growth on the structural reliability and performance of the MEC and the extent of marine growth for the site-specific conditions.

6.9 Seabed movement and scour

The component or support structure of the MEC shall be designed taking into account the influence of seabed movement and scour.

The analysis of seabed movement and scour, and the design of appropriate protection shall conform to the requirements of ISO 19901-4.

6.10 Ship collisions

The effect from maritime traffic and service vessel collisions shall be considered.

6.11 Other environmental conditions

The designer shall take into account environmental conditions such as: air temperature, humidity, air density, solar radiation, rain, hail, snow and ice, chemically active substances, mechanically active substances, salinity causing corrosion, lightning, water density and viscosity, water temperature and any other environmental condition that may impact the MEC. The probability of simultaneous occurrence of climatic conditions shall be taken into account.

7 Loads and load effects

7.1 General

The integrity of the load-carrying components of a MEC structure shall be verified to an acceptable safety level as defined in Clause 5. The ultimate and fatigue strength of structural members shall be verified by calculations and/or tests.

Scale model tank testing and field test data may be used as a support for calculations to verify the structural design.

7.2 Loads

The loads described in Table 2, which are relevant for the specific MEC site and geometry, shall be considered in all design calculations.

An analysis of the dynamic response of the MEC shall be performed.

Table 2 – Types of loads that shall be considered

Load	Description and design approach
Gravitational and inertial loads	Static and dynamic loads resulting from gravity, vibration, rotation and seismic activity.
Actuation loads	Result from the operation and control of the MEC. The interaction of the MEC control system with the low-frequency motions of the structure shall be considered in the control system design and load analysis. The designer shall pay close attention to the assessment of fatigue stresses and the fatigue life where resonance and dynamic amplification of motions happen.
Hydrostatic loads	Result of still water pressure acting on the immersed surfaces of a body.
Hydrodynamic loads	Result of stationary and dynamic loads that are caused by water flow and its interaction with the immersed body. Hydrodynamic loads depend on the water kinematics, water density, water depth, the shape of the immersed structure, and hydro-elastic effects. It covers wave loads, current loads, etc. as described in 7.3.2. and Table 2.
Wave loads	Result of interaction of the wave with the structure. A relevant wave theory shall be used to calculate wave kinematics parameters such as water particle velocities and accelerations at MEC components. For submerged components of the MEC, periodic pressure variations from passing waves shall be considered. In the analysis of wave-induced loads, the influence of marine growth and of appurtenances, if not explicitly modeled, shall be considered.
Breaking wave loads	Result of breaking wave impact loads that can lead to dynamic magnification, depending on the duration of the impact relative to the natural period of the structure. In the case where a MEC is installed close to the shoreline, fatigue loading due to breaking waves shall be considered. Since the analysis of breaking wave loads contains many uncertainties, model tests are recommended for the evaluation of the loads. Annex G provides guidance relating to shallow water hydrodynamics and the influence of site characteristics on the nature and dimensions of breaking waves.
Wave slamming loads	Result of passing wave interaction with MEC components. Where structural components of the MEC (e.g. platforms), cannot resist the wave impact, the latter shall be avoided providing sufficient distance between the probable highest wave elevations with a 50-year recurrence period and the lower edge of the MEC component.
Greenwater loads	Result of overtopping of a body of seawater during severe wave conditions. Structural members exposed to greenwater shall be designed to withstand appropriate design head pressures.
Current loads, including river currents	Result of water flowing around a structure producing variable pressures and flow paths. Turbulence may be within the resonant frequencies of structural components of the MEC and impose significant loading on the structure. Due to the vertical velocity profile of the current cyclic bending moments can arise and shall be considered in the design of the MEC where relevant. Cavitation can impose additional loads on the structure and shall be considered. Periodic loading due to passing waves on current may act on the MEC and shall be considered where relevant. The influence of marine growth and of appurtenances on current loads shall be considered. Current loads on mooring lines and other components connected to the structure shall be accounted for in the analysis using appropriate drag coefficients.
Vortex shedding	Dynamic loads determined by the geometry of the structure and the velocity of the currents and waves.
Aerodynamic loads	Quasi-static and dynamic loads that are caused by the airflow and its interaction with the MEC's components above the water surface. Determined by average wind speed, the turbulence intensity, the density of the air and the aerodynamic shape of the MEC's components above the water surface and their interactive effects, including the aero-elastic effects.
Vessel impact	Determined by vessel size, mass, speed, and incident angle. The indirect interaction are typically dominated by the vessel wake, vessel induced velocity and propeller/rudder effects.

Load	Description and design approach
Debris impact loads	Includes fouling from floating debris, such as fishing nets and plastic waste that may include large entrained masses, such as floating logs, chemical debris and fuel slicks.
Array effects	Includes loads from mechanical, mooring or other interconnections between neighboring units, hydrodynamic sheltering and other interaction effects between devices or other structures in proximity.
Seismic loads	Includes direct loads generated by seabed movements and fluid loads caused by the seismically induced fluid motions such as tsunamis.
Topside icing	Includes stability and structural issues caused by icing of the structure above the waterline.
Ice loads	Results from a fast sea or river ice cover and/or dynamic loading caused by wind and current induced motion of ice floes and cause significant fatigue loading.
Construction loads	Includes loads during fabrication, assembly, transportation and installation of the MEC.

7.3 Design situations and load cases

7.3.1 General

For design purposes, the life of a MEC can be represented by a set of design situations covering the various conditions that the MEC may experience. In this subclause the derivation of design load cases is described.

The load case shall be determined from the combination of specific installation, maintenance, and operational modes or design situations with the external conditions. All relevant load cases with the corresponding probability of occurrence shall be considered in conjunction with the behaviour of the control and safety systems.

The design load cases used to determine the structural integrity of the MEC shall be calculated from the following combinations:

- normal design situations and normal external conditions;
- fault design situations when the MEC is operating with a single major system failure and appropriate external conditions;
- normal design situations and extreme external conditions; and
- design situations for transportation, installation, maintenance and decommissioning and the appropriate external conditions.

If any correlation exists between an extreme external condition and a fault situation, a realistic combination of the two shall be considered as a design load case.

7.3.2 Interaction with waves, currents, wind, water level and ice

MECs shall be analysed considering the interaction with waves, currents, wind, water level and ice. Theoretical formulations developed for ships, offshore structures and coastal engineering problems can be used for analysing MECs as per guidance provided in 5.3.

The combination of extreme external conditions shall be performed in a way that results in the global extreme environmental action on the structure with the combined specified recurrence period of 50 years.

If there is no project site information available about the combination of the extreme external conditions, the recurrence periods as stated in Table 3 can be used to derive environmental combinations for a 50-year recurrence period. The adverse directional alignment of wind, waves and currents shall be considered. A worst case directional alignment need not necessarily be the co-alignment of environmental loads and the interaction of wind, current and waves may be relevant.

Table 3 – ULS combinations of uncorrelated extreme events

Environmental combinations	External event and recurrence period (years) to define characteristic value of corresponding load effect					
	Waves	**Current**	**Water level**	**Wind**	**Ice**	**Comment**
1	5	5	50	50	–	
2	50	5	50	5	–	
3	5	50 (wind) 18 (tidal)	50	5	–	
4	–	5	MSL	5	50	
5	50	5	50	50	–	For windswell

7.3.3 Design categories

Normal, extreme, abnormal and transport and erection design categories are defined in Table 4.

Table 4 – Design categories

Design category	Design situation
Normal	Normal operation Normal operation plus fault Parked/idling Parked/idling plus fault
Extreme	Parked/idling Parked/idling plus fault Survival Survival plus fault
Abnormal	Earthquake/tsunami Parked/idling plus major fault Survival plus major fault Rare ULS fault conditions Accidental events
Transport and erection	Installation Maintenance Decommissioning

7.3.4 Limit states

7.3.4.1 General

The structural performance of a whole structure or part of it shall be described with reference to a specified set of limit states beyond which the structure no longer satisfies the design requirements. The following limit states shall be considered.

7.3.4.2 Ultimate limit state (ULS)

Ultimate limit state (ULS) places a structure at the cusp of failure, and typically corresponds to the maximum load-bearing capacity. The following failure modes shall be considered when determining the ULS:

- loss of static equilibrium of the structure, or of a part of the structure, considered as a rigid body (e.g. overturning or capsizing);
- failure of critical components of the structure caused by exceeding the ultimate strength (in some cases caused by repetitive actions) or the ultimate deformation of the components;
- transformation of the structural geometry (collapse or excessive deformation);
- loss of structural stability (buckling, etc.);
- loss of station keeping (free drifting); and
- sinking.

7.3.4.3 Fatigue limit state (FLS)

The fatigue limit state, which generally corresponds to the effect of cyclic loading, includes the following states:

- cumulative damage due to repeated loads; and
- reduction of structural integrity beyond safety factor allowance.

7.3.4.4 Serviceability limit state (SLS)

Depending on the design and function, the serviceability limit state is determined by various limiting values that are oriented towards the normally envisaged use. Limits to be observed include:

- deformations or movements that affect the function of structural or non-structural components;
- excessive vibrations producing discomfort for maintenance personnel or affecting non-structural components or equipment (especially if resonance occurs);
- local damage (including cracking) that reduces the durability of a structure or affects the use of structural or non-structural components;
- corrosion that reduces the durability of the structure and affects the properties and geometrical parameters of structural and non-structural components; and
- motions that exceed the limitations of equipment.

7.3.4.5 Accidental limit state (ALS)

The ALS check ensures that local damage or flooding does not lead to complete loss of integrity or performance of the structure.

The intention of this limit state is to ensure that the structure can tolerate specified accidental and abnormal events and maintain structural integrity for a sufficient period to enable evacuation to take place, where necessary.

7.3.5 Partial safety factors

The target safety level for a MEC shall be assumed to be SL2 according to Clause 5 and the probability of failure shall be less than 10^{-4}.

A partial load safety factor γ_{f} shall take into account the probability of the load occurring and that certain limiting values will not be exceeded with a given probability. γ_{f} reflects the uncertainty of the loads and their probability of occurrence (e.g. normal and extreme loads), possible deviation of the loads from the characteristic values, plus the accuracy of the load model (e.g. gravitational or hydrodynamic forces). Partial load safety factors are defined for the ULS limit state for design categories in combination with the load sources in Table 5.

If the loads of different origins can be determined independently of each other, the partial safety factors γ_f for the loads shall be 1,0 for FLS, SLS and ALS conditions.

The partial load safety factors in 7.3.5 are valid for all MEC components except for the mooring systems. For the mooring system please refer to Clause 11.

In many cases, especially when unsteady loads lead to dynamic effects, the load components cannot be determined independently of each other. In these cases, the highest partial safety factor γ_f of the corresponding limit state/design category shall be applied for the loads.

Table 5 – ULS partial load safety factors γ_f for design categories

Source of loading	**Unfavorable loads**				**Favorable loads**
	Design category				**All design categories**
	Normal (N)	**Extreme** (E)	**Abnormal** (A)	**Transport/erection** (T)	
Environmental	1,35	1,35	1,1	1,5	0,9
Operational	1,35/1,5[b]	1,35	1,1	1,5	0,9
Gravity	1,1/1,35[a]	1,1/1,35[a]	1,1	1,35	0,9
Other inertial forces	1,35	1,35	1,1	1,35	0,9
Heat influence	-	1,35	-	-	0,9

[a] For masses not being determined by weighing.

[b] For MECs working within ±5 % of the structural resonance (e.g. point absorber).

The partial load safety factors γ_f are based on safety level 2 according to Clause 5. If a different target safety level as per Clause 5 is chosen for the MEC design, γ_f shall be adjusted accordingly.

In order to cope with the fact that the technology of many designs is new and yet unproven, the partial load safety factors in Table 5 may be increased. To ensure reliable design values, the uncertainties and variances of the loads are covered by the partial load safety factors γ_f as follows:

$$F_d = \gamma_f \cdot F_k \tag{9}$$

where:

F_d is the design value of the load;

F_k is the characteristic value of the load;

γ_f is the partial safety factor for the load. The partial load safety factors are independent of the materials used and are stated for all load components under consideration. Refer to Clause 9 for guidance on material factors.

7.3.6 Simulation requirements

Dynamic simulations utilizing a structural dynamics model shall be used, where appropriate, to calculate load effects on the MEC. Certain load cases have a stochastic current and/or wave input.

When dynamic simulations are used, the total period of load data for these cases shall be long enough to ensure statistical reliability of the estimated characteristic load effect.

- For stationary load cases for tidal energy converters (TECs) (e.g. power production), at least six 10 min stochastic realizations shall be required for each mean current speed considered in the simulations. Constrained wave methods may be used for this purpose.
- For stationary load cases for wave energy converters (WECs), at least six 3 h stochastic realizations shall be required for each sea state considered in the simulations. This requirement may be relaxed and shorter realizations may be assumed if the designer is able to demonstrate that the estimated extreme response is more conservative than that obtained with 3 h realizations. Constrained wave methods may be used for this purpose.
- For transient load cases for both TECs and WECs (e.g. stopping procedures) at least six 10 min simulations shall be carried out for each event at the given current speed and/or sea state.

Longer simulation periods may be required for mooring systems with low natural frequencies.

The mean value and the turbulence of the current speed and/or the significant wave height used as input to load cases requiring dynamic simulation shall be appropriate to the chosen simulation period.

More guidance about the simulation approach can be found in Annexes A and D.

7.3.7 Design conditions

7.3.7.1 General

The combination of the design categories with the limit states leads to a load case matrix. At a minimum, the relevant design load cases as defined in Tables 6 and 7 shall be considered for the design of the MEC. If other realistic combinations lead to more severe loading, these shall also be considered.

The wave heights and current speeds derived from the environmental conditions in Tables 6 and 7, may be represented by a set of discrete values provided that the resolution is sufficient to assure accuracy of the calculation. A regular wave with the respective significant wave height and the normal steady current model may be assumed for TECs. In the definition of the design load cases, reference is made to the environmental conditions described in Clause 6.

For parts of the MEC that are exposed to wind and where wind is relevant for loading, a steady wind model may be used. The response shall be estimated from a quasi-steady analysis with appropriate corrections for dynamic response.

In all design conditions, the designer shall ensure that the number and resolution of the normal sea states considered are sufficient to account for the fatigue damage associated with the long-term distribution of metocean parameters.

Table 6 – Design load cases for WEC

Design category	Design condition	Limit states	Wave conditions	Current conditions	Water level	Other conditions
Normal (N)	Normal operation	ULS, FLS, SLS	NSS $H_{\mathrm{s,in}} \le H_{\mathrm{s}} \le H_{\mathrm{s,out}}$	NCM $U = U_1$	NWLR	
		ULS, FLS	No waves	NCM $U_{\mathrm{in}} \le U \le U_{\mathrm{out}}$	NWLR	Ice
	Normal operation plus fault	ULS, FLS, SLS	NWH $H_{\mathrm{s,rated}} \le H_{\mathrm{s}} \le H_{\mathrm{s,out}}$	NCM $U = U_1$	NWLR	Grid loss, grid failure, fault in controller
	Emergency shut-down procedures	ULS, SLS	NWH $H_{\mathrm{s,rated}} \le H_{\mathrm{s}} \le H_{\mathrm{s,out}}$	NCM $U = U_1$	NWLR	
	Start/normal shut-down procedures	ULS, FLS, SLS	NWH $H_{\mathrm{s,rated}} \le H_{\mathrm{s}} \le H_{\mathrm{s,out}}$	NCM $U = U_1$	NWLR	
	Parked	ULS, FLS, SLS	NSS $H_{\mathrm{s,in}} \le H_{\mathrm{s}} \le H_{\mathrm{s,out}}$	NCM $U = U_1$	NWLR	
Extreme (E)	Parked/survival	ULS, SLS	ESS $H_{\mathrm{s}} = H_{\mathrm{s50}}$	ECM $U = U_5$	EWLR	Wind: EWM ($V = V_5$)
		ULS	ESS $H_{\mathrm{s}} = H_{\mathrm{s50}}$	ECM $U = U_5$	EWLR	Wind: EWM ($V = V_5$) Grid loss
		ULS	ESS $H_{\mathrm{s}} = H_{\mathrm{s50}}$	ECM $U = U_5$	NWLR	Ice: $H = H_{50}$
Abnormal (A)	Major fault	ULS	ESS $H_{\mathrm{s}} = H_{\mathrm{s50}}$	NCM $U = U_1$	NWLR	Safety system relevant faults, short circuit, brake failure
	Parked plus occurrence of fault	ULS, FLS	ESS $H_{\mathrm{s}} = H_{\mathrm{s1}}$	ECM $U = U_1$	EWLR	Wind: EWM ($V = V_1$)
	Vessel impact	ULS	NWH $H_{\mathrm{s}} = H_{\mathrm{s,T}}$	NCM $U = U_{\mathrm{T}}$	NWLR	
	Earthquake, tsunami	ULS	NSS + tsunami	NCM $U = U_1$	NWLR	

Design category	Design condition	Limit states	Wave conditions	Current conditions	Water level	Other conditions
	Loss of stability and leakage	ALS	ESS $H_\mathrm{s}=H_\mathrm{s50}$	ECM $U=U_5$	EWLR	Wind: EWM ($V=V_5$)
	Loss of station keeping/loss of line	ALS	ESS $H_\mathrm{s}=H_\mathrm{s50}$	ECM $U=U_5$	EWLR	Wind: EWM ($V=V_5$)
Transport / erection (T)	Transport, installation and maintenance	ULS	To be specified by the manufacturer			
	Maintenance	ULS	ESS $H_\mathrm{s}=H_\mathrm{s1}$	ECM $U=U_1$	NWLR	Locked state

Key

ESS	extreme stochastic sea state
EWM	extreme steady wind model
EWLR	extreme water level range
NCM	normal steady current model
NSS	normal stochastic sea state
NWH	normal steady wave height
NWLR	normal water level range

Table 7 – Design load cases for TEC

Design category	Design condition	Limit states	Current conditions	Wave conditions	Water level	Other conditions
Normal (N)	Normal operation	ULS, FLS, SLS	NTM $U_{\mathrm{in}} \leq U \leq U_{\mathrm{out}}$	NWH $H_{\mathrm{s}} = H_{\mathrm{s1}}$	NWLR	
		ULS, FLS	NCM $U_{\mathrm{in}} \leq U \leq U_{\mathrm{out}}$	no waves	NWLR	Ice/extreme temperatures
	Normal operation plus fault	ULS, SLS	NCM $U_{\mathrm{rated}} \leq U \leq U_{\mathrm{out}}$	NWH $H_{\mathrm{s}} = H_{\mathrm{s1}}$	NWLR	Grid loss, grid failure, fault in controller
	Emergency shut-down procedures	ULS, SLS	NCM $U_{\mathrm{rated}} \leq U \leq U_{\mathrm{out}}$	NWH $H_{\mathrm{s}} = H_{\mathrm{s1}}$	NWLR	
	Start/normal shut-down procedures	ULS, FLS, SLS	NCM $U_{\mathrm{rated}} \leq U \leq U_{\mathrm{out}}$	NWH $H_{\mathrm{s}} = H_{\mathrm{s1}}$	NWLR	
	Parked	ULS, FLS, SLS	NTM $U_{\mathrm{in}} \leq U \leq U_{\mathrm{out}}$	NWH $H_{\mathrm{s}} = H_{\mathrm{s1}}$	NWLR	
Extreme (E)	Parked/survival	ULS, SLS	ETM $U = U_{50}$	EWH $H_{\mathrm{s}} = H_{\mathrm{s5}}$	EWLR	Wind: EWM ($V = V_5$)
		ULS	ETM $U = U_{50}$	EWH $H_{\mathrm{s}} = H_{\mathrm{s5}}$	EWLR	Wind: EWM ($V = V_5$) Grid loss
		ULS	ETM $U = U_5$	-	NWLR	Ice: $H = H_{50}$
Abnormal (A)	Major fault	ULS	NCM $U_{\mathrm{rated}} \leq U \leq U_{\mathrm{out}}$	NWH $H_{\mathrm{s}} = H_{\mathrm{s1}}$	NWLR	Safety system relevant faults, short circuit, brake failure
	Parked plus occurrence of fault	ULS, FLS	ETM $U = U_1$	EWH $H_{\mathrm{s}} = H_{\mathrm{s1}}$	EWLR	Wind: EWM ($V = V_1$)
	Vessel impact	ULS	NCM $U = U_{\mathrm{T}}$	NWH $H_{\mathrm{s}} = H_{\mathrm{sT}}$	NWLR	
	Earthquake, tsunami	ULS	NTM $U = U_{\mathrm{rated}}$	NSS + tsunami	NWLR	

Design category	Design condition	Limit states	Current conditions	Wave conditions	Water level	Other conditions
	Loss of stability and leakage	ALS	ETM $U=U_{50}$	ESS $H_s=H_{s5}$	EWLR	Wind: EWM ($V=V_5$)
	Loss of station keeping/loss of line	ALS	ETM $U=U_{50}$	ESS $H_s=H_{s5}$	EWLR	Wind: EWM ($V=V_5$)
Transport / erection (T)	Transport, installation and maintenance	ULS	To be specified by the manufacturer			
	Maintenance	ULS	ETM $U=U_1$	EWH $H_s=H_{s1}$	NWLR	Locked state

Key

ESS	extreme stochastic sea state
ETM	extreme turbulent current model
EWH	extreme steady wave height
EWM	extreme steady wind model
EWLR	extreme water level range
NCM	normal steady current model
NSS	normal stochastic sea state
NTM	normal turbulent current model
NWH	normal steady wave height
NWLR	normal water level range

7.3.7.2 Normal operation (power production)

In this design condition, the MEC is in operation and connected to the electrical grid. The assumed MEC configuration shall take into account any imbalance of the PTO unit, where relevant. The maximum mass and hydrodynamic imbalances specified for manufacture shall be used in the design calculations.

In addition, deviations from theoretical optimum operating situations, such as yaw misalignment (e.g. for tidal energy converters) and control system delays, shall be taken into account in the analyses of operational loads.

This design condition includes loads resulting from wave loading and hydrodynamic turbulence (currents). Normal sea state (NSS) conditions shall be assumed for WECs and the turbulent current model (NTM) shall be considered for TECs. The significant wave height, peak spectral period and direction for each normal sea state shall be selected, together with the associated mean current speed, based on the long-term joint probability distribution of metocean parameters appropriate to the anticipated site (typically represented with a scatter diagram).

7.3.7.3 Operation plus occurrence of fault or loss of load (electrical network)

Any fault in the control system (including control induced failures that lead to uncontrolled excitations) as well as faults causing trigger of the safety system or any fault in the PTO unit (e.g. generator short circuit in electrical systems) that is significant to the MEC loading shall be assumed to occur during power production. It may be assumed that independent faults do not occur simultaneously. The occurrence of a fault in the control system, which is considered a normal event, shall be analysed. Exceedance of the limiting values of the control system (over-speed, stroke length limitation, etc.) shall be investigated. These faults shall be considered as normal events.

The occurrence of faults causing trigger of the safety system or faults in the PTO that are considered to be rare events shall be analysed. Exceedance of the limiting values for the safety system (over-speed, stroke length limitation, overpower, short circuit, vibrations, shock, runaway of the blade pitch, failure of a braking system, etc.) shall be investigated. These faults shall be considered as abnormal events.

If a fault causes an immediate shut-down or the consequent loading can lead to significant fatigue damage, the probable number of shut-downs and the duration of this extraordinary design situation shall be considered.

7.3.7.4 Start-up

This design condition includes all events resulting in loads on the MEC during the transitions from any standstill or idling situation to power production.

The probable number of start-up procedures at different levels shall be considered. The levels shall be selected based on the long-term joint probability distribution of metocean parameters appropriate to the anticipated site.

7.3.7.5 Normal shut-down

This design condition includes all the events resulting in loads on the MEC during normal transitions from power production to a stand-by condition (standstill or idling).

The probable number of shut-down procedures at different levels shall be considered. The levels shall be selected based on the long-term joint probability distribution of metocean parameters appropriate to the anticipated site.

If applicable, further shut-down procedures shall be taken into account due to site-specific requirements, such as shadow criteria or conditions for installation within a MEC array (curtailment strategy).

7.3.7.6 Emergency shut-down

This design condition covers manual actuation of the emergency pushbutton. For this load case, the PTO unit shall be brought to a standstill (or idling in case of MECs without braking devices). The probable number of emergency shut-down procedures shall be considered for different operational levels. The levels shall be selected based on the long-term joint probability distribution of metocean parameters appropriate to the anticipated site. The maximum level to be considered is the limiting condition for maintenance.

7.3.7.7 Parked (normal)

For this design condition, the PTO unit is in stand-by mode (standstill or idling) in normal environmental conditions.

Irregular sea state conditions shall be assumed. The significant wave height, peak spectral period and direction for each normal sea state shall be selected, together with the associated mean current speed, based on the long-term joint probability distribution of metocean parameters appropriate to the anticipated site. The designer shall ensure that the number and resolution of the normal sea states considered are sufficient to account for fatigue damage associated with the long-term distribution of metocean parameters.

7.3.7.8 Parked/survival (extreme)

For this design condition, the PTO is in standstill or idling mode. For some designs, the MEC may be operational and connected to the electrical grid. Extreme environmental conditions with a recurrence period of at least 50 years shall be considered for this design condition.

Either the steady current model or the turbulent current model shall be used. If the turbulent current model is used, the response shall be estimated using a full dynamic simulation. If the steady current model is used, the response shall be estimated from a quasi-steady analysis with appropriate corrections for dynamic response.

Additionally, either regular waves or irregular sea state shall be considered. If a stochastic sea state is considered, the response shall be estimated using a full dynamic simulation. If regular waves are used, the response shall be estimated from a quasi-steady analysis with appropriate corrections for dynamic response.

The 50-year recurrence value of the significant wave height for WECs and the 50-year recurrence value of the mean current speed for the TECs shall be considered. The recurrence value is a measure of the probability that a given event will be equaled or exceeded in any given year.

Note that hurricanes observe a different distribution function of extremes when compared to conventional storms caused by fronts and depressions. In areas where hurricanes may occur, two sets of extreme conditions shall be derived.

7.3.7.9 Parked/idling plus fault conditions

This design condition considers the non-stand-by state (standstill or idling) resulting from the occurrence of a fault. Deviations from the normal behaviour of a parked MEC, resulting from faults in the PTO unit, shall require analysis. If any fault produces deviations from the normal behaviour of the MEC in parked situations, the possible consequences shall be considered.

The fault condition shall be combined with extreme environmental conditions and a recurrence period of 50 years.

If a grid failure with duration of up to one week may occur and no backup energy system or redundant electricity supply is provided, the behaviour of mechanical brakes and the safety system shall be considered in the load assumptions.

Either the steady or turbulent current model shall be used for design situations. If the turbulent current model is used, the response shall be estimated using a full dynamic simulation. If the steady current model is used, the response shall be estimated from a quasi-steady analysis with appropriate corrections for dynamic response.

Additionally, either regular waves or irregular sea state shall be considered. If irregular sea state is considered, the response shall be estimated using a full dynamic simulation. If the regular waves are used, the response shall be estimated from a quasi-steady analysis with appropriate corrections for dynamic response.

The 50-year recurrence value of the significant wave height for WECs and the 50-year recurrence value of the mean current speed for TECs shall be considered.

7.3.7.10 Vessel impact

Both impacts from maintenance vessels and more severe impacts may occur from vessels passing the area of an MEC array shall be considered.

7.3.7.11 Loss of stability, watertight integrity, leakage

The suitable standards (such as IMO International Code on Intact Stability) that cover stability and watertight integrity can be used as a guide by applying it as far as applicable to a MEC. When the device is manned these considerations are particularly important.

Temporary phases such as transportation to site, cofferdams used for access, installation or removal may require a marine operations assessment (using guidelines for ships or offshore structures). Minimum design requirements for watertight integrity, strength of the device, closing devices for access hatches or openings, bilge and ballast systems, ventilation arrangements shall be considered.

For floating MECs, the buoyancy, stability and behaviour during the various transportation, ballasting and trimming operations shall be analysed. Compartmental flooding and survivability shall be considered.

7.3.7.12 Loss of station keeping

For MECs that are held in position by mooring systems, the situation after loss of station-keeping shall be considered. The loss of one or more mooring lines shall be analysed, depending on the redundancy of the mooring system. The situation shall be combined with extreme environmental conditions with a recurrence period of 50 years.

7.3.7.13 Earthquake, tsunami

The loading caused by sub-sea earthquakes shall be taken into account in regions at risk of seismic activities. The investigation of earthquake-generated loads is based on the combination of the current and wave loads and earthquake acceleration with a recurrence period of 500 years.

The loading caused by earthquakes shall be combined with normal external conditions. All relevant load cases shall be taken into account.

Tsunami-type waves resulting from sub-sea earthquakes may have to be considered in particular cases. It will be decided from case to case, depending on the probability of occurrence, whether a tsunami and the resulting loading have to be considered in connection with the design earthquake, or as an accidental load.

7.3.7.14 Transport/installation/maintenance

The manufacturer shall state all the environmental conditions and design situations assumed for transport, installation and maintenance of the MEC, and especially up to which maximum average current speed, significant wave height and oblique inflow the MEC may be installed and maintained. The maximum current speed and/or the significant wave height specified by the manufacturer shall apply for active work on the MEC. If the environmental conditions exceed the specified limiting values, the work shall be halted.

In the case of maintenance, particular consideration shall be given to the effect of the various locking devices and the maintenance position that may have been adopted. Verification of standstill without the PTO unit lock activated shall be provided up to a defined oblique inflow and/or a defined significant wave height.

In addition, the situation shall be taken into account that the MEC has to be abandoned in the locked condition. For this design condition, environmental conditions with a recurrence period of one year shall be considered.

Long periods where the MEC is not fully installed or is without grid connection shall be considered in fatigue and ultimate load analysis. Although the period to be considered shall be case-specific, a period of 3 months may be used as a guide.

An operational boat impact may arise during operation of vessels in the vicinity. An impact with the dedicated maintenance/installation boat shall be considered. The size of the maintenance vessel (displacement) shall be stated by the operator or designer of the project.

The maximum permissible significant wave height and/or current speed for vessel operations near the MEC installation shall be stated in the Operation and Maintenance (O and M) manual. Any areas where vessels are not permitted to operate in close proximity shall also be specified in the O and M manual.

Functional loads occurring during installation and maintenance of the MEC shall be considered. These may be:

- weight of tools and mobile equipment;
- loads from operation of cranes and other conveyance equipment;
- loads from transport operations, for example helicopter; and
- mooring/fendering loads from vessels serving the MEC.

The operator or designer shall specify all functional loads, weight of tools and equipment. The specifications shall also contain indications regarding permissible load combinations and limitations. Any such limitations shall be stated in the O and M manual.

7.3.7.15 Ice

Refer to ISO 19906:2010, A.6.4.2 for guidance on design for ice conditions.

8 Materials

8.1 General

There are many factors that influence material selection for MECs. Consideration shall be given to:

- component shape;
- dimensional tolerances required;
- mechanical properties (static, dynamic and fatigue strength and stiffness);

- corrosion properties (temperature, seawater properties, surfaced, submerged, depth, etc.);
- effect of combining material systems; and
- life-cycle cost (e.g. cost of material, cost of manufacture, cost of maintenance and cost of installation and removal).

None of these factors shall be viewed in isolation as there is a complex interaction between them. Primary consideration shall address the manufacturing process proposed for candidate material systems.

8.2 Material selection criteria

Only suitable materials with documented mechanical properties shall be used for the force- and moment-transmitting components of a MEC. Materials chosen shall be matched to the demands to be made on the device, particularly the type of load (i.e. static, shock, or oscillating), environmental conditions and component geometry. Clause 9 addresses “partial factors for material” that shall be applied in the LRFD method to account for uncertainties of material physical properties.

Required design analyses and material tests shall be specified by the MEC certification body. The type and extent of material testing depends on the importance of and stress on a component and on the variability associated with the manufacturing process.

A material with suitable fracture toughness for the actual design temperature and thickness shall be selected. Fracture toughness is dependent on temperature and material thickness. For metals, fracture toughness in the weld and the heat-affected zone is also very dependent on the welding procedure.

Cyclic wave or machinery loads can induce mechanical vibrations that can lead to early failure. The ability of structural material systems to passively mitigate structural vibration (damping characteristics) shall be considered.

The corrosion resistance, density, coefficient of thermal expansion, thermal conductivity, electrical resistivity, and magnetic properties of candidate materials systems shall be considered based on their importance to the device design and operation. When combining dissimilar materials within a structure, special attention shall be paid to the compatibility of physical properties (especially thermal expansion and galvanic potential).

The friction coefficient against support, clamps etc. (both first movements and after a large number of cycles) shall be considered. Wear resistance is a property of the entire wear system and shall be measured for the entire system. Friction coefficient values shall be measured in the relevant temperature range and environment. Consideration shall be given to surface roughness, surface finish and the presence of any substance that may act to cause the actual friction coefficient to differ from the ‘dry’ friction coefficient.

The fatigue strength, crack initiation and growth, effects of loading rate, frequency (e.g., low cycle, high cycle), mean stress, notch effects, biaxial effects, crack initiation and creep crack growth of materials considered for MEC construction shall be considered.

For metallic materials, the most important tools in defining the fatigue capacity of a structure are the S-N curves that give the number of cycles until damage occurs at given dynamic stress levels. S-N curves for the parent material and welded structural details shall be used to ensure that the dynamic stress level is below the given limit for the anticipated fatigue life of the device. The use of higher-strength materials to reduce weight increases static and dynamic stress levels, thus a structure may be more susceptible to fatigue loading.

When selecting composite materials, design for cyclic loads shall consider reduction of elastic properties as a result of matrix cracking. The design of composite components and development of device failure mode, effects and criticality analysis (FMECA) shall consider failure modes that may not be apparent using only visual inspection.

Long-term material properties are affected by environmental exposure conditions. Long-term data (especially temperature) shall be obtained for the environment and exposure conditions the material is to be used in.

Material selection shall take into account the fact that permanent static loads may cause creep (plastic deformation with time), stress rupture, static strength reduction, or stress relaxation (accompanied by a reduction of the elastic modulus).

Maritime structures can experience accelerated wear when subjected to the effects of cavitation or erosion. Small-scale test procedures to quantify cavitation have proven to be problematic. Therefore, evaluation of material cavitation and erosion resistance shall rely on empirical performance data or full-scale testing.

8.3 Environmental considerations

The environmental impact of long-term deployment shall be considered when selecting MEC material systems. These include hydrolytic resistance and ultra violet radiation susceptibility. Empirical data or accelerated test methods shall be used to characterize materials.

Structural materials above the lowest waterline shall be selected based on service temperatures equal to the lowest daily mean temperature for the area where the unit is to operate. External structures below the lowest waterline need not be designed for service temperatures lower than 0 °C (32 °F). A higher service temperature may be accepted if adequate supporting data can be presented relative to the lowest average temperature applicable to the relevant actual water depths.

In general, materials that have shown to be benign in a marine environment shall be selected for deployed devices. When hazardous materials shall be used, a hazard risk assessment and mitigation plan shall be developed. Substances that biomagnify up the aquatic food chain shall be avoided. These include heavy metals, such as cadmium, mercury, lead and polychlorinated biphenyls (PCBs).

Consideration shall be given to the possible detrimental environmental consequences should the device experience catastrophic failure at sea. This includes both material components that sink and those that remain at the ocean’s surface.

8.4 Structural materials

8.4.1 General

Structural materials are defined as the materials used to fabricate the device’s primary structure and foundation. Materials used for secondary structure, such as equipment foundations and mechanical elements are also covered by this subclause.

8.4.2 Metals

8.4.2.1 General

The primary metal used for offshore structures is carbon steel, although stainless steel may be used in oxygenated environments and aluminum for weight-critical applications. Other non-ferrous metals may be suitable for device components.

8.4.2.2 Carbon steel

Selection of steel shall be based on design temperature (normally based on lowest daily mean temperature), structural categories (floating units or bottom fixed units) and plate thickness.

ISO 19902 specifies methodologies for classification of steel properties and requirements for inspection and testing during fabrication.

The essential requirements for carbon (structural) steel are strength, toughness and weldability. Strength shall be determined by tensile testing of specimens and the toughness shall be determined by fracture toughness testing.

Fabrication and welding of steel members shall be carefully qualified through non-destructive testing (NDT), mechanical tests and welder qualification procedures. Test specimens shall reflect the production weld procedure, including weld orientation.

8.4.2.3 Stainless steel

Stainless steels generally exhibit outstanding corrosion resistance but can be subject to corrosion under certain environmental conditions. Strength and corrosion performance varies for different types of stainless steel and heat treatments. Consideration shall also be given to the risk of galvanic corrosion of adjacent materials, particularly carbon steel and aluminum.

NOTE 1 Corrosion resistance can be adversely affected if the component is used in a non-oxygenated environment.

NOTE 2 Stainless steel passivation unipotentializes the stainless steel with the oxygen absorbed by the metal surface, creating a monomolecular oxide film that enhances corrosion resistance.

8.4.2.4 Aluminum

Only aluminum alloys that are suited to the marine environment shall be used. Proper processing and suitable corrosion protection shall be applied in order to prevent contact corrosion. Stress corrosion cracking shall be minimized by using plate with greater than 3 % manganese (except in high heat applications).

Special attention to joint details, filler materials, weld procedures and post-weld heat treatment is required when welding aluminum alloys.

Consideration shall be given to aluminum anodizing, an electrochemical process that provides a durable corrosion resistant, anodic oxide finish.

8.4.3 Concrete

In a hostile environment such as seawater, special attention shall be paid to ensure the long-term durability of concrete structures. Concrete durability is dependent on using appropriate materials and design considerations. In particular, designs shall consider the likelihood of crack propagation occurring when members are in service.

The composition and processing of concrete shall be in accordance with ISO 19903. The desired material compressive strength shall always be specified. In addition, tensile strength, modulus of elasticity and fracture energy shall also be specified if the structure is subject to these types of loads.

Floating concrete structures require the use of lightweight aggregate that results in a material 20 % less dense than normal concrete.

All embedded metal reinforcement shall be covered by a minimum of 50 mm of concrete.

8.4.4 Composites

8.4.4.1 General

Composite materials are sometines referred to as fibre-reinforced plastics, or FRP. These heterogeneous materials contain fibrous reinforcement materials that are encapsulated in either a thermoset (reaction cured) or thermoplastic (solidified upon cooling) resin system. The architecture and orientation of reinforcing materials shall be selected to resist anticipated loading. Process parameters influence material mechanical properties and shall be considered in conjunction with material selection.

Composite strength degrades with moisture absorption. The designer shall consider sealing laminates to avoid moisture intake and appropriate design margin to account for this effect.

8.4.4.2 Laminates

Laminates shall be specified by designating each ply by type and orientation in the stack, as well as resin system and fibre volume. Thermoplastic resin systems shall be selected and tested as required for thermoset resin systems, with a particular emphasis placed on elevated temperature and creep performance. The mechanical material properties needed for design shall be obtained using the ISO test standards shown in Table 8. Test specimens shall reflect the “as-built” composite component.

Table 8 – ISO test standards

ISO Standard	Description
ISO 527-1	Plastics – Determination of tensile properties – Part 1: General principles
ISO 13003	Fibre-reinforced plastics – Determination of fatigue properties under cyclic loading conditions
ISO 14126	Fibre-reinforced plastic composites – Determination of compressive properties in the in-plane direction
ISO 14125	Fibre-reinforced plastic composites – Determination of flexural properties
ISO 14129	Fibre-reinforced plastic composites – Determination of the in-plane shear stress/shear strain response, including the in-plane shear modulus and strength, by the ±45° tension test method
ISO 14130	Fibre-reinforced plastic composites – Determination of apparent interlaminar shear strength by short-beam method
ISO 15024	Fibre-reinforced plastic composites – Determination of mode I interlaminar fracture toughness, G_{IC}, for unidirectionally reinforced materials

The following three types of properties are relevant in the design:

- static properties;
- properties under constant permanent static loads or deformations; and
- properties under cyclic loads or deformations.

Due consideration shall be given to take into account the effect of environment on properties. The combination of water and high temperature may be more critical than the individual effects of temperature and water.

8.4.4.3 Sandwich structures

A sandwich structure is made up of a lightweight core embedded between two faces (or skins). Faces are typically made of two FRP laminates. Sandwich laminates are very efficient for resisting out-of-plane loads, such as hydrostatic and hydrodynamic forces. However, sandwich laminates have more failure modes than solid laminates and these failures may be more difficult to detect with visual inspection. Good skin-to-core bonds and maintenance of watertight integrity shall be verified with manufacturing quality assurance documentation.

8.4.4.4 Mechanical and physical properties

a) Static properties

The static properties after exposure to long term loads and environment may be more representative of the design strength than the static properties of a new material. Static properties are generally assumed to be identical to quasi-static properties, measured at a testing strain rate of about 1 % per minute. If loading rates in the component differ from this rate, tests shall be made at the relevant rates or corrections of the data shall be considered.

b) Properties under long term static and cyclic and high rate loads

Creep behaviour of the composite sandwich structure, stress rupture under permanent static loads, static strength reduction due to permanent static loads, stress relaxation, change of modulus of elasticity under cyclic loads, cycles to failure under fatigue loads, static strength reduction due to cyclic loading, and effect of high loading rates due to shock loads/impact shall be documented if relevant to the application.

c) Other properties including thermal expansion coefficient, swelling coefficient for water or other liquids, diffusion coefficient, thermal conductivity, friction coefficient, wear resistance and the associated effects shall be considered as applicable.

d) Influence of the environment on properties

Due consideration shall be given to take into account the effect of environment on laminates and core materials. The fibre/matrix interface can have an important influence on the environmental resistance. The interface properties are influenced by the type of fibre, the sizing, the matrix, and the processing conditions.

The effects of the following shall be considered:

- temperature;
- water;
- chemicals; and
- UV radiation.

e) Influence of process parameters

Changes to the process parameters in the production of composite laminates may influence some or all material parameters. A re-qualification of the materials data shall be done if the production process is not similar to the original process.

8.5 Compatibility of materials

When different structural materials are used in combination, attention shall be given to isolate materials that may create electrolytic corrosion, such as dissimilar metals (even of the same alloy). Particular care shall be taken when small components can act as anodes in conjunction with surrounding dissimilar materials. Careful attention shall also be paid to matching material strain characteristics and thermal expansion coefficients.

9 Design of primary structures for wave and tidal/current energy converters

9.1 General

Clause 9 provides principles, technical requirements and guidance for design of primary MEC structures for MECs and shall be used in conjunction with the normative references in Clause 2.

The structural behaviour of MEC components shall be investigated for construction, handling, transportation, and erection as well as during the service life of the structure.

9.2 Design of steel structures

9.2.1 General

The ultimate strength capacity of structural elements in yielding and buckling shall be assessed using a rational and justifiable approach. The structural capacity of all structural components shall be checked considering both excessive yielding and buckling.

9.2.2 Load and resistance factor design (LRFD)

The LRFD method explicitly incorporates the effects of random variability of both strength and loads. The target safety level is based on loads acting on the structure and resistance of the structure or resistance of the materials in the structure.

The LRFD method is based on the concept that the design load (F_d) does not exceed the design resistance (R_d):

$$F_\mathrm{d} \le R_\mathrm{d} \tag{10}$$

The design resistance R_d is determined as follows:

$$R_\mathrm{d} = \Phi\, R_\mathrm{k} \tag{11}$$

where:

R_k is the characteristic resistance;

Φ is the resistance factor.

The resistance factor relates to the material factor γ_M as follows:

$$\Phi = \frac{1}{\gamma_\mathrm{M}} \tag{12}$$

where:

γ_M is the material factor.

The material factor γ_M for plated and tubular structures is 1,10. Table 9 gives material factors for buckling of shell structures.

Table 9 – Material factors γ_M for buckling

Type of structure	$\lambda \le 0{,}5$	$0{,}5 < \lambda < 1{,}0$	$\lambda \ge 1{,}0$
Girder, beams stiffeners on shells	1,10	1,10	1,10
Shells of single curvature (cylindrical shells, conical shells)	1,10	0,80 + 0,60λ	1,40
λ =	reduced slenderness parameter $\sqrt{\frac{f_\mathrm{y}}{f_\mathrm{E}}}$		
f_y =	specified minimum yield stress		
f_E =	elastic buckling stress for the buckling mode under consideration		
NOTE The slenderness is based on the buckling mode under consideration.			

A partial resistance factor is applied to the strength of each member, joint, and foundation component to determine its design resistance. Each component shall be proportioned to resist the internal forces, R.

9.2.3 Ultimate limit state

Structural capacity checks of structural components shall consider both excessive yielding and buckling. The structural analysis may be carried out as linear elastic, simplified rigid-plastic, or elastic-plastic analyses. Either first order or second order analyses may be applied.

a) Ductility

   It is a fundamental requirement that all failure modes are sufficiently ductile such that the structural behaviour will be in accordance with the anticipated model used for determination of the responses. Brittle failure modes shall, therefore, be avoided or shall be verified to have excess resistance compared to ductile modes.

b) Shell structures

   The buckling stability of cylindrical and un-stiffened conical shell structures and the interaction between shell buckling and column buckling shall be designed in accordance with ISO 19902.

c) Tubular members, tubular joints and conical transitions

   Checking of tubular members and interaction between local shell buckling and column buckling, and effect of external pressure shall be based on guidance provided in ISO 19902. Cross-sections of tubular members are characterized by their ability to develop plastic hinges and resist local buckling. Guidance is available in ISO 19902:2007, Clauses 13, 14, A.13 and A.14.

9.2.4 Fatigue limit state

Fatigue assessment shall be based on stress/cycle (*S-N)* data, determined by fatigue testing of the relevant welded detail, and the linear damage hypothesis. Fracture mechanics may be used for fatigue analyses as supplement to *S-N* data. Fracture mechanics may be used in the assessment of acceptable defects, evaluation of acceptance criteria for fabrication and for planning in-service inspection. Data for seawater environment shall be used for calculation of crack growth based on fracture mechanics. Fatigue assessment shall be conducted for welded joints and other forms of stress concentration as per ISO 19902.

Design fatigue factors (DFF) shall be applied to the design fatigue life to increase the probability for avoiding fatigue failure. The DFFs are dependent on the significance of the structural components with respect to structural integrity, availability for inspection and repair, and failure consequences

9.2.5 Serviceability limit state

The serviceability limit state shall be considered to ensure design compliance. Attention shall be paid to accelerations, displacements and distortions that may affect the operational performance of equipment and systems or may result in damage to coating and painting.

9.3 Design of concrete structures

9.3.1 General

The design of concrete structures shall be performed in accordance with ISO 19903, covering all aspects relevant to MEC primary structure. The safety methodology shall include the exposure levels, life safety category of structure, and consequence of failure. An exposure level consistent with an unmanned structure may be considered, assuming the consequence of failure to be medium for the concrete structure based on FMEA results. The requirements for the design of structures with such exposure levels are similar to the design of unmanned offshore concrete structure based on environmental and functional loads, including accidental loads and consideration of the high consequence of failure.

The design of concrete support structures shall be performed according to limit state design and the design shall provide adequate strength in all design conditions.

9.3.2 Limit states

The partial factors for material shall be such that a safety level consistent with that presented in ISO 19900 and ISO 19903 is obtained.

9.3.3 Bending moment and axial force

The ULS capacity for bending moment and axial force shall be determined by applying plastic design analysis techniques. The average calculated compressive strain over the cross-section shall not exceed established limits.

The definition of variables, calculation methodologies and formulae regarding bending moment and axial force capacity under various reinforcement scenarios shall follow the guidance provided in ISO 19903.

9.3.4 Slender structural members

As per ISO 19903, non-linear behaviour shall be considered in structural analysis where slender members are in compression and deflections can cause significant action effects (imperfection bending or buckling).

The compressive force in slender compression members shall be assumed to have an unintended eccentricity calculated in accordance with specified tolerances for curvature and inclination for the individual members.

Lateral buckling or torsional buckling of slender beams and columns due to torsional displacements shall be accounted for accordingly.

9.3.5 Transverse shear

The design shall be based on a combination of simultaneous action of transverse shear and in-plane forces on the structural component. In members like shells, plates and slabs, the interaction of in-plane forces shall be included.

9.3.6 Torsional moments

The capacity to resist torsional moments shall be checked for tensile and compression failure. If the load transfer in the ultimate limit state is not dependent on the torsional capacity, the design can normally be performed without considering torsional moments.

Torsional reinforcements shall be provided as required for torsional moments in combination with shear forces or axial forces. For torsional moments in combination with bending moments, axial force or shear force, the required reinforcement may be calculated as the sum of required reinforcement for each force.

9.3.7 Bond strength and anchorage failure

Design for resistance against bond and anchorage failure shall be done in accordance with ISO 19903, including rules for required lap length, bundled reinforcement bar and welded wire fabric development length, and pre-stressed reinforcement.

Post tensioning anchorages shall be designed for the ultimate strength of the tendon. Reinforcement is to be provided, where required, to prevent bursting or splitting.

9.3.8 Fatigue limit state

The design for fatigue for all possible failure modes shall include concrete in compression/compression or compression/tension, transverse shear considering both shear tension and shear compression, reinforcement considering both main bars and stirrups including bond failure, and pre-stressing reinforcement.

Fatigue design may alternatively be undertaken utilizing methods based on fatigue tests and cumulative damage analysis, methods based on fracture mechanics, or a combination of these.

For structures subject to multiple stress cycles, it shall be demonstrated that the structure will endure the expected stresses during the required design life. Calculation of design life at varying stress amplitudes can be based with cumulative linear damage theory.

9.3.9 Serviceability limit state

The serviceability limit state shall consider properties of the materials under short- and long-term actions and the effect of shrinkage, temperature and imposed displacements.

9.3.10 Stresses in pre-stressed reinforcement

The stresses in the pre-stressed reinforcement shall not exceed 0,8 f_y for any combination of actions, where f_y is the specified minimum yield stress. During pre-stressing, however, stresses up to 0,8 f_y may be permitted provided it is documented that this does not harm the steel, and if the prestressing force is measured directly.

9.3.11 Stresses in concrete

When a pre-stressing force acts within a concrete compression zone, the stress at the outer compressive fibres of the concrete shall not exceed the lesser of 0,6 f_{ckj} or 0,5 f_{ck} in the serviceability limit state, where f_{ckj} is the characteristic cylinder strength for cylinders with height/diameter ratio 2:1 and f_{ck} is the characteristic concrete compressive strength.

9.3.12 Detailing of reinforcement

Positioning and arrangement of ribbed bars, welded wire fabric, shear reinforcement, ducts for pre-stressed reinforcement, concreting, minimum concrete cover, splicing of reinforcements, bending of bars, and minimum area of reinforcement shall be as per ISO 19903.

9.3.13 Corrosion control

Annex C presents detailed descriptions of corrosion protection of steel, concrete and composite structures. According to 8.4.3, all embedded metal reinforcement shall be covered by a minimum of 50 mm of concrete.

9.4 Design of grouted connections

9.4.1 General

Guidelines in ISO 19903 are applicable to grouted tubular connections and grouted conical connections in monopile support structures.

9.4.2 Design principles

ISO 19903 shall be followed in designing a grouted connection with or without shear keys. Shear keys can reduce the fatigue strength of the tubular members and of the grout due to the stress concentrations around the shear keys. Guidance is given to determine the design axial force, interface transfer stress, static capacity of grouted connections, and evaluate the effect of combined loading, interface transfer strength and fatigue assessment. The design rules for grouted connections in ISO 19903 shall be followed for axial loading combined with torque and for bending moment combined with shear loading.

9.5 Design of composite structures

9.5.1 General

Subclause 9.5 provides specifications for design, materials, fabrication and installation of load-carrying Fibre Reinforced Plastic (FRP) laminates, including sandwich structures and components.

9.5.2 Design principles

9.5.2.1 General

Composite structure shall be designed using the limit state design method.

The basic approach of the limit state design method consists of recognizing the different failure modes related to each functional requirement and associating to each mode of failure a specific limit state beyond which the structure no longer satisfies the functional requirement. Different limit states shall be considered, each limit state being related to the kind of failure mode and its anticipated consequences.

Design failure modes shall consider all possible failure mechanisms at the material, laminate and structure level. Design equations shall be formulated using the LRFD format, where partial safety factors (load factors and resistance factors) are applied to the load effects (characteristic load values) and to the resistance variables (characteristic resistance values) in the design computations.

Structures or structural components shall be designed with different structural safety requirements, depending on the safety level to which the structure or part of the structure belongs. Safety levels are based on the consequence of failures related to the Ultimate Limit State (ULS). As an alternative to design according to the LRFD format Structural Reliability Analysis (SRA) may be used providing that an equivalent safety level is achieved. The target reliability shall be based on the limit state category, the failure type and the safety level.

9.5.2.2 Limit states

Ultimate limit state (ULS) and serviceability limit state (SLS) shall be considered in the design composite structure.

9.5.2.3 Design by LRFD method

The design by LRFD method shall be based on ISO 2394. Load factors shall include direct and indirect loads (e.g. wave load on a structure, functional load, and accidental loads). The environment shall be taken to ambient temperature or moisture that may cause degradation of material strength. Resistance factors shall take into account manufacturing variability and associated material characterization uncertainties.

9.5.2.4 Combination of load effects and environment

The combination and severity of load effects and or environmental conditions shall be determined taking into account the probability of their simultaneous occurrence. Permanent load effects and permanent environmental conditions shall be taken into consideration in all combinations of load effects and environmental conditions.

The following load effect and environmental conditions shall be considered:

- load effects and environmental conditions for ultimate limit state;
- load effects and environmental conditions for time-dependent material properties; and
- load effects and environmental conditions for fatigue analysis.

9.5.2.5 Load effect and environmental conditions for ultimate limit state

The combination of characteristic load effects and environment shall be determined such that the combined characteristic effect has a recurrence period of 50 years. When several stochastic load effect and or environmental conditions occur simultaneously, the most unfavorable combination shall govern the ultimate limit state.

9.5.2.6 Load effect and environmental conditions for time-dependent material properties

The sustained load effect values or the fatigue load effect values (if relevant) and the sustained environmental values shall be used for the time-dependent material properties.

9.5.2.7 Load effect and environmental conditions for fatigue analysis

All load effect fluctuations imposed during the entire design life shall be taken into account when determining the long-term distribution of stress or strain ranges. The fatigue load effects shall be combined with the sustained environmental values for the fatigue analysis.

9.5.2.8 Direct combination of loads

The combination of load effects and environmental conditions shall be used. If transfer functions and structural analysis are linear, loads or moments can be combined.

9.5.2.9 Safety, model and system factors

The safety provisions based on consequences of failure and service classes (frequency of service interruptions or restrictions caused by service limit state (SLS) modes of failure) shall be based on the safety methodology for the device and types of failure. The selection of partial safety (model and system) factors shall be based on selected safety level.

Partial load effect factors, γ_F shall be applicable to the characteristic values of the local response of the structure. The uncertainties in the local response are associated with the uncertainties on the loads applied to the structure through the transfer function.

Partial resistance factors, γ_M account for uncertainties associated with the variability of the strength. The combined load effect and resistance factor, γ_{FM} may be taken as the product of γ_F and γ_M. The safety factor γ_{FM} depends on the following:

- target reliability level, expressed in terms of annual probability of failure;
- characteristic values for load effects and resistance; and
- type of distribution function for load effects and resistance.

The partial load effect and resistance factor $\gamma_{FM} = \gamma_F \times \gamma_M$ and may be calibrated against different target reliabilities. The target reliabilities shall correspond to annual probabilities of failure.

The required target reliability level depends on the following:

- the limit state (ULS or SLS);
- the safety level; and
- the failure type (brittle, plastic or ductile).

The target safety levels shall be selected as per Clause 5. A simplified set of partial safety factors may be used whenever a satisfactory probabilistic representation of the load effects is not available.

Load model factors, γ_{Sd} shall account for uncertainties and inaccuracies in the transfer function, the analysis methods and dynamic effects.

Resistance model factors, γ_{Rd} shall account for differences between true and predicted resistance values given by the failure criterion. A summary of typical model factors is given in Table 10.

Table 10 – Summary of model factors

Failure criteria	Model factors γ_{Rd}
Fibre failure	1,0
Matrix cracking	1,0 to 1,15
Delamination	1,0 to 2,0
Yielding	1,0
Ultimate failure of orthotropic homogeneous materials	1,25
Displacements	1,0
Stress rupture	0,1 to1,0
Fatigue	0,1 to1,0

A system effect factor, γ_{S} is given for the entire system. Depending on how the components are connected to form a system, the target probability of failure for individual components may need to be lower than the target probability of failure of the entire system. If the system effect is not relevant, γ_{S} = 1,0. A value of γ_{S} = 1,10 can be used as a first approach. In certain cases, a system may consist of parallel components that may support each other and provide redundancy, even if one component fails. In this instance, a system factor smaller than 1 may be used if it is based on a rigorous structural reliability analysis.

9.5.3 Joints and interfaces

Structural requirements for composite material joints and interfaces are based on achieving the same level of reliability as the structure. If metal components are part of a joint or interface, the metal components shall be designed to be compatible with the composite structure.

Joints are load-bearing connections between structures, components or parts. The following three basic types of joints shall be considered:

- Laminated joints are joints fabricated from the same constituent materials as the laminates that are joined, such as over-laminations, lap joints, and scarf joints. These joints can use either primary or secondary bonds.
- Adhesive joints are joints between laminates, cores or between laminates and other materials for example metals that utilize a specialty adhesive matrix.
- Mechanical joints use fasteners and bolted connections.

Material selection and fabrication environment critically affect the durability of structural joints. The effects of time, thermal stresses, fatigue and long-term creep shall be considered for all joints and interfaces.

10 Electrical, mechanical, instrumentation and control systems

10.1 Overview

The electrical, mechanical, instrumentation and control systems of a MEC include all equipment installed in each device up to and including the MEC point of common connection with the grid. The designer shall consider failures in the electrical, mechanical, instrumentation and control systems that can have critical impacts on the integrity of the MEC primary structure.

10.2 General requirements

Faults, as well as normal operation, can influence loading on the primary structure and give resonant response of both structural and mechanical elements (both passively and actively).

Therefore, the designer shall carry out a FMECA for the electrical, mechanical, instrumentation and control systems to ensure that none of the failure modes can critically increase the resonant response of the structural, mechanical or electrical elements (see 5.9).

The impact of the electrical, mechanical, instrumentation and control systems upon the loading of the primary structure when positioning the control system elements shall be addressed.

The electrical, mechanical, instrumentation and control systems of a MEC and every component such as converters, controllers, generators, transformers and cables shall comply with applicable regional regulations. The design of the electrical system shall take into account the fluctuating nature of power generation from MECs and effects of the marine environment, such as humidity, corrosion, bio-fouling, motion and inclination.

The lightning protection of a surface piercing or floating MEC shall be designed in accordance with IEC 62305-3. All MEC protection system circuits that could possibly be affected by lightning and other transient overvoltage conditions shall be protected according to IEC 61643-11.

Any part of the electrical system that can excite the MEC generator shall automatically be disconnected from the grid and remain safely disconnected in the event of loss of power at the MEC, subject to local grid requirements.

Isolation from all sources of supply will be particularly important when using permanent magnet or other types of generator capable of self-excitation, and where work or testing on the device, subsea cable system or connectors is likely to require electrical isolation from the generator as well as from the shore supply. Isolation requirements shall be considered at the design stage. If remotely operated equipment is selected for isolation purposes, it will require careful design to ensure firstly that it can be confirmed that the remote equipment has operated correctly to provide isolation and secondly that the equipment can be secured in the isolated position.

10.3 Abnormal operating conditions safeguard

The MECs control methodology requirements shall be summarized in a functional design specification that describes the objectives and attributes of the electrical, mechanical, instrumentation and control systems in terms of functional capability at locations (on-board, electrical substation, control centre, etc.).

Within the functional design specification, the designer shall demonstrate that all necessary precautions have been taken to prevent the MEC transitioning into an abnormal condition or state due to conditions such as, but not limited to:

- loss of the control system;
- electrical and/or mechanical component failure;
- loss of communication with the device;
- loss of load; and
- over-speed.

If an abnormal condition or state occurs, the MEC electrical, mechanical and control system shall transition to an offline safe condition or state.

The primary structure shall be designed for loads arising from such abnormal conditions.

11 Mooring and foundation considerations

11.1 Overview

11.1.1 General

Clause 11 includes additional requirements for the consideration of station keeping of major structural elements of MECs, including the design of the geotechnical interface.

The design of moorings and foundations for MECs has unique challenges over conventional offshore structures and these shall be considered to ensure the appropriate design and mechanical integrity of such structures. In particular, there are unique technical challenges that depend on the type of MEC being considered. In many cases, established mooring and foundation methods for conventional marine structures are not appropriate.

11.1.2 Unique challenges for wave energy converters

a) Wave-induced response

Wave energy converters may have structures designed to amplify wave loads and induce a motion response to absorb energy from the prevailing wave climate. This structural loading and motion response shall be resisted by the foundation and moorings systems in extreme wave conditions.

b) Shallow deployment sites exposed to ocean wave climates

For economic power export, WECs are deployed close to the market for energy, usually meaning structures are deployed in water depths within the range 15 m to 100 m. As such, the applicability of deep-water assumptions (λ/d > 0,5) does not often apply for extreme waves. Such waves can have amplified horizontal water particle excursions and non-linear phenomena including wave breaking are more prevalent.

Designing mooring systems to comply with ever-larger horizontal excursions induced by shallow water extreme waves is difficult owing to the small vertical spans available in relatively shallow-water tether mooring systems to accommodate such compliance.

In shallow water, there is significant wave-induced hydrodynamic shear at the seabed with the consequent effect of:

- loading on seabed foundation structures; this is especially the case for low-density gravity base structures (e.g. self-installing gravity base structures), where such large volume structures can attract significant wave loading on the foundation itself;
- lack of stable sediment accumulations for drag embedded anchors owing to seabed scour; and
- severe scouring of the seabed and undermining of foundations.

11.1.3 Unique challenges for tidal energy converters

Where TECs are deployed in tidal streams exposed to ocean waves, similar issues to those described above for wave energy converters apply, especially for floating installations. The issues of lack of seabed sediment due to strong currents exist, as sediments can be mobilized and transported away from the site and rocky seabeds and large boulders are common geotechnical issues. Wave-induced loading on foundation structures also apply and wave loading on any turbine ducting shall also be considered.

11.2 Tethered floating structures

Tethered floating structures are supported by their own buoyancy forces and are tethered to the seabed for the purpose of station-keeping such that there is a degree of compliance to dynamic environmental loading on the structure. Tethered station-keeping systems will comprise of one or more tethers to connect the floating structure to an anchor in a fixed earth reference.

Tethers will generally be made of steel chain, steel wire, synthetic fibre rope, or elastomeric cable elements. The tether may also include buoyant elements and/or clump weights.

Anchors will comprise drag anchors, anchor piles (driven, jetted, suction, drilled or grouted), and other anchor types, such as gravity anchors, suction anchors and plate anchors.

When orientation is important for safety or operational considerations, the station-keeping system shall be designed to maintain adequate position reference and directional control. Passive station-keeping systems include catenary mooring, taut-line mooring, spring buoy and tension leg systems. Active systems include dynamic positioning using thrusters or motorized winches to change mooring line tensions.

The adequacy of the station-keeping systems for moored floating structures shall be demonstrated by adhering to the requirements of IEC TS 62600-10.

11.3 Fixed structures

The structural analysis of the foundation of a fixed offshore MEC shall be performed in accordance with the ISO offshore structural design standards cited in this subclause or other recognized offshore design standards. If offshore design standards other than the ISO standards are used, it shall be demonstrated that at least the same level of structural reliability with respect to ultimate strength and fatigue is obtained.

The design load cases (see Clause 7) and associated load and resistance factors (see Clause 9) shall be used as the basis of the structural design of the foundation. Note in particular that the conversion of waves and tidal currents through controllable PTO machinery can result in significant dynamic loading that shall be considered in the load cases as prescribed in Clause 7.

The foundation design and analysis shall comply with ISO 19900. Geotechnical and foundation specific requirements that are applicable to a broad range of offshore structures are based on ISO 19901-4. The design of piled foundations that have a traditional association with fixed steel structures is detailed in ISO 19902. Particular requirements for the design of shallow gravity foundations that have a traditional association with fixed concrete structures are detailed in ISO 19903. Where appropriate, the principles for concrete gravity bases can also be applied to steel gravity base solutions, which may be desirable to reduce environmental loading on the gravity base itself in shallow water.

The foundation shall be designed to carry static and dynamic (repetitive as well as transient) actions without excessive deformation or vibrations in the structure. Special attention shall be given to the effects of repetitive and transient actions on the structural response, as well as on the strength of the supporting soils. The possibility of movement of the sea floor against foundation members shall be investigated. The loads caused by such movements, if anticipated, shall be considered in the design.

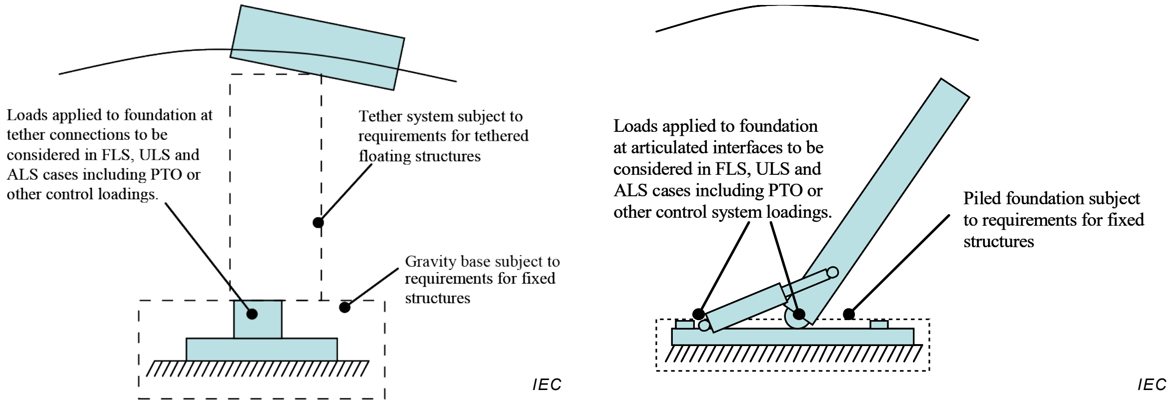
Loads acting on the foundation during transport and installation shall be taken into account. For piled structures, an analysis shall be undertaken to calculate the fatigue damage sustained by the pile as it is driven into the seabed. The fatigue analysis shall consider the loads associated with pile driving impact, taking account of the structural dynamics of the pile and stress increases due to the details of the pile design and the pile driving process.

11.4 Compound MEC structures

Compound MEC structures combine the function of station-keeping with other MEC functions, such as:

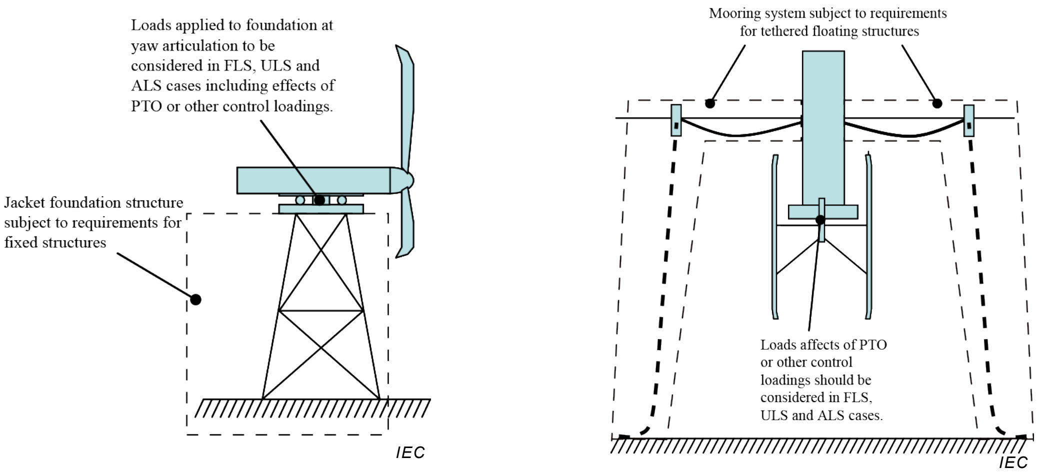
- the provision of a reaction to PTO forces that permits energy conversion from wave induced or current induced loads;

- where controllable power conversion machinery (e.g. hydraulic cylinders, linear generators, hose-pump elements) transfers the environmental loads from the primary wave-activated structure to the anchor reference point, forming an essential part of station-keeping for a large portion of the MEC structure; and
- attitude control – a controllable actuator delivers loads between the foundation and the MEC to affect optimal orientation of the structure to enhance energy conversion.



a) WEC using tether to transmit wave loads from wave-activated buoy to a reaction given by a gravity base foundation. The tether could also connect to a controllable PTO, included either within the foundation or buoy.

b) A flap type wave energy conversion device with a piled foundation base. Articulations permit the flap kinematics and provide a PTO reaction for a hydraulic cylinder.



c) Fixed horizontal axis tidal energy conversion turbine with yaw articulation

d) Free-floating, compliantly moored vertical axis tidal energy conversion turbine.

Figure 2 – Examples of compound position mooring systems for wave (a, b) and tidal (c, d) energy conversion systems

The resulting compound station keeping systems (see Figure 2) can depend on a combination of tether, fixed and articulated structural elements as well as controllable power conversion elements. In such cases, the issue of station keeping is less clearly divisible from the general structural integrity of the MEC and the provisions in 11.2 to 11.4. The considerations for fixed foundations and the station keeping of compliantly moored floating structures shall all apply, as follows:

a) Compound structures with tethers

Where tether elements are included in the MEC such that their failure would result in a loss of station keeping for all or a portion of the MEC structure, the requirements for tethered floating structures (see 11.2) shall be applied for the purpose of designing all tethers and associated attachments. The requirements of tethered floating structures shall also be used to determine the required design safety factor at interfaces to other parts of the structure (either the fixed part of the structure or free floating part of the structure) and the corresponding interface loads shall be included for the assessment of load combinations under Clause 7. Consideration shall be given to ALS load cases, including provision for redundancy due to failed tether elements. Where the MEC includes active control systems (such as power conversion hydraulics, linear generators, etc.) such that the load in the tether and its attachments are influenced significantly, then the control response shall be considered in any tether or fixed foundation load assessment allowing for all applicable operating scenarios, control settings and possible control ALS failure conditions (see Clause 7).

b) Compound structures with articulations

Where articulations are included in the MEC such that their failure would result in a loss of station keeping for a proportion of the MEC structure, the design load cases and associated load and resistance factors specified in Clauses 7 and 9 shall be used to ensure the integrity of articulated joints and associated attachments. Partial failure conditions of joints and articulations shall be considered in load cases to determine ALS foundation load cases. Where the articulation elements include active control systems such that loads applied to the foundation are influenced significantly, then the control response shall be considered in the foundation load and resistance assessments allowing for all applicable operating scenarios, control settings and possible ALS failure conditions (see Clause 7).

12 Inspection requirements

12.1 General

The manner in which a marine energy converter (MEC) is operated and maintained will have a significant impact on the integrity of the primary structure and functionality throughout its design life. In order for any maintenance and inspection to be effective, it shall be considered in a holistic manner throughout the design, construction, commissioning and operation of the MEC.

The requirements for a robust inspection and maintenance strategy will vary according to the type of MEC and the offshore environment in which it is working. Given the harsh environmental conditions which MECs experience, access for inspection and maintenance and in-situ working can be difficult to achieve in a safe manner, hence it will be necessary in many cases to recover the MEC back to shore or harbour prior to undertaking any inspection and maintenance work.

Maintenance and inspection activities can expose workers to a number of potential hazards. The planning stage of maintenance or inspection activities shall identify all potential hazards and identify means of reducing or eliminating exposure to these hazards. The maintenance strategy shall identify all local and national health, safety and environmental requirements that may apply to ensure the proposed activities comply.

12.2 Consideration during the design stage

The planned inspection and maintenance strategy shall be considered during the design stages to ensure that it is practical, economic and safe. The safety of personnel engaged in inspection and maintenance is paramount and should be considered through the undertaking of appropriate risk assessments to eliminate, or limit, the need to expose personnel to dangerous working environments. However, human safety is outside the scope of this document and designers should refer directly to local and national regulations.

The opportunity to use monitoring of structural integrity and other systems to provide a safe and continuous assessment of MEC structural integrity and functionality shall be evaluated at the design stage and, where feasible, adopted.

12.3 Inspection and maintenance planning

The designer shall give due consideration to the individual subsystems and components that may have a much reduced design life compared to the MEC system. Such a strategy shall consider three main categories as a minimum:

- time-based maintenance (where maintenance intervals are prescribed for the MEC system, subsystems, equipment and components);
- condition-based maintenance: this involves monitoring the condition of the MEC system, subsystems, equipment and components and maintenance is scheduled when certain conditions are met; and
- risk/reliability based maintenance (where maintenance intervals are determined based on the risk to and reliability of the MEC system, subsystems, equipment or components).

The designer shall identify the risks associated with the design, operation and maintenance activities as well as the mitigating measures using recommendations defined in Clause 7. The inspection and maintenance strategy shall be developed once these risks and mitigating measures are identified to ensure any requirements are considered from a risk perspective and the risk of human injury, significant environmental pollution or very high economic or political consequences are reduced to an acceptable level. The strategy shall satisfy appropriate local and national codes and regulations.

The developer shall communicate the inspection and maintenance strategy within a MEC specific Operation and Maintenance (O and M) manual that shall be issued to the owner/operator. In detailing the strategy and general operational requirements, the O and M manual shall include, but not be limited to the following:

- any maintenance or inspection activities that require special training;
- safe operating limits and system descriptions that consider local site conditions;
- maintenance inspection periods and procedures;
- for parts subject to wear: criteria for replacement;
- procedures for functional check of protection subsystems;
- start-up and shut-down procedures;
- an alarms action list;
- emergency procedures plan; and
- compliance with appropriate occupational health and safety regulations and marine regulations.

12.4 Data management

All inspection and maintenance activities shall be documented to reflect the requirements of the governing strategy specified in the O and M manual and shall include the reporting of the following information, as applicable:

- MEC identification;
- subsystem, equipment or component identification;
- operating hours to date, including operational modes that factor into fatigue analysis, such as energy produced;
- shut-down hours to date;
- date and time of fault reported;
- date and time of service or repair;
- nature of failure, fault or service (random or systematic);
- details of tests and inspections;

- recording of remedial action taken (part replacement, repair, identified for further monitoring);
- review of outstanding issues from previous activities; and
- details of personnel and equipment used.

Data shall be reported in an objective manner and shall justify its conclusions and include photographic documentation as considered appropriate. Relevant data from the design, construction and commissioning stages shall be available and understood to act as a baseline for in-service inspection and maintenance activities.

Feedback from in-service inspection and maintenance activities can provide valuable information to inform the following:

- possible revision/amendment to the governing strategy and hence the O and M manual;
- develop a greater understanding of component reliability and the degradation of structures or structural elements in the real sea environment and whether they continue to comply with the governing basis of design;
- highlight any findings or deviations reported during previous inspection and maintenance activities that have been remedied or not dealt with; and
- identify possible issues for future structural integrity monitoring.

Data shall be obtained during the in-service life in a systematic way that will enable an industry wide involvement of manufacturers, technology developers, operators, certification organizations and regulatory agencies.

12.5 Condition assessment and integrity evaluation (against performance requirements)

The findings from the inspection/maintenance carried out during the in-service life are to be compared with the expected behaviour of the structure and equipment identified during the design and commissioning phases.

Inspection and maintenance shall focus on detecting signs of degradation (corrosion, wear, cracks, tolerances, leaks). Degradation shall be limited to the range expected in the design. Findings deviating from the expected range require investigation. This could be, but not limited to, reviewing the design methodology and reviewing the actual conditions of operation.

At the early stage of technology development, the level of uncertainties on the design methodology and actual conditions of operation are much larger than what is observed in conventional and well-established technologies. Thus, an essential part of the technology development is the assessment of the condition of the structure and equipment during operation. Monitoring combined with results from inspection provides a full understanding of the technology (failure modes and degradation).

For MECs, the use of risk assessment is an adequate way to identify the areas of uncertainty and associated risk level for the technology to perform as required. As risk management is a continuous process, monitoring and inspection should feed back into the risk management and technology development to recalibrate the risks and effort required during the in-service life.

When planning and recording the monitoring and inspection activities, data collection is a key step in the identification of performance, failures, and reliability (see 12.4).

12.6 Maintenance execution

All inspection and maintenance activities shall be carried out in accordance with the O and M manual and shall be performed by personnel suitably trained or instructed in this activity. Access for inspection and maintenance of a MEC will be a key consideration. Because of the nature of MEC and the harsh environment, it might be necessary to recover the MEC to shore prior to undertaking any maintenance work due to limited safe access for inspection and in-site working. Where in-site maintenance is considered, consideration shall be given to provision of refuge areas for personnel on the MEC. An appropriate risk assessment, or similar, shall be undertaken to determine safe methods of undertaking the work.

An emergency procedures plan shall be defined as part of the O and M manual and the required actions of the operating personnel prescribed. The plan shall require that where there is a fire or apparent risk of structural damage to the MEC or its components, no one should approach the MEC unless the risk is specifically evaluated.

13 Life cycle considerations

13.1 General

The designer shall consider the entire life cycle of the MEC and the effects of both frequent and infrequent operations on the integrity of the primary structure. Fabrication, transportation and installation phases for MECs are significantly different than the operational phase and decommissioning phase. Each of these phases can impose loads on the primary structure that can affect the engineering integrity of the collective system. Careful planning is required to provide an appropriate level of protection against damage from all hazards that may lead to failure of the primary structure, injury to personnel, damage to equipment or damage to the environment.

The designer shall consider the rigging, lifting and movement of components, assemblies and modules during fabrication. Transportation planning shall consider all logistics and loads associated with movements at the fabrication site, road transport, pier-side activity, lift transfers and water transport. Due consideration shall be given to weight, height, width, length, in-water draft, and overhead clearance. Installation planning shall consider all associated operations including removal and reinstallation for maintenance and decommissioning. Changes in state, such as on-land to floating, floating to submerged and submerged to bottom shall be considered. The designers of a MEC shall provide an installation manual clearly describing the fabrication, transportation and installation requirements for the MEC, moorings, power cables and anchoring system. The installation of MECs shall be performed by personnel trained or instructed in these activities.

The designer shall consider and provide operational procedures, to include maintenance, inspection, and decommissioning to the owners/operators. The designer shall consider fatigue and degraded material condition during design and permitting for removal and decommissioning at end of useful life.

The site of a marine energy facility shall be prepared, maintained, operated and managed so that work can be performed in a safe and efficient manner in accordance with appropriate regulations and permitted requirements. This shall include:

- marking of individual structures, or fields of structures;
- installation of power cables between individual MECs, transformer stations, and shore;
- monitoring of the facility by the operator;
- procedures to prevent unauthorized access, where appropriate; and
- contingency plans to address the possibility of individual MEC units breaking loose and becoming floating or submerged hazards.

Detailed installation engineering and planning shall be carried out. Checklists of planned activities shall be prepared and comprehensive records shall be maintained during construction and commissioning to provide as-built data. Planning and independent reviews shall consider:

- design, testing and certification of lift points;

- movements on land;
- route considerations, including contingency mooring and anchoring locations;
- cross-section related current, wave and wind forces with respect to available tug capabilities and backup tugs;
- tug contact points; and
- centre of gravity, stability and risk of capsizing (static and dynamic stability requirements).

The transportation plan, including the towing plan, shall consider all aspects of MEC movement, launch, placement and mooring, including:

- weather windows for transportation and installation;
- damage control contingencies and monitoring systems;
- lashing and sea fastening for inertial loads;
- modularity and assembly at sea;
- freeboard of hatches and maintenance openings and risk of down-flooding;
- role of independent surveyor prior to movements on land and to sea;
- role of harbour and coastal pilots;
- launch considerations:
  - clearance of submerged hazards; and
  - dynamics and irreversible/unstoppable launching procedures;
- transitions in centre of gravity and centre of buoyancy and associated risks of capsizing:
  - physics of floating device;
  - physics of submerged device;
  - physics of bottomed device;
  - transitions between states;
  - limbering of tanks;
  - abnormal hydrostatic pressures;
  - lifts at sea:
    - snap loads; and
    - entrained mass of water;
  - tensioning the mooring; and
  - power cable connections.

When appropriate, installation personnel shall use approved personal protective equipment, such as eye, feet, hearing, and head protection. Fire safety issues shall be considered during all aspects of the MEC life cycle, especially during confined entry activities. All personnel climbing or working above ground or water level shall be trained in such work and shall use approved safety belts and safety climbing aids. Personnel working on or near the water shall wear approved life jackets at all times. Consideration shall be given to the use of survival suits in cold climates when risk of immersion is imminent.

All equipment shall be kept in good repair and be suitable for the task for which it is intended. Cranes, hoists and lifting equipment, including all slings, hooks and other apparatus, shall be periodically tested and approved for safe lifting.

Particular consideration shall be given to avoid installation of the MECs under unusual conditions, such as: hail, lightning, high winds, earthquake, icing, high waves, and extreme tidal conditions.

Installation procedures shall be such that, if necessary, work can be broken off without causing danger to personnel or unacceptable loads on the MEC. In the case of a MEC that changes state from floating to submerged or bottomed, appropriate measures shall be taken to control buoyancy and stability. The critical ballasting and stability control precaution measures shall be included in the installation manual.

Prior to any construction activity at the site of a marine energy facility, any planned temporary or permanent structure considered to be an obstacle to marine navigation and aviation shall be promulgated with adequate advance notice and shall be indicated on relevant maps and databases providing position, extent and elevation in accordance with the requirements of the governing regulatory agency. Obstacle lighting and marking shall comply with local and national regulations and codes.

13.2 Planning

13.2.1 General

The assembly, transportation and installation of MECs and associated equipment shall be planned in order that the work is carried out safely and in accordance with local and national regulations. As appropriate, the planning shall include:

- detailed drawings and specifications of the work and quality assurance plan;
- procedures for safe execution of excavation work, blasting and other activities that have to do with foundation and underwater construction (for example pile driving, laying of scour protection and cable laying);
- procedures for the proper handling of embedded items, such as foundations, bolts, anchors and reinforcement steel;
- procedures for concrete composition, delivery, sampling, pouring, finishing and placement of conduits;
- procedures for installation of anchors, moorings and MECs;
- health, safety and environmental rules for offshore work, including safety rules for diving and down-flooding; and
- evacuation procedures (including procedures for monitoring of wind conditions and sea states to determine when evacuation is in order).

13.2.2 Installation conditions

During the installation of MECs, the site shall be maintained in such a state that it does not present personnel safety or navigation risks.

13.2.3 Site access

Access to a site shall be planned to ensure safety, including the following considerations:

- barriers and routes of travel;
- navigation areas to be avoided (ATBAs) or exclusion zones;
- anticipated traffic;
- access site weight bearing capacity;
- movement of equipment at the site;
- ship-to-MEC access; and
- control of MEC movement.

13.2.4 Environmental conditions

During installation, environmental limits specified by the manufacturer shall be observed. Items such as the following shall be considered:

- wind and current speed;
- snow and ice;
- ambient temperature;
- lightning;
- visibility;
- rain;
- wave height; and
- insufficient water depth.

13.3 Documentation

The manufacturer of a MEC shall provide drawings, specifications and instructions for assembly procedures and installation of the equipment to the owner/operator. The manufacturer shall provide details of all loads, weights, lifting points and special tools and procedures necessary for the safe handling and installation of the MEC. The manufacturer shall provide a risk assessment of all hazardous activities.

13.4 Receiving, handling and storage

Handling and transport of equipment during installation shall be performed with equipment confirmed to be suitable to the task and in accordance with the handling equipment manufacturer's recommended practice.

13.5 Assembly of and installation of MECs

13.5.1 General

A MEC shall be assembled according to the manufacturer's instructions. Inspection shall be carried out to confirm proper lubrication and pre-service conditioning of all components. The adequacy of corrosion prevention measures shall be verified after final assembly.

A MEC shall be installed by personnel trained and instructed in proper and safe offshore work practices. Where specified by the MEC manufacturer for safe installation or assembly, special tools, jigs and fixtures and other apparatus shall be used.

Apart from specific training having to do with marine installation, training shall include at least:

- first aid;
- procedures particular to offshore (for example the use of life rafts, life jackets, safety harnesses, special suits, offshore survival);
- evacuation procedures, including for wounded or unconscious persons;
- use of boats, helicopters and offshore access systems (with special attention to safe transfer procedures at night or with high sea states); and
- all equipment shall be suitable for the task for which it is intended. Lifting and special purpose equipment, such as cranes, hoists and lifting equipment, including all slings, hooks and other apparatus, shall be tested and approved for safe lifting.

No part of a MEC electrical system shall be energized during installation unless it is necessary for the installation process. In this case, the energization of such equipment shall be carried out in accordance with a written procedure provided by the MEC supplier.

All elements where motion (rotation or translation) may result in a potential hazard shall be secured from unintentional movement throughout the installation process.

13.5.2 Access

Access for inspection and maintenance of a MEC will frequently be a key consideration. The harsh environmental conditions existing where these devices are generally located lead to limited safe access for inspection and on-site working. Because of the nature of these devices, it might be necessary to recover the device to shore or harbour prior to undertaking any maintenance work. Where on-site maintenance is considered, consideration shall be given to provision of refuge areas for personnel on the device.

Design shall take into consideration the need to remove components requiring maintenance, while ensuring that elements remaining on the seabed require little or no maintenance during their service life. Where electrical, hydraulic or other fixed connections exist between the device and shore, due consideration shall be given to how this connection will be made and broken safely and reliably during the operational life if it is intended to remove the device for maintenance. Electrical connections shall be isolated while maintenance is undertaken.

The intended level of inspection shall be considered in light of the cost and risk associated with undertaking inspection and repair. The use of additional or increased design factors to reduce the probability of failure of mechanical, structural or electrical systems may reduce the need for inspection.

The safety of personnel engaged in inspection and maintenance shall be considered at the design stage to limit the need to expose personnel to dangerous working environments.

The opportunity to use monitoring of structural integrity and other systems to provide a safe and continuous assessment of performance shall be evaluated at the design stage where appropriate. Feedback from these techniques can assist in the planning of maintenance and inspection activities.

13.6 Fasteners and attachments

Threaded fasteners and other attachment devices shall be installed according to the MEC manufacturer's recommended torque and/or other instructions. Fasteners identified as critical shall be checked and procedures for confirming installation torque and other requirements shall be obtained and used. Suitable locking mechanisms shall be used on threaded fasteners subject to vibration.

In particular, inspection shall be carried out to confirm the following:

- proper assembly and connection of guys, cables, turnbuckles, gin poles and other apparatus and devices; and
- proper attachment of lifting devices required for safe installation.

13.7 Cranes, hoists and lifting equipment

Cranes, hoists and lifting equipment, including all hoisting slings, hooks and other apparatus required for safe installation, shall be adequate for safe lifting and final placement of the loads. Manufacturer's instructions and documentation with respect to installation and handling shall provide information on expected loads and safe lifting points for components and/or assemblies. All hoisting equipment, slings and hooks shall be periodically tested and certified for rated safe load. Special attention shall be paid to ensure lifting equipment is not exercised beyond its rated radius for a given load.

13.8 Decommissioning

The developer and designer shall consult with the appropriate regional authorities responsible for the deployment site for guidance on the requirements in preparing and submitting a decommissioning programme and environmental life cycle impact assessment.

The decommissioning phase of the device, or an array of devices, can have a significant impact on the project costs and environment life cycle impact assessments that are required to satisfy statutory and policy constraints, and therefore the viability of a project.

In preparing the decommissioning programme, the developer shall consider the following factors relating to the decommissioning phase and disposal:

- conditions of lease of the deployment site (e.g. full reinstatement required);
- licensing regulation requirements imposed by environmental licensing authorities;
- weather conditions necessary for decommissioning;
- tidal and sea state conditions needed for decommissioning;
- length of time required for decommissioning;
- recovery methodology;
- specialist vessels, plant, equipment and contractors needed for decommissioning;
- seabed conditions;
- risk assessment for decommissioning;
- environmental impact both during and after decommissioning and disposal;
- anticipated impacts on local benthic communities, habitat and marine organisms; and
- health and safety impacts.

The designer shall consider the post-decommissioning phase of the MEC life cycle. The MEC and supporting infrastructure may be fully or partially recovered, reused at other sites, recycled, or to be disposed on land.

The post-decommissioning phase of the MEC can significantly impact the design process and its components, as follows:

- A MEC can be fully recovered for reuse at other sites, although this is dependent on the condition and suitability of the structure when recovered. Where necessary, components can be renewed or replaced.
- A MEC can be partially recovered. For example, the environmental impact assessment might encourage the use of a scarified support structure or foundation to promote colonization of marine organisms long after the decommissioning of the device, assuming this is in agreement with regional guidelines. Alternatively, the support structure or foundation can be left in place to accommodate a MEC in the future given the sustainable nature of marine resources and condition of the structure.
- The electrical cable may need to be recovered or left in place, depending on regional guidelines. Recovery, or decommissioning in-place, is considered to be part of the overall decommissioning programme.
- The device shall be robustly designed for its viable design life and for decommissioning, and able to resist the expected loads and surrounding conditions in accordance with a recognized design methodology.

Given the conservative nature of the design process, it is quite possible that the useful lifetime can be extended beyond the original design life, although this will be subject to a rigorous assessment prior to the decommissioning phase of a project. As a minimum, it is recommended that a thorough review of as-built details and design checks and the implementation of an inspection and testing programme shall be adopted to evaluate the condition of the device and components and to verify their suitability for the proposed application or extended life. The possibility of further damage during removal and transportation shall also be considered. Further guidance on the reuse of structures is provided in ISO 19902.

Annex A
(normative)

Load definition and load combinations

A.1 Load combinations

A rigorous investigation of the proposed device and supporting structure shall be undertaken to identify potential limit states where the device would no longer meet the reliability or availability requirements discussed in Clause 5. As a minimum, adequate consideration shall be given to the following:

- overall device stability against translation or overturning forces;
- stability of any sub-components where relevant;
- performance of ground anchorage, including consideration of ground fatigue;
- structural capacity and fatigue performance of structural components; and
- operational limits on mechanical equipment, seals and bearings.

In selecting appropriate limit states, consideration shall be given to achieving a "soft" or ductile failure by ensuring that, where possible, limit states with energy absorbing capacity and less serious consequences are reached before those resulting in sudden or catastrophic failure. For instance, a gravity base should slide rather than overturn in an overload event and structural members should fail by yielding rather than by undergoing buckling or rupture. This is particularly important where loading is subject to great uncertainty, as in prototype devices.

Based on identified limit states, all load cases where these limit states could be exceeded shall be identified to enable design assessment. Design load cases to be considered are described in 7.3.7.

For all cases, consideration shall be given to device faults that could affect the device loading (including failure to engage survival mode when required) and additional load cases introduced to investigate these. Additional load cases are also likely to be necessary to consider non-axial flow conditions. Flow eccentricity can arise due to fabrication and installation tolerances, from misalignment of the flow due to non-reciprocity of the local tidal currents and from wave induced currents across the device. The same applies for wave directions. Sufficient load cases are required to ensure that the worst-case combinations of all of these are considered in the design.

It is important that the level of uncertainty surrounding the behaviour of the marine device at an early stage of development is considered when defining the basic load cases. Because the non-linear behaviour and interaction of PTO and control may not allow all possible load cases to be identified during tank testing or sea-trials, a risk assessment may be necessary to identify all aspects of behaviour relevant to design. This is particularly the case with respect to accidental load cases and aspects that may be site-specific or of infrequent occurrence. Additional or increased uncertainty factors and a robust design approach shall be used to accommodate the possibility of unexpected response characteristics.

Consideration shall also be given to corrosion, marine growth and the behaviour of the export cables or connections. Additional load cases shall be introduced to enable these situations to be properly understood. The effect of heat generated by mechanical components shall also be considered, particularly where the mechanical properties of any materials used exhibit temperature dependence within the range of expected operating conditions.

The design storm is that storm with a probability of exceedance chosen such that the safety levels in Clause 5 are achieved. Where operational limitations are placed on the device, such as shutting down in severe storms, the limits shall be clearly documented and robust and fail-safe systems identified that will enable these limits to be adhered to.

Where it is necessary to stop the device at any point, the loads induced in doing so, including thermal loads, shall be considered in all load cases under which a stop condition may arise.

In devices where the electrical components are integrated as discrete subsystems independent of the structure, the electrical machine manufacturer will generally undertake the required electromagnetic analysis. However, where electromagnetic components are integrated into the structure of the device, a detailed analysis of electromagnetic effects will be required. This analysis shall fully account for the effects of tolerances and misalignments of components as well as all structural dynamics, electrical dynamics and thermal effects. Electromagnetic forces are highly sensitive to the size of the air or water gap and a sufficiently accurate linked multi-physics analysis shall be undertaken to address this.

The derivation of input parameters (such as loading) shall include derivation of the uncertainty associated with the input parameter, as well as an understanding of the associated probability distribution. Sufficient additional load cases shall be studied to establish the sensitivity of any analysis to variation in the input parameters. Where the analysis outcomes are found to be sensitive to a particular input, a conservative value of that input shall be selected. For stochastic variables, the design shall be undertaken assuming a value of the input with a 5 % probability of exceedance. For deterministic variables, or stochastic variables with unknown variation, the worst credible value of the relevant input occurring during the load case under consideration shall be chosen.

When the underlying processes are comprised of the sum of independent variables, their effect on the demand and capacity functions shall be combined using a normal distribution function. If the uncertainty can be represented as a product of the variables, the interaction between capacity and demand shall be characterized using a lognormal distribution function.

A.2 Load calculations

For all load cases identified, sufficient analysis shall be undertaken to accepted practice to establish that the probability of exceeding any of the identified limit states falls within the limits set out in Clause 7.

Analysis shall be based on an appropriate model of the underlying physics. The appropriate selection of a simplified model shall be governed by the sensitivity of the device under consideration to the simplifications implied by the analytical model. Consideration shall be given to the need to analyse significant numbers of load cases, and the consequent need to limit the analysis cost. It may frequently be desirable to use a simplified analysis model for the bulk of the analytical work if this approach has been validated against a more accurate but more costly model.

NOTE For example, a blade-element momentum (BEM) analysis of a tidal turbine might be validated against experimental trials or a suitably rigorous series of Computational Fluid Dynamics (CFD) investigations.

The analytical approach shall be chosen such that as a minimum the following physical effects are captured:

- tidal variation in mean current speed and direction and water depth;
- variation in current speeds and turbulence levels with depth (shear flow);
- wave induced currents and accelerations;
- wave heights and periods; and
- water particle velocities and accelerations.

Consideration shall be given to the adequacy of the model in understanding the following effects:

- the influence of three-dimensional flow;
- structural dynamics and potential for modal coupling;
- fluid – structure interaction, including hydro-elasticity;
- unsteady hydrodynamic effects; and
- the non-linear interactions between waves, currents and turbulence.

It should be recognized that general flow analysis techniques do not fully capture turbulent separation effects (particularly blade stall and stall dynamics).

The approximations inherent in many industry approaches to wave and current interaction should be understood, with an appreciation that some of these approximations are not appropriate in strong tidal flows.

Where linear assumptions are used at any point, the resulting level of error shall be quantified and appropriate limits placed on the range of applicability of the approximation.

Where a fully dynamic model of the structure is being used to undertake non-linear analysis, sufficient periods of time shall be analysed to ensure that the output values are statistically stationary. It should be noted that the 1 h period generally taken to be adequate for wind driven events is not appropriate to loadings driven by wave or tidal effects. Where wave loading is important, a period of not less than 3 h shall be analysed for each load case, unless a shorter period can be justified by an understanding of the wave spectra at the installation location.

In determining the length of analysis time required for any given load case, consideration should be given to the effect of the initial conditions chosen and the length of starting flow that should be discarded. In general, it will be necessary to neglect a portion of output at the start of the simulation period. Determination of the length of time to be neglected shall be based on statistical analysis of typical output data.

Where random variables are introduced into the model to capture stochastic variables (such as turbulence), sufficient further analysis shall be undertaken to understand sensitivity to the chosen random seed value.

Stresses on many parts of the structure and mechanical assembly are likely to be multi-axial in nature. If orthogonal time series output is used as a design input for structural or fatigue calculations, care should be taken to maintain both the magnitude and direction of these inputs. Alternatively, for survival load cases, the most critical load values occurring in all orthogonal time series may be taken to act simultaneously.

Because most devices in a marine environment are governed by combinations of tidal current, turbulence and waves (all of which display difference statistical characteristics) analysing all combinations of all possible inputs to produce a full scatter diagram for fatigue analysis may result in an excessive number of load cases. To avoid this, it is possible to separate the load effects due to different statistical processes by making analytic (potentially linear) assumptions about the load combinations over short ranges of input values. In selecting these simplifying assumptions, the extent of error introduced shall be understood and appropriately accounted for in the selected safety factor. Fatigue damage due to each process can be recombined to produce a combined damage value based on accepted approximate methods. Significant approximation is involved in this approach, but this may be preferable to undertaking a conventional rain flow count based on insufficient modelled data.

A.3 Floating and moored devices

Where a device is not fixed to the seabed, dynamics of the six rigid body degrees of freedom shall be considered. Additional rigid body degrees of freedom due to mechanical linkages or other design features shall also be considered. Design of structural and mechanical systems shall take due account of the following additional effects:

- inertial forces, both rotational and translational, arising from acceleration of part or all of the devices;
- abrupt forces arising from support non-linearities, for example a mooring line becoming taut or engagement of mechanical stops;
- forces arising from impact of the water/air interface on the device – i.e. wave slap and wave slam; these forces can be substantial and are in addition to normal hydrodynamic forces;
- loads arising from water overtopping the device ('green water');
- transient loads and pressures in the hydraulic system, where relevant, taking account of the appropriate fluid properties;
- effects arising from the operation of the control system; and
- effects of biofouling (weight and drag) on structural components.

Due to the non-linear nature of the system response, frequency domain analysis techniques relying on linear recombination are unlikely to adequately model the device. A time domain analysis will generally be necessary to obtain a full understanding of the behaviour and performance of the energy converter. The time domain analysis shall in principal be sufficiently detailed and robust to adequately capture the following effects:

- coupling of hydrodynamic and inertial behaviour;
- non-linear behaviour of mooring devices and mechanical systems; and
- motion of fluid within the device.

In practice, it may not be possible to capture all physical effects to a sufficient level of detail within a single analysis model. Where this is the case, additional experimental or numerical investigations shall be undertaken to gain an adequate understanding of the overall device behaviour. IEC TS 62600-10 shall be used for the design of MEC mooring systems.

A.4 Flow analysis methodology

Tidal turbines are frequently designed making use of Blade Element Momentum (BEM) models. These rely on an assumption of two-dimensional flow around discretized blade elements. The overall wake effects are accounted for in a coupled one-dimensional momentum model. Various empirical corrections are required to account for tip and hub losses, stall behaviour and wake dynamics. As the aspect ratio of the blades decreases, three-dimensional flow becomes more important and the BEM approach becomes subject to error. The dynamic effects of wave and turbulence on the wake are only captured in an incomplete way and calibration against experimental results is required. Lifting line and vortex panel blade modeling techniques that overcome some of the limitations with respect to wake effects are under development but are not yet being widely used.

Because the BEM method has a relatively low computational cost, it is frequently combined with a structural and mechanical model to understand the dynamic behaviour of a turbine system. Key cases shall be validated against results obtained by other means, particularly where stall behaviour or wake dynamics are considered important.

Wave energy converter behaviour is complex and difficult to model analytically in an accurate manner using presently available analysis techniques. A staged approach to the understanding of the converter behaviour and calibration of numerical analysis shall be adopted, moving progressively from tank tests to sea trials. At each stage, validation of the numerical analysis against experimental work shall be undertaken to confirm that the model represents an accurate reflection of the true device behaviour.

The behaviour of wave and tidal devices in an array may differ significantly from that of an individual device and a methodology shall be established to monitor and understand these differences as part of the development of a device array.

Care shall be used where Computational Fluid Dynamics (CFD) is relied upon at any stage of the design, in particular when based on unsteady Reynolds Averaged Navier-Stokes (RANS) analysis. It should be recognized that the validity of unsteady RANS analysis relies on spectral separation between the smeared turbulent eddies and resolved flow, which in many cases does not exist. An understanding of the resulting error shall be developed based on comparison with experimental or other numerical work. Nevertheless, a properly conducted RANS model can provide useful engineering knowledge. The accuracy of CFD is generally highly dependent on the mesh type and density, the turbulence model used and input of physical parameters. Large Eddy Simulation (LES) can in principle overcome many of the difficulties associated with RANS, but the computational cost is greater, limiting practical use for MECs. In any case, results of CFD models should be carefully compared with experimental results.

Where CFD is used to model a TEC, movement of the blades through the flow shall be explicitly captured. A sufficiently dense mesh over a substantial distance downstream (typically 10 rotor diameters) is required to capture wake behaviour. For other MECs, studies should be undertaken to understand the extent of wake simulation required.

Annex B
(normative)

Reliability issues

B.1 General

Reliability is a key aspect to be considered in the development of MECs. Since such devices are not easily accessible due to offshore location, maintenance is more complicated and costly compared to onshore equipment. Moreover, in the case of failure, a device may be inaccessible over a prolonged period of time due to harsh weather conditions that will lead to a major increase in the device downtime. Thus, a higher level of reliability is required for MECs compared to similar onshore devices. Developing a reliability strategy and setting targets for reliability during the design phase are discussed in Clause 5.

A MEC consists of structural, mechanical, electrical and control systems that are interdependent. Thus, it is essential to check not only the reliability of each of the systems separately but also the device as a whole. A MEC should be sufficiently robust, i.e. it shall be ensured that, as far as practicable, failure of a component in one of the systems would not cause damage to a major part of the device or shut down the device for a long period of time. When this cannot be provided (e.g. by redundancy), the component is considered to be critical and a higher level of reliability should be required for it.

A detailed FMECA or similar type of review shall be undertaken during the design phase, after prototype testing and before the device goes into production in order to ensure all areas of poor reliability have been identified. The identified areas can then be focused on for more detailed analysis.

B.2 Structure and foundation

The supporting structure, including foundation, is a critical system for safe operation of a MEC. Its failure may lead to loss of the whole device and other more severe consequences, such as major environmental pollution or loss of life. If it is not practicable to design the system without any critical component(s) (i.e. a component whose failure leads to collapse or loss of the whole system or a major part of it) a higher level of reliability shall be required for such a component.

Due consideration shall be given at the design stage to the adverse effects of deterioration processes (corrosion, wear out, etc.) and fatigue on the reliability of structural components and their connections over the design life of a device. Zones within the structural system identified as potentially problematic in this context shall be inspected on a regular basis over the device life.

B.3 Mechanical system

An important aspect to be considered in the context of the reliability of MECs is that many mechanical components used in these devices have been initially developed for other environmental and operating conditions. Effects of marine environment, motions and accelerations (in particular, for floating devices), corrosion, and longer maintenance intervals on the reliability of these components shall be taken into account. To determine the required reliability of the components their target design life shall be specified.

Information about the reliability of mechanical components shall be collected and documented by testing or service experience. The use of service experience is very valuable, especially if a relevant load and operating history is documented.

B.4 Electrical system

For the electrical system, effects of actual operating and environmental conditions on the reliability of components shall be taken into account. As a minimum, single mode failures shall be avoided. Where analysis or testing has identified vulnerability, steps shall be taken to prevent such failures occurring. Where this has been achieved by duplication and redundancy, checks shall be made that each element is totally independent of the other by separation of equipment, cabling, auxiliaries and energy sources (batteries, fuel tanks and accumulators).

CO_2 or other similar fire fighting systems shall be considered if the internal compartment volumes are small enough.

Power factor correction capacitors for induction generators are considered to be components requiring particular reliability focus. It is recommended that fast protection be provided to remove them from the generator circuit should a capacitor fault occur.

B.5 Control and protection system

If the device is normally unmanned and risks to personnel are low, the need for IEC 61508 type safety integrity level assessment control systems can be restricted to all but the most critical components, such as the emergency shut-down facilities. However, the reliability of the electrical and electronic equipment within the device shall be kept high, not only due to the need to ensure continuity of output power, but also to keep intervention costs to a minimum by extending maintenance intervals.

The mean time between failure (MTBF) for electronic and control components are usually quoted by manufacturers and can provide the basis for selecting high reliability components.

B.6 Instrumentation

Separation and redundancy of instrumentation and control systems is important. As an example, if a fault within a device not equipped with fire fighting facilities results in a fire, some physical separation of duplicated systems may give vital additional time to transmit data about the cause of the failure before the device is lost.

B.7 Testing during qualification

A robust testing programme shall be established in order to address all performance and reliability issues. These shall include:

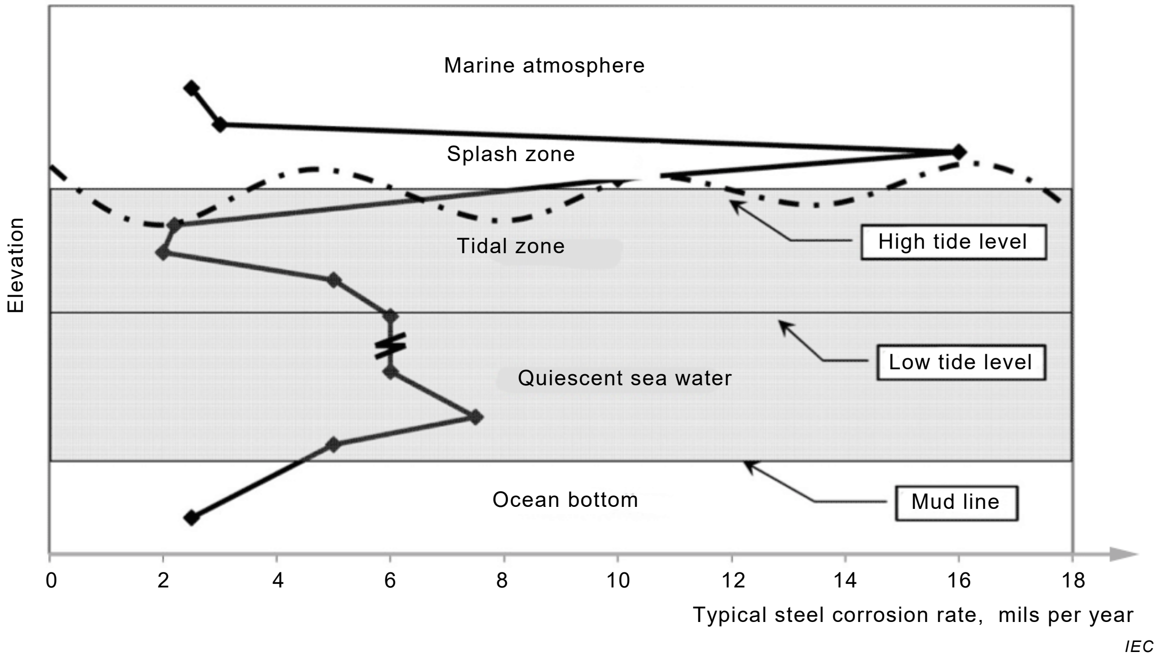
- response to communication failure;
- response to power failure;
- performance of the response – is the time from command to action taking too long?
- redundancy testing;
- system stress testing (by introducing overload data onto the system to see how it performs);
- communication protocol testing if it is a proprietary protocol; and
- software testing and validation.

Annex C
(normative)

Corrosion protection

C.1 General

As MECs will be working in a highly corrosive marine environment, structural materials shall be suitably protected or the impact of corrosion shall be offset by material thickness corrosion allowances. The designer shall identify which corrosion zones (see Figure C.1) each component of the device will exist within before considering forms of corrosion protection during design. Note that corrosion rates will be higher in tidal environments where scouring is possible. Cost, maintenance required and lifetime of the protection method against corrosion shall also be considered.



SOURCE: AULT, J Peter, *The Use of Coatings for Corrosion Control on Offshore Oil Structures*, Journal of Protective Coatings and Linings, Volume: 23, Issue Number: 4, Technology Publishing Company, 2006

Figure C.1 – Profile of the thickness loss resulting from corrosion of an unprotected steel structure in seawater (1 mil = 0,025 4 mm)

C.2 Steel structures

C.2.1 General

Steel structures are subject to direct attack by chlorides in seawater or in the marine atmosphere. Unprotected carbon steelwork will suffer significant degradation within the service life of structures and due consideration shall be given to ensuring adequate durability and performance. The decision on the most adequate method of protection against corrosion shall be evaluated considering inspection regime, position of the structure (or part of) relative to the splash zone, criticality of fatigue and corrosion allowances.

Protection of carbon steel structures is generally achieved by the provision of some combination of sacrificial thickness, an appropriate coating system and/or the application of cathodic protection. The use of appropriately specified stainless steel may also be considered in oxygenated environments.

C.2.2 Corrosion rates

The rate of corrosion of unprotected carbon steel is dependent on a range of environmental parameters including temperature, salinity and the material grade. ISO 11306 gives guidance as to likely corrosion rates in a range of environments. However conditions in the splash zone are likely to be more onerous. Very high corrosion rates may occur in tropical waters and subsea internal heated areas.

The corrosion rates shall be determined based on previous similar service experience in the deployment area. In the absence of accurate information, the basis for design shall define a corrosion rate. Consideration shall also be given to aggressive local corrosion (pitting and grooving). The inspection regime shall confirm the corrosion rates assumed in the design.

Calculations for ultimate and fatigue limit states shall be carried out with the minimum wall thickness expected at the end of the design life. Consideration shall also be given to scour of steel elements in contact with or embedded in the seabed (i.e. piled structures), as very high rates of steel loss can occur in some seabed conditions. Consideration shall be given to ice scoring in arctic waters.

C.2.3 Protective coatings

Reference may be made to ISO 12944 for general guidance as to the design and specification of coating systems. However the specification of specialized marine coatings is not covered in this document and reference shall also be made to coating manufacturers and classification society rules and guidelines. For areas that are not continuously submerged (such as the splash zone), suitable protection shall be provided through the application of protective coatings that have good hydrolytic, abrasion and ultraviolet (UV) resistance. Protective coatings shall be periodically monitored and maintained to ensure proper corrosion control. Consideration shall be given to the use of organic zinc-rich primers, higher build epoxies, and polysiloxane systems to enhance the longevity of applied coatings.

Where coatings are used, consideration shall be given to the rate and extent of deterioration of the coating and the provision of increased demand on the cathodic protection system as a result of this deterioration. If a marine coating is relied upon as the primary protection for a submerged structure, consideration shall be given to provision of a secondary protection system (i.e. cathodic protection) to limit the impact of scratches or other damage to the coating occurring during installation and operation. Also, the potential for the coating to become damaged due to particles in the flow and saltation shall be given adequate consideration.

Enhancement of corrosion processes by marine growth (e.g. through corrosive metabolites), commonly referred to as Microbiologically Influenced Corrosion (MIC), shall be considered. Marine growth may further interfere with systems for corrosion control, including coatings, linings and cathodic protection.

Anti-fouling paint containing the organotin tributylin (TBT) shall not be used in accordance with the International Convention on the Control of Harmful Anti-fouling Systems on Ships.

C.3 Cathodic protection

C.3.1 General

Submerged MECs can be effectively protected by cathodic protection using galvanic anodes or via impressed current systems. General considerations of cathodic protection are given in ISO 12473. Cathodic protection shall be designed in accordance with EN 12495, for fixed structures and EN 13173, for floating. Where an impressed current system is to be relied upon, sufficient secondary protection shall be provided for the period between maintenance opportunities in the event of system failure.

Cathodic protection is not effective in the splash zone and in these areas an allowance of a sacrificial thickness together with the use of an appropriate protective coating shall be considered. In areas subject to impact or wear, special consideration shall be given to the appropriate choice of coating.

Excessive levels of cathodic protection shall be avoided to minimize the possibility of cathodic disbonding of coatings and hydrogen embrittlement of welds and high strength steels.

For internal flooded steelwork, cathodic protection may be employed either with or without coatings, cladding or corrosion inhibitors.

C.3.2 Closed compartments

Closed compartments can be used to slow corrosion rates for un-protected steel exposed to seawater. The oxygen within the compartment is depleted and limits the amount of corrosion. Careful consideration shall be taken in evaluating the corrosion rates and overall structural integrity of these compartments including:

- volume of oxygen and water within the compartment, for calculation of corrosion rates and pressure effects due to loss of oxygen;
- expected number of openings of the compartment during design life (i.e. during maintenance);
- possible water and air leak paths;
- anaerobic corrosion; Microbial Induced Corrosion (MIC) is increased within oxygen-starved atmospheres;
- build-up of gases if cathodic protection is employed; and
- fatigue.

There is little data on fatigue for partially corroded steel. Therefore, a conservative fatigue assumption shall be used.

C.3.3 Stainless steel

Where provision of cathodic protection or other protection cannot be achieved due to electrical isolation or other reasons, the use of marine grade stainless steel may be considered in oxygenated environments.

Consideration shall be given to galvanic corrosion between stainless steel and carbon steel components. In general, small areas of stainless steel in contact with much larger areas of carbon steel (i.e. stainless steel fasteners) are acceptable. Where larger areas of stainless steel are required, appropriate measures of ensuring electrical isolation will be required.

C.4 Concrete structures

C.4.1 General

Concrete structures containing reinforcing or pre-stressing steel are vulnerable to chloride-induced corrosion. Relatively small amounts of material loss can lead to significant damage due to the volume of corrosion products generated and protection of embedded steel against chlorides is important to ensure the durability of the structure. Plain concrete elements are not vulnerable to chloride-induced corrosion, although attention shall be paid to any cast-in steel elements.

C.4.2 Provision of adequate cover

The provision of sufficient concrete cover (50 mm) to steel elements is generally the primary means of protection against corrosion as it limits chloride ingress. Use of less porous concrete will reduce the rate at which chloride ions penetrate the concrete and thus extend the protection achieved with a given concrete thickness – this is generally achieved by specification of a higher strength grade.

Minimum concrete cover for corrosion protection is a function of environmental class and sensitivity of reinforcement to corrosion. Characterization of the corrosion environment shall be carried out with reference to ISO 19903.

For partially submerged concrete elements, consideration shall be given to the risk of enhanced corrosion of the reinforcement due to formation of corrosion cells with the exposed reinforcement. In this situation, the use of stainless steel or composite rebar reinforcement or adequate cathodic protection shall be considered.

Concrete exposed to wave borne sand, rocks and sediment in energetic marine environments may be subject to abrasion or scour. Appropriate allowance shall be made for any consequent reduction in the cover to reinforcement over the life of the structure. Careful consideration shall also be given to structural and other sources of cracking that will increase chloride ingress.

C.4.3 Use of stainless steel or composite reinforcement

Reinforcement exposed to seawater or marine atmosphere due to concrete defects, embedment plates, penetration sleeves or other cast in elements will normally require corrosion protection. Consideration shall be given to the use of a suitable marine grade stainless steel or composite reinforcement for cast-in or exposed elements. Where the main reinforcement is to be carbon steel, stainless elements shall be electrically isolated from the main body of reinforcement.

In the case of concrete structures that are to be constructed in-situ, consideration shall be given to the likely ingress of air and waterborne chlorides into the concrete mix. The use of stainless steel reinforcement shall be considered in these situations in addition to the provision of adequate cover. The use of stainless reinforcement may also be considered in circumstances where inspection and repair of the concrete elements is likely to be disproportionately expensive or difficult.

C.4.4 Cathodic protection of reinforcement

Corrosion protection to carbon steel reinforcement and cast in elements may also be achieved by the use of an appropriate cathodic protection system. Reference shall be made to ISO 12473, for the design and specification of these systems. Particular care shall be taken when it is intended to protect pre-stressing steel using cathodic protection due to the risk of hydrogen embrittlement. This is a particular risk with impressed current systems.

Where attached or adjacent steelwork is provided with cathodic protection, allowance shall be made for interaction between this and the reinforcing or pre-stressing steel. In particular, attached or adjacent steelwork has in practice frequently been found to be electrically continuous with the reinforcing steel. Appropriate allowance shall then be made for the resulting drain on the cathodic protection system.

C.5 Non-ferrous metals

Non-ferrous metals commonly used in marine applications may be subject to a range of corrosion types. Specification of appropriate material grades and protection systems shall be undertaken with reference to appropriate recognized standards and specialist literature.

C.6 Composite structures

Galvanic corrosion shall be considered when carbon fibre composites are in contact with metal. Usually the metal degrades first, but in some cases, damage to the matrix and the fibres can also happen. Carbon composites shall be electrically isolated from metal components.

C.7 Compatibility of materials

When different structural materials are used in combination, attention shall be given to isolate materials that may create electrolytic corrosion, such as dissimilar metals (even of the same alloy). Particular care shall be taken when small components can act as anodes in conjunction with surrounding dissimilar materials. Sacrificial anodes shall be included in a design when different materials are used.

C.8 Chains, steel wire and fibre rope

Corrosion of chains and steel wire ropes used for mooring of floating MECs shall be designed with consideration of corrosion.

Fibre rope segments in mooring lines are normally protected by an outer jacket, which is to have adequate resistance to hydrolysis, chemicals, ultraviolet, fish bite, friction and shear while retaining adequate flexibility at minimum exposure temperatures in order to meet the requirement to protect the rope core.

Annex D
(normative)

Operational and structural resonance

D.1 General

The designer shall take into account the harmonic response both for structural and mechanical elements. Whilst structural damping can be expected to be quite low, hydrodynamic damping can be quite significant and should be estimated where practical.

It should be noted that avoiding natural frequencies will not eliminate all fatigue stresses.

D.2 Control systems

As the control system can influence resonant response of both structural and mechanical elements (both passively and actively), the designer shall carry out an FMEA for the control system to ensure that there are no failure modes which can increase the resonant response of either the structural or mechanical elements (e.g. loss of blade, out of balance rotor shaft or damaged gearbox bearings).

D.3 Exciting frequencies

The designer shall ascertain on which part of the device all forces or moments are acting and in which plane.

NOTE For any device there are forces or moments applied that are of a cyclical nature. The frequency at which these forces occur can be considered as exciting frequencies with respect to the harmonic response. These frequencies can be fixed, random or a function of another frequency. The most significant forces are fluid acting on the support structure, waves and the cyclic passing of turbine blades (or other moving components of the MEC). For TECs turbulence slicing can be significant as this can often generate periodic forces at the passing frequency of the blades somewhat larger than those caused by support structure shadow alone. Some of the excitation can be termed broadband excitation, containing a range of frequencies.

D.4 Natural frequencies

Both structural and mechanical elements will have primary and higher order natural frequencies. All natural frequencies that could be excited by exciting frequencies shall be identified. Due account shall be taken of added mass that submerged structural and mechanical elements can be influenced by. If a structural frequency is close (say within 10 %) of a hydrodynamic frequency, there is a tendency for them to move together. Vortex Induced Vibration (VIV) is an example of this problem. The mode shapes of all natural frequencies shall be considered so that it is understood how such frequencies can be excited.

Where it is intended to avoid operating at a natural frequency the three most common approaches taken are to:

- ensure that the stiffness of the structural or mechanical elements is low such that the natural frequency will occur sufficiently below the exciting frequency;
- ensure that the stiffness of the structural or mechanical elements is relatively high such that the natural frequency will occur above the exciting frequency; and
- ensure that there is sufficient damping of the structural or mechanical elements such that the response to an exciting frequency will not result in the fatigue stresses induced being significant in comparison to the mean stresses.

Using the first approach requires the least amount of material in order to achieve a lower level of stiffness. However, the designer needs to be careful that whilst the first natural frequency is below any exciting frequency, the second (or third, etc.) mode of natural frequency is also not close to any exciting frequency. The second approach is the simplest method of avoiding a harmonic response. The third approach is difficult to achieve unless a separate damping component is added.

D.5 Analysis

Any analysis shall have three parts to it as follows:

- the natural frequencies shall be identified together with the mode shapes;
- the exciting frequencies shall be identified; and
- the relationship between the two shall be clarified.

The simplest way of identifying the relationship between the natural frequencies and the exciting frequencies is by means of a Campbell diagram (ISO 13373-2). The Campbell diagram shall indicate the exciting frequencies associated with various operating (or running) conditions of the device.

Any points where the natural frequencies and the exciting frequencies coincide shall be noted. For the design to be acceptable, the margin between natural frequency and operating speed range shall be at least ±20 %.

If a natural frequency is found to be within ±20 % of the operating speed range, then a forced response calculation that takes into account the damping of the system shall be carried out. Ideally, the model should reflect all six degrees of freedom. It is recommended that any natural frequencies that are found within ±20 % of operating speed range have a damping coefficient greater than 0,4, or an amplification factor less than 2,5.

NOTE When undertaking vibration analysis, software often considers only one degree of freedom. This approach has some limitations. For example non-resonant vibration in one degree of freedom can excite resonant frequencies in another degree of freedom. This can be a particular problem when a system has a mechanism for coupling vibration in one degree of freedom to another degree of freedom.

D.6 Balancing of the rotating components

When considering lateral (also known as whirling) vibration of rotating components, the designer shall take into account the effect of balancing. The following standards may be of assistance in this regard.

- ISO 19499, *Mechanical vibration – Balancing – Guidance on the use and application of balancing standards*.
- ISO 1940-1, *Mechanical vibration – Balance quality requirements for rotors in a constant (rigid) state – Part 1: Specification and verification of balance tolerances*.
- ISO 1940-2, *Mechanical vibration – Balance quality requirements of rigid rotors – Part 2: Balance errors*.
- ISO 11342, *Mechanical vibration – Methods and criteria for the mechanical balancing of flexible rotors*.

Annex E
(informative)

Requirements for a basis of design

E.1 General

Although not exhaustive, it is recommended that the basis of design incorporates the guidance provided in Annex E. The EMEC Guidelines for Design Basis of Marine Energy Conversion Systems is also recommended. A flow chart detailing a typical procedure to develop a basis of design is provided in Figure E.1 below.

Details of a Quality Assurance (QA) system shall be appropriate to the level of design being undertaken. The design process shall be carried out in accordance with an internationally recognized quality management system.

The design practices of the designer’s organization shall be identified, including departmental instructions to ensure the orderly and controlled preparation of design and subsequent verification.

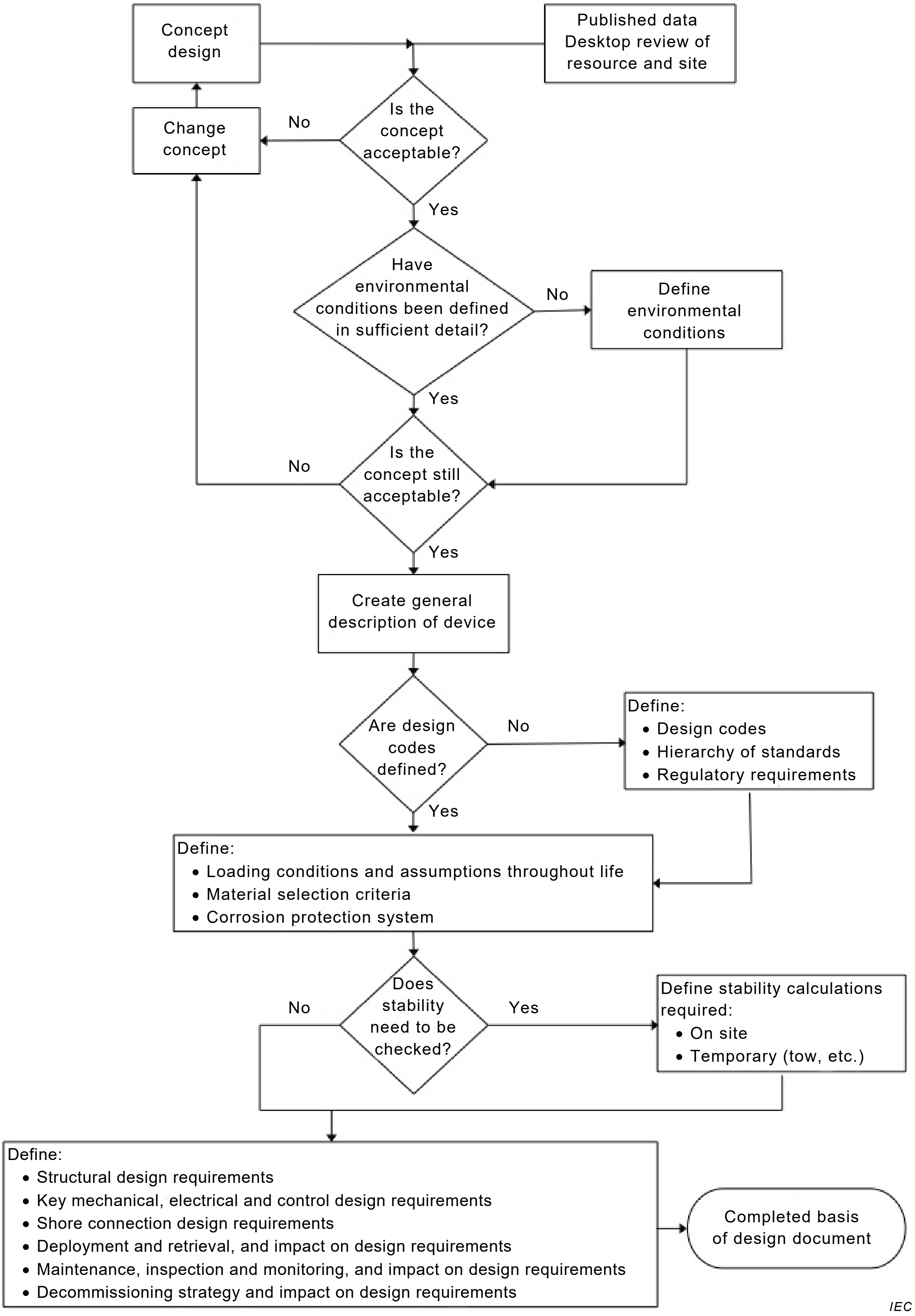
Provision shall be made for the identification, documentation and appropriate approval of all design change and modifications, both during the design and manufacturing stages.

Methods shall be prescribed for resolving incomplete, ambiguous or conflicting requirements.

Design inputs shall be identified, such as sources of data, preferred standard parts or materials and design information. Procedures shall be provided for their selection and review by the manufacturer for adequacy.

Details of a Quality Assurance (QA) system shall be appropriate to the level of design being undertaken. The design process shall be carried out in accordance with an internationally recognized quality management system. Some aspects shall be given special attention during the design process, as outlined below.

The design practices of the designer’s organization shall be identified including departmental instructions to ensure the orderly and controlled preparation of design and subsequent verification.



SOURCE: Adapted from EMEC Guidelines

Figure E.1 – Quality assurance system

E.2 Design life

As a minimum, the design life of a MEC can be generally taken as the period of time for a project to be considered financially viable. Therefore, the design shall take account of the local ambient conditions, imposed loading and rates of deterioration (i.e. corrosion of structural steel) that are to be expected during this period. The design life of individual components, and target replacement schedule can also be defined.

E.3 Design standards

Applicable design standards to be used and the hierarchy that shall be followed when there are various standards that impact design are as follows:

International standards for Marine energy – Wave, tidal and other water current converters (e.g. IEC 62600 series).

Other International standards (e.g. ISO, IEC).

E.4 Regional regulations

Due consideration shall also be given to applicable local, regional and national regulations, statutes, codes and standards.

E.5 Environmental conditions

E.5.1 General

The basis of design shall describe the various environmental phenomena that the device will be exposed to and therefore is fundamental to the design. It is at this point that a designer might find that additional data is required before developing the concept design and, if this is the case, Annex E provides direction on how to obtain such data.

E.5.2 Meteorology and climatology

Meteorological and climatologically processes shall be considered. Although not all may be applicable to a specific device, the following key processes have been identified to assist the developer’s understanding of the key environmental considerations and their potential impacts.

Wind loading is an important consideration, particularly if part of the MEC extends above the water surface. Wind data will also assist in the forecast of wave parameters in the absence of recorded offshore wave data.

For many locations, some historical data may be available. This may be fairly general and not take into account local effects. The designer shall decide if the accuracy of the historical data is sufficient.

E.5.3 Air/water conditions

Estimates are to be made of minimum and maximum air temperatures that may influence the structural design of the device, particularly exposed elements. Water temperature and salinity may also have an influence on design and historical data for the device location shall be obtained.

E.5.4 Water level

There are various ways water level can change. It is important that these are considered as this could influence the type and size of the support structure.

a) Tide levels

   The designer shall decide if the accuracy of the available data is sufficient for the design process. If no suitable information is available, then measurements would need to be taken over a suitable time period of at least 1 year.

b) Storm surge

   Wind from a storm can raise water levels and if this coincides with a high tide then the sea level can rise above the normal high tide level. This is known as a storm surge. Historical data will give an indication of previous storm surges and the impact on water levels. Storms can also produce extremely low water levels.

c) Sea level rise

   The possibility of changing sea level shall be considered. The actual values of such changes are difficult to quantify. Predications of sea level rise should be treated with caution, as the accuracy of such predictions is uncertain. However, the designer should understand the sensitivity of the design to sea level rise.

E.5.5 Currents

Design current velocities are to be established, taking account of all relevant components, including the following:

- tidal currents;
- circulation currents;
- wind driven current;
- storm surge generated current; and
- current turbulence.

E.5.6 Waves

The design of most devices will need to take into account the action of the waves and the wave loading (slam, overtopping, wave processes, green seas, etc.).

E.5.7 Marine life

Marine growth can increase loads on structures and mooring lines. The extent of marine growth that can be expected will vary from one location to another.

Account is to be taken in the design of build-up of marine growth on the anchor lines, and/or the structure (floating or fixed), and the resulting increase in load. The thickness of marine growth taken into account shall be stated in the O and M manual and shall not to be exceeded in service.

E.6 Seabed conditions

E.6.1 General

Critical to design of the support structure and foundation, the seabed geotechnical and bathymetric conditions at the proposed location of deployment shall be defined.

E.6.2 Bathymetry and coastal topography

MEC performance will be significantly affected by the bathymetry and coastal topographic features of the area of deployment. For this reason, it will be necessary to understand how the bathymetry and topographic features could change the performance of the device. It will also be necessary to carry out a review of the bathymetry and topographic features of the proposed installation site.

E.7 Material standards and testing

In order to ensure consistency, materials shall be referenced to an ISO standard. For instance terms such as ’mild steel’ shall be avoided, as the term might have different meanings within different organizations and locations.

Annex F
(informative)

Wave spectrum

F.1 Overview

Spectral models are used to obtain an estimate of the entire wave spectrum from known values of the significant wave height and wave period as obtained from hindcast calculations or by direct measurement. It is often useful to describe a sea state using a linear random wave model by specifying a wave spectrum. Two-parameter spectral formulations are generally preferred for offshore engineering applications. The parameters required for defining a wave spectrum are the significant wave height, H_s and the peak period, T_P.

The most accurate wave spectrum is based on local geography, bathymetry and severity of the sea state. However, the most frequently used spectra for wind-generated seas are the Pierson-Moskowitz (PM) spectrum, for a fully developed sea, and the JONSWAP spectrum, for a developing sea. Both spectra describe wind conditions associated with the most severe sea states. For swell spectra, information can be found in ISO 19901-1.

The best results are obtained if these spectra are used with site-specific parameters that consider fetch and shallow water effects.

F.2 The Pierson-Moskowitz spectrum

The PM spectrum is applicable to a fully developed sea, i.e. when the growth of the waves is not limited by the fetch. For many areas, this will be the case most of the time and the PM spectrum is, therefore, often used for fatigue analysis. The spectral density of the surface elevation is given by:

$$S_{PM}(f) = 0{,}3125 \cdot H_s^2 \cdot f_P^4 \cdot f^{-5} \cdot \exp\left(-1{,}25\left(\frac{f_P}{f}\right)^{-4}\right) \tag{F.1}$$

where:

H_s is the significant wave height (m);

f_P is the peak frequency (= 1/ T_P) (Hz);

f is the frequency (Hz).

Figure F.1 shows the PM spectrum for a sea state with H_s equal to 2,25 m and T_P equal to 7,13 s.

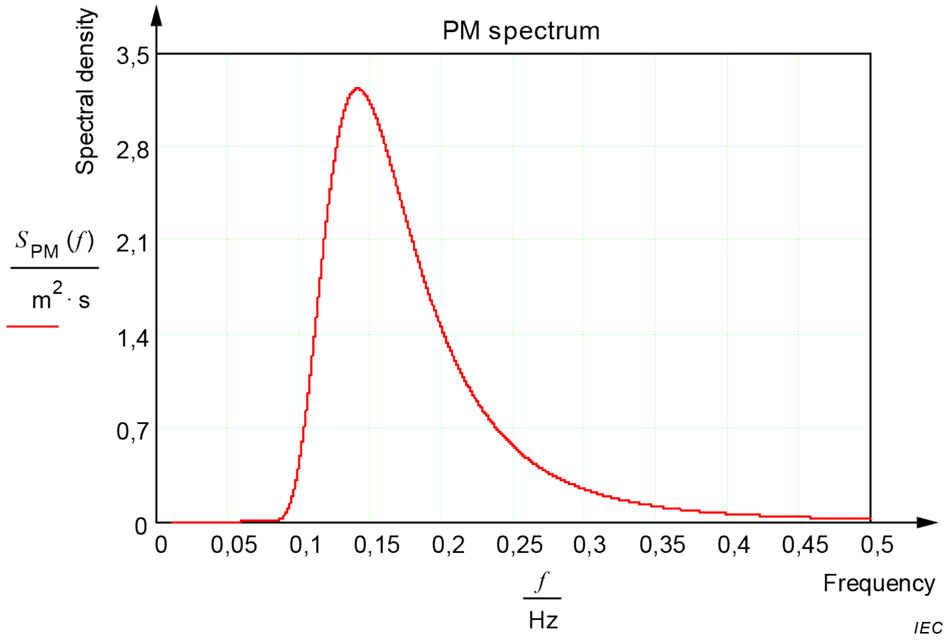


Figure F.1 – PM spectrum

The JONSWAP spectrum is formulated as a modification of the PM spectrum for a developing sea state in a fetch-limited situation. The spectrum was derived to account for a higher peak and a narrower spectrum in a storm situation for the same total energy as compared with the PM spectrum. Therefore, the JONSWAP spectrum is often used for extreme event analysis.

For the JONSWAP spectrum, two modification factors are introduced: a peak enhancement factor, γ^{α}, and a normalizing factor, $C(\gamma)$. The first factor increases the peak and narrows the spectrum; the second reduces the spectral density to ensure that both spectral forms have the same H_s (energy). For γ = 1, the JONSWAP spectrum reduces to the PM spectrum.

The spectral density of the surface elevation is given by

$$S_{JS}(f) = C(\gamma) \cdot S_{PM}(f) \cdot \gamma^{\alpha} \tag{F.2}$$

where:

γ is the non-dimensional peak-shape parameter

$$C(\gamma) \text{ is the normalizing factor } = \frac{\int_0^{\infty} S_{PM}(f) df}{\int_0^{\infty} S_{PM}(f) \gamma^{\alpha} df} \tag{F.3}$$

Figure F.2 shows a comparison between the JONSWAP spectrum and the PM spectrum for a typical North Sea storm sea state (H_s = 14,4 m, T_P = 15,4 s and γ = 3,3).

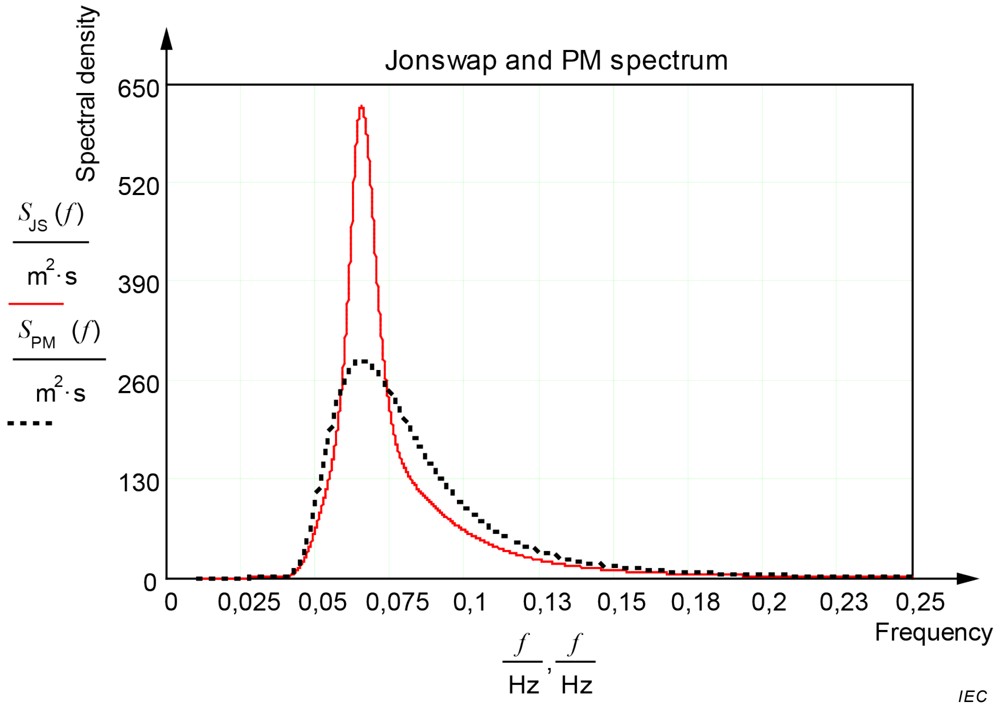


Figure F.2 – JONSWAP and PM spectrums for typical North Sea storm sea state

In lieu of more detailed information, the following values may be used

$$\alpha = \exp\left(-\frac{(f - f_P)^2}{2\sigma^2 f_P^2}\right) \tag{F.4}$$

where:

$\sigma =$ 0,07 for $f \le f_P$

$\sigma =$ 0,09 for $f > f_P$

Peak-shape parameter:

$$\gamma = \begin{cases} 5 & \text{for} \quad \frac{T_P}{\sqrt{H_s}} \le 3{,}6 \\ \exp\left(5{,}75 - 1{,}15\frac{T_P}{\sqrt{H_s}}\right) & \text{for} \quad 3{,}6 \le \frac{T_P}{\sqrt{H_s}} \le 5 \\ 1 & \text{for} \quad \frac{T_P}{\sqrt{H_s}} > 5 \end{cases} \tag{F.5}$$

with H_s in m and T_P in s.

Normalizing factor:

$$C(\gamma) = 1 - 0{,}287 \cdot \ln\gamma \tag{F.6}$$

The normalizing factor shall be equal to unity for γ = 1.

The JONSWAP spectrum is expected to be a reasonable model for

$$3{,}6 < T_\mathrm{P} \big/ \sqrt{H_\mathrm{s}} < 5 \tag{F.7}$$

Where the peak period T_P is in seconds and the significant wave height H_s is in metres and shall be used with caution outside this interval.

F.3 Relationship between peak and zero crossing periods

The following approximate relationship exists between the peak period T_P and the zero-crossing period T_Z. This relationship is valid for both the PM spectrum and the JONSWAP spectrum.

$$T_\mathrm{Z} = T_\mathrm{P} \cdot \sqrt{\frac{5+\gamma}{11+\gamma}} \tag{F.8}$$

For γ = 1, the following relationship is found for the PM spectrum

$$T_\mathrm{P} = 1{,}41 \cdot T_\mathrm{Z} \tag{F.9}$$

F.4 Wave directional spreading

In the design of offshore structures, all waves are normally assumed to propagate in one direction, namely in the direction of the wind. All waves are thus assumed long-crested (2-dimensional). The one-dimensional wave spectra given above reflect this situation.

However, most real seas are composed of many large and small waves propagating in many directions, i.e. the wave energy at a point has both an angular distribution and a distribution over a range of frequencies. Such waves are called short-crested, as they do not have a long crest. Wave direction and spreading significantly influence the wave loads on offshore or coastal structures and the sediment transport in a surf zone. As compared to long-crested waves, they represent a reduction in the wave action, which may be expressed in a two-dimensional wave spectrum $S(f,\theta)\,S(f,\theta)$, where θ is a direction relative to the wind direction.

$$S(f,\theta) = S(f) \cdot D(f,\theta) \tag{F.10}$$

where:

$S(f)$ is the one-dimensional wave spectrum;

$D(f,\theta)$ is the directional spreading function.

The spreading function $D(f,\theta)$ is generally not known, and is, therefore, normally substituted by a symmetric, frequency independent function $D(\theta)$ over a sector on either side of the main direction. The directionality function fulfils the requirement:

$$\int_{-\pi}^{\pi} D(\theta) d\theta = 1 \tag{F.11}$$

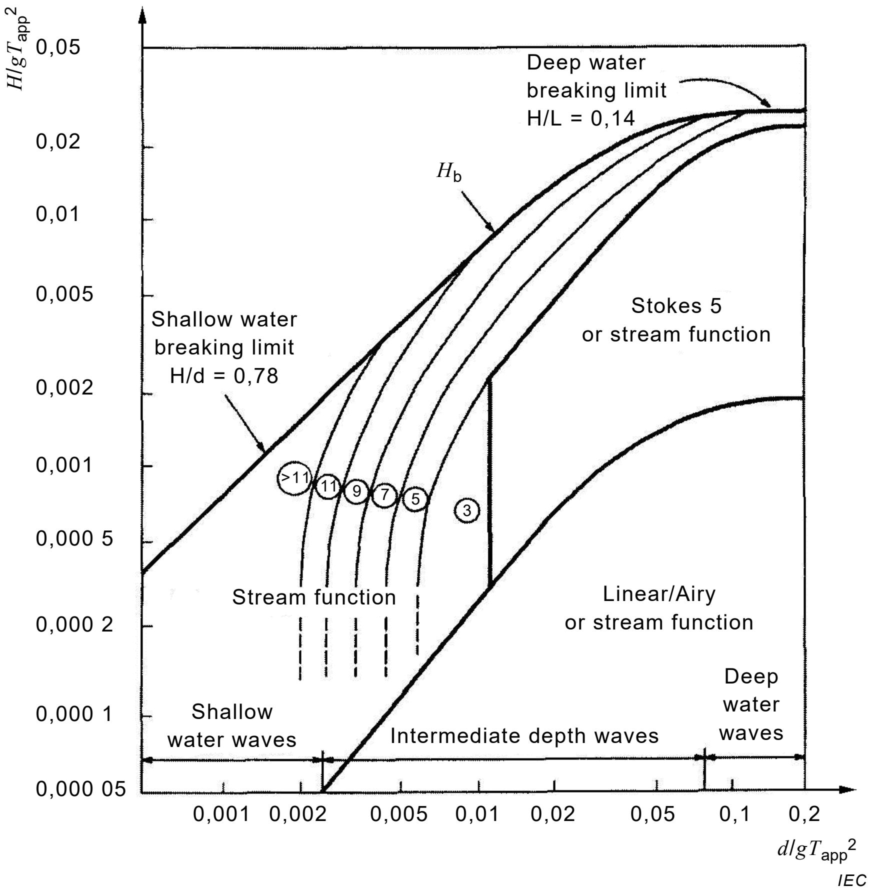
Normally, directional information is difficult to measure and validate. In practical design of fixed offshore structures, especially in shallow areas, unidirectional sea states are used.

Annex G
(informative)

Shallow water hydrodynamics and breaking waves

G.1 Selection of suitable wave theories

The kinematics of two-dimensional regular waves can be predicted using several periodic wave theories. Different theories provide approximate solutions to the same differential equations with appropriate boundary conditions. A waveform that is symmetric about the crest and propagates without changing shape is computed by all the theories. The theories differ in their functional formulation and the degree to which they satisfy the non-linear kinematic and dynamic boundary conditions at the wave surface. Figure G.1 provides guidance on the selection of suitable regular wave theories as a function of normalized wave height and water depth.



Key

$H/gT_{app}2$	is the dimensionless wave steepness
d	is the mean water depth
$d/gT_{app}2$	is the dimensionless relative depth
T_{app}	is the apparent wave period
H	is the wave height
H_b	is the breaking wave height
g	is the acceleration of gravity

SOURCE: Atkins, 1990; Modified by API Task Group on Wave Force Commentary

Figure G.1 – Regions of applicability of stream functions, stokes V, and linear wave theory

In deep water, waves of small height are approximately linear in nature. Regular waves in this region are sinusoidal in shape and may be modelled using linear Airy wave theory or a low-order stream function solution.

As the wave height is increased or the water depth reduced, wave steepness becomes greater and the height of the wave crest above the still water level becomes greater than the depth of the trough below the same datum. The wave profile and water particle kinematics can no longer be described accurately using linear wave theory. Stream function theory can be suitably applied over a wide range of depths. Stokes 5th order wave theory may be used to model steep waves in deep water.

As wave height is further increased or the water depth further reduced, the horizontal velocity of water particles in the wave crest will at some point exceed the wave celerity and the structure of the wave will break down. Water particles are ejected forward from the crest and the wave is said to break.

Further description of wave theories and their ranges of application may be found in ISO 19901-1.

G.2 Modelling of irregular wave trains

Irregular wave trains that represent random sea states may be modelled as a summation of sinusoidal wave components, each described by Airy theory. In intermediate or shallow water depths, the accuracy of Airy theory should be assessed.

Linear Airy wave theory defines water particle kinematics from the sea floor to the still water level. A wave stretching technique may be applied to take account of the varying height of the water surface. Wheeler-stretching and delta-stretching are two suitable methods and are described in ISO 19901-1:2015, A.8.4 and A.9.4.1.

The presence of a compact structure in the wave field may significantly influence the nature of the waves approaching the structure through scattering in many directions. Such cases require a diffraction analysis to be performed using the MacCamy-Fuchs [MacCamy 1954] correction to account for wave diffraction effects on applied structural loads.

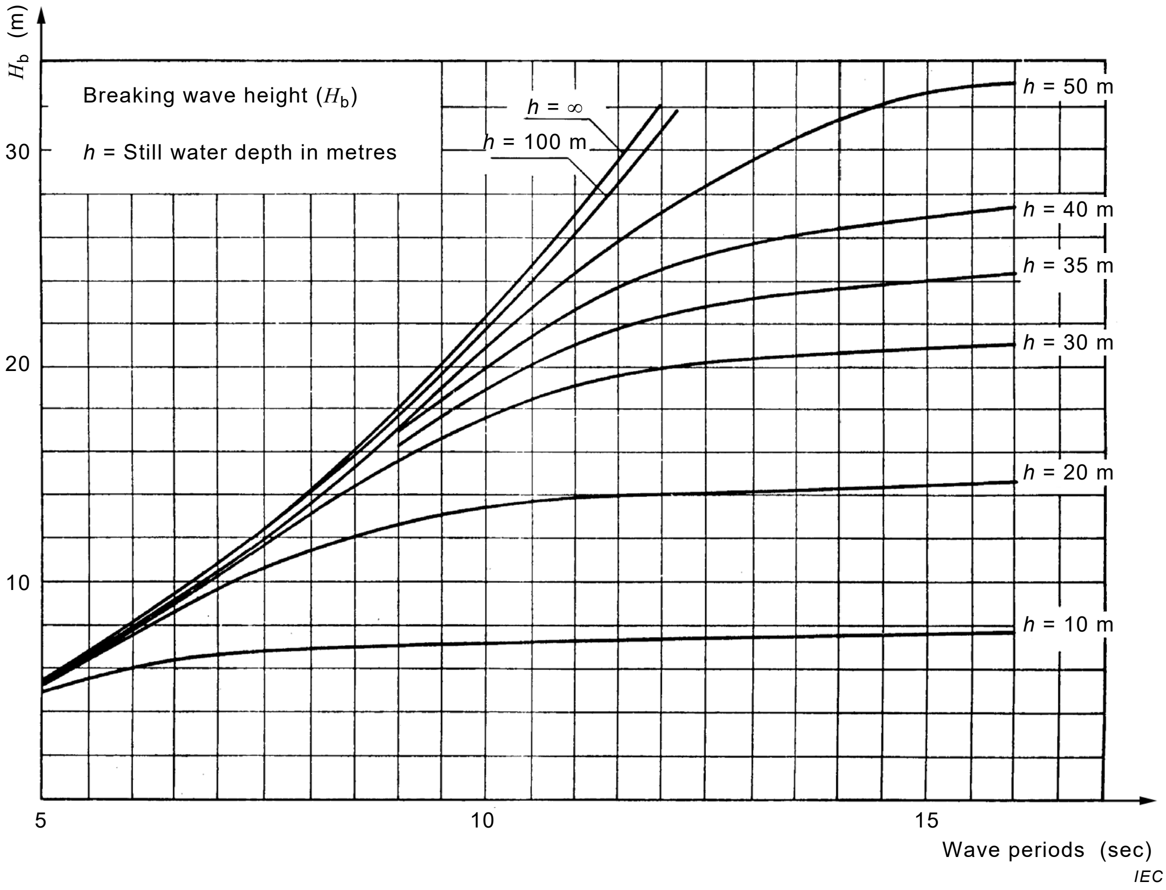
In shallow waters the surface elevation distribution will deviate from a Gaussian distribution and the distribution of individual wave heights will deviate from a Rayleigh distribution. In these cases, the wave height distribution developed for shallow water sites by Battjes and Groenendijk [Battjes and Groenendijk 2000] may be used.

G.3 Breaking waves

Waves may break in different ways, depending principally on the ratio of deep-water wave steepness to sea floor slope.

In shallow water, the empirical breaking limit of the wave height is approximately 78 % of the local water depth. The presence of a sloping sea floor (still water depth decreasing in the direction of wave propagation) can lead to breaking waves which are significantly higher than limiting height regular waves in the same local water depth. Guidance is provided by Barltrop and Adams [Barltrop and Adams 1991].

The breaking wave height as a function of wave period for different water depths is given in Figure G.2.



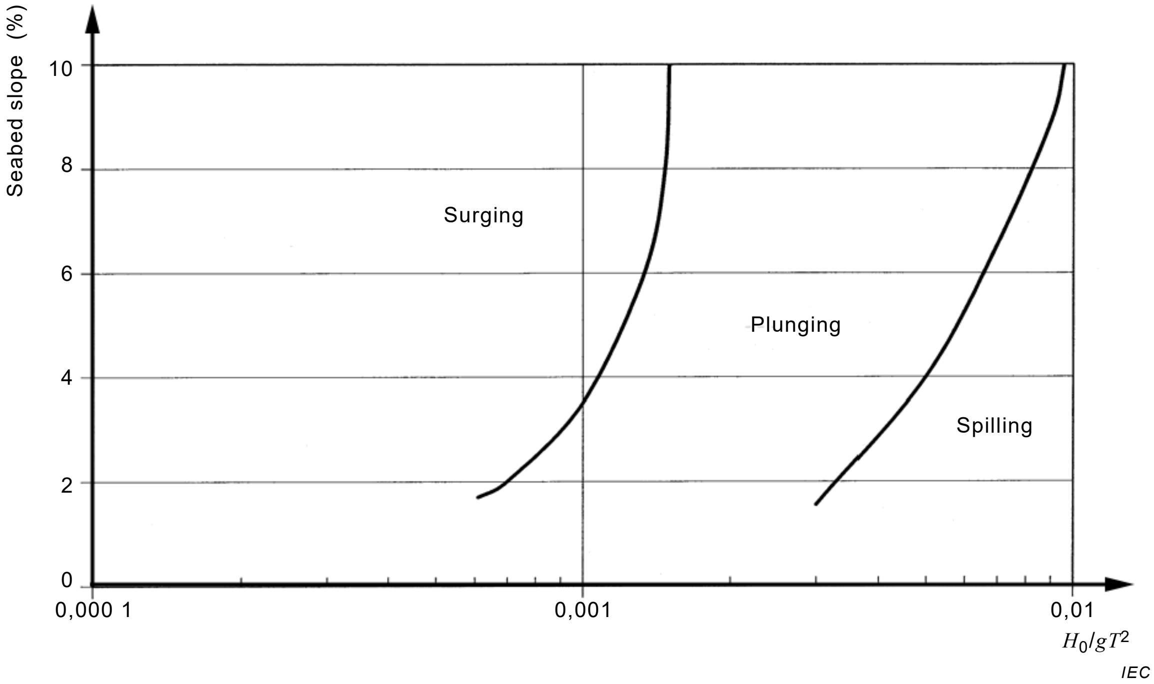
SOURCE: Recommended Practice DNV-RP-C205, Oct. 2010, pp.31

Figure G.2 – Breaking wave height dependent on still water depth

There are three types of breaking waves depending on the wave steepness and the slope of the seabed:

- surging breaker;
- plunging breaker; and
- spilling breaker.

Figure G.3 indicates which type of breaking wave can be expected as a function of the slope of the seabed, the wave period T and the wave height H_0 in deep waters.



SOURCE: DNV-OS-J101

Figure G.3 – Transitions between different types of breaking waves as a function of seabed slope, wave height in deep waters and wave period

Formation of a particular breaker type depends on the non-dimensional parameter

$$\beta = H_b/(g\,T^2\,m) \tag{G.1}$$

where H_b is the wave height at breaking and m is the beach slope, assumed to be constant over several wavelengths.

Spilling breakers are characterized by foam spilling from the crest down on the forward face of the wave. They occur in deep water or on gentle beach slopes. Spilling breakers usually form when $\beta > 5$.

Plunging breakers occur on moderately steep beach slopes. They are characterized by a well-defined jet of water forming from the crest and falling onto the water surface ahead of the crest. Plunging breakers form when $0{,}1 < \beta < 5$.

Surging breakers occur on relatively steep beaches where there is considerable reflection with foam forming near the beach surface. Surging breakers form when $\beta < 0{,}1$.

The collapsing wave forms lower down the forward face of the wave and is a transition type between plunging and surging breakers, $\beta \sim 0{,}1$

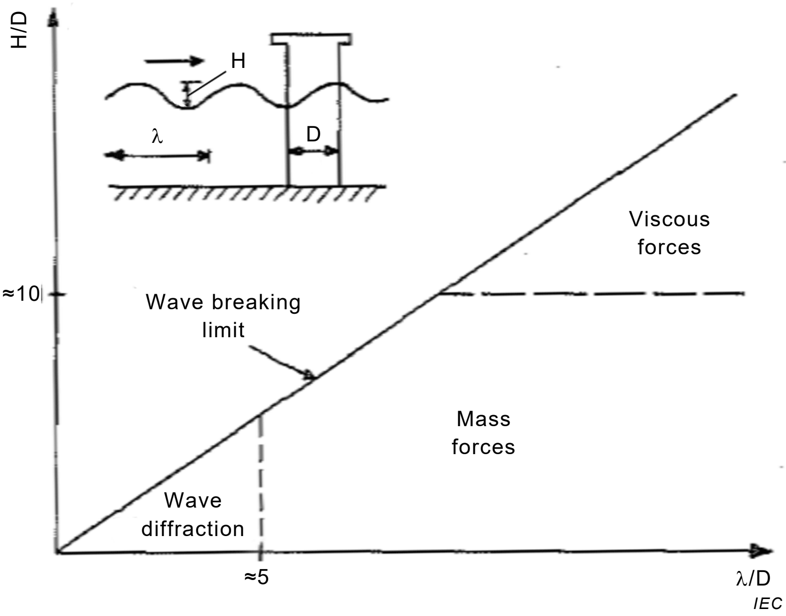
The occurrence and type of breaking waves may also be influenced by the presence of the structure itself, especially for compact structures.

Annex H
(informative)

Guidance on calculation of hydrodynamic loads

H.1 General

Depending on wave parameters and the type of structure, both viscous effects and potential flow effects shall be considered in determining wave loads. Figure H.1 may be used as a guide to establish the relative importance of viscous and different types of potential flow effects.



SOURCE: DNV-OS-J101

Figure H.1 – Relative importance of mass, viscous drag and diffraction forces on marine structures

When the characteristic dimension of the body is less than 20 % of the wavelength, flow separation effects will be insignificant and the modification of the flow by the presence of the body will be minimal. In such cases, the Morison equation may be used to calculate wave force on the slender member. The perpendicular force per unit length on a strip of circular cylinder is [Morison, et al., 1950; McCormick, 2010; Dean, et al. 2010]:

$$dF = \rho C_\mathrm{m} \pi \frac{D^2}{4} \dot{u} + \frac{1}{2} \rho C_\mathrm{d} D u |u| \qquad \text{(H.1)}$$

where:

dF is the force;

ρ is the density of the fluid;

D is the diameter of the member;

u is the undisturbed fluid velocity perpendicular to the member;

$\dot{u}$ is the undisturbed fluid acceleration perpendicular to the member;

C_d is the drag coefficient;

C_m is the inertia coefficient.

The fluid kinematics shall be determined using a recognized wave theory. The wave theory shall be selected with due consideration of the water depth at the site. The empirical drag and inertia coefficients, C_d and C_m, are functions of the Reynolds number, the Keulegan-Carpenter number and surface roughness. Possible increase of cross-sectional area and change of roughness caused by icing or marine growth shall be considered. Guidance on selecting suitable values for C_d and C_m is given in ISO 19902. When the structure itself is moving, the relative velocity form of the Morison equation shall be used instead:

$$dF = \rho C_m \pi \frac{D^2}{4} \dot{u} - \rho (C_m - 1) \pi \frac{D^2}{4} \ddot{x} + \frac{1}{2} \rho C_d D (u - \dot{x}) |u - \dot{x}| \qquad \text{(H.2)}$$

where:

$\dot{x}$ is the normal velocity of the cylinder itself, and

$\ddot{x}$ is the normal acceleration of the cylinder itself.

Computational fluid mechanics (CFD) methods where the full Navier-Stokes equations are solved can be useful in estimating loads and responses. The software shall have been previously verified and validated for the type of structure being analysed. When prior validation is lacking or when new types of structures are designed, model tests or full-scale tests shall be carried out to validate theoretical predictions.

H.2 Large bodies

For large structures that span more than 20 % of the wavelength, flow separation effects shall be considered. In such cases, the solution to the wave/structure interaction problem may be based on potential flow theory. A previously validated computer programme based on potential flow theory and accounting for radiation and diffraction shall be used. If a frequency domain analysis is used, both first and second order (in wave slope) wave forces may be required. The first order parameters include the oscillatory wave exciting force acting at the wave frequency as well as the added mass and radiation damping. The second order forces include the steady wave drift force, slowly-varying difference-frequency forces and the sum-frequency forces. The slowly-varying forces are important when MECs are softly moored, as they could potentially induce resonance in the soft moorings. The sum-frequency forces are important when MECs are taut moored, as they could induce resonance in the taut moorings. For moored systems, the effect of the mooring system on the structure response may have to be accounted for in determining wave loads. Proximity to other bodies and the resulting hydrodynamic coupling effects shall be considered. If there are interconnections or mechanical coupling with other dynamic systems, those coupling effects may have to be considered to correctly predict wave-induced motions.

Radiation-diffraction programmes implementing the boundary element method using free surface Green functions are prone to erroneous results at a set of frequencies called “irregular frequencies”. These frequencies correspond to wavelengths that are shorter than the body dimensions. Care shall be taken to identify and eliminate such erroneous results. Methods to predict irregular frequencies for simple geometries are available in [Patel, 1989]. Many modern radiation diffraction programmes are also capable of suppressing the effect of irregular frequencies by imposing an artificial lid on the interior free surface.

H.3 Hybrid structures

For structures composed of both large diameter structure and slender members, a hybrid method may be used in which potential flow theory is used to predict wave forces on the large body and the Morison equation is used to predict wave forces on the slender member. The large body will modify the wave kinematics to be applied in the Morison equation.

H.4 Short term statistics

In a stochastic approach involving a frequency domain analysis with the design sea state represented by an appropriate wave elevation spectrum, the short term "extreme" of the first order load or response shall be estimated based on a Rayleigh distribution of amplitudes as follows:

$$F_\alpha = \sqrt{2\ln\left(\frac{T}{T_z\alpha}\right)}\sqrt{m_0} \tag{H.3}$$

where:

F_α is the maximum single amplitude of the first order load or response;

T is the exposure duration;

α is the probability that F_α will be exceeded;

m_0 is the variance of the load or response process;

T_z is the zero-crossing period of the load or response process.

α shall be taken as maximum 0,10 and the exposure duration T shall be taken to be minimum 3 h.

In shallow water, wave heights will be limited by the water depth. Therefore use of the unmodified Rayleigh distribution for representing the distribution of wave heights or load amplitudes may be on the conservative side. Other probability distributions for wave heights in shallow water have been proposed (e.g. [Mai, et al. 2010; Caires, et al., 2012]). They are permissible if validated by measured site-specific wave data.

H.5 Breaking wave loads

Impact loads from breaking waves depend on the type of breaking waves. A distinction is made between surging, plunging and spilling waves. For plunging waves, an impact load model may be used to calculate the forces on the structure. The impact force from a plunging wave can be expressed as:

$$F = \frac{1}{2}\rho C_s A u^2 \tag{H.4}$$

where:

u is the water particle velocity at the plunging wave crest,

A is the area of the structure which is assumed exposed to the slamming force,

C_s is the slamming coefficient.

For a smooth cylinder, the slamming coefficient shall not be taken less than 3,0. The upper limit for the slamming coefficient is 2π. For spilling breakers, the total load can be calculated using a strip theory where the slamming coefficient for each strip is a function of the submergence of the strip, decaying from 5,15 when the wave hits the strip to 0,8 when the strip is fully submerged [DNV-OS-J101].

IEC 61400-3:2009, Annex D gives guidelines for estimating breaking wave impact loads on fixed vertical or inclined cylindrical structures.

H.6 Dynamic loads due to turbulent flow

The dynamic force acting on a body due to turbulent flow depends on the length scale of turbulence and body shape. The force is related to the velocity fluctuations by the fluid dynamic admittance $H(f)$ and given by:

$$S_{\mathrm{FF}(f)} = 4{C_\mathrm{D}}^2\left(S_{\mathrm{VV}}(f)/V^2\right)H^2(f) \tag{H.5}$$

where:

$S_{\mathrm{FF}}(f)$ is the power spectrum of force in the mean flow direction;

$S_{\mathrm{VV}}(f)$ is the power spectrum of velocity in the mean flow direction;

C_D is the drag coefficient;

V is the incident velocity;

$H(f)$ is obtained from tabulated data (e.g., Naudascher, Eduard, and Donald Rockwell. *Flow-induced vibrations: an engineering guide*. Courier Dover Publications, 2012.)

Bibliography

EMEC Guidelines

Guidelines for Design Basis of Marine Energy Conversion Systems, EMEC, 2009

Guidelines for Reliability, Maintainability and Survivability of Marine Energy Conversion Systems, EMEC, 2009

International standards, regional standards, national standards, company standards

ABS Guide for building and classing offshore wind turbine installations

American Society of Civil Engineers Design Guideline, ASCE-7-05, section 2.2 – The Load Equations

API RP 2A "*Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms – Load and Resistance Factor Design*", April 1997

API RP 2A "*Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress Design*", December 2002

API RP 2A-WSD *Planning, Designing and Constructing Fixed Offshore Platforms, Working Stress Design*

API RP 2SK *Design and Analysis of Stationkeeping Systems for Floating Structures*

BS EN 1992-1:2004 – *Design of Concrete Structures – General Rules and rules for buildings*

BS 6744:2001 – *Stainless Steel bars for the Reinforcement of, and use in, Concrete*

Det Norske Veritas and Risø National Laboratory, *Guidelines for Design of Wind Turbines*, 2nd edition 2002.

DNV Offshore Standard DNV-OS-J101, *Design of Offshore Wind Turbine Structures*, June 2004.

DNV Offshore Standard DNV-OS-C301, "*STABILITY AND WATERTIGHT INTEGRITY*", October 2010

DNV Offshore Standard DNV-OS-J101, "*Design of Offshore Wind Turbine Structures*," October 2007

DNV *Guidelines on design and operation of wave energy converters*, Commissioned by the Carbon Trust and carried out by Det Norske Veritas, May 2005

DNV *Rules for planning and execution of marine operations*

DNV-OS-E301 *Offshore Standard for Position Mooring*

DNV-OS-J101 *Design of offshore wind turbine structures*

DNV-RP-C205 *Environmental Conditions and Environmental Loads*, April 2007.

DNV-RP-F205 *Global performance analysis of deepwater floating structures*

DNV-RP-H103 *Modeling and analysis of marine operations*

EN 12696:2000 – *Cathodic Protection of Steel in Concrete*

EN 1998-1 *Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings*

Germanischer Lloyd, "*Guideline for the Certification of Ocean Energy Converters, Part 1: Tidal energy converters*," DRAFT 2005

Germanischer Lloyd, "*Guideline for the Certification of Offshore Wind Turbines*", 2005.

Germanischer Lloyd, "*Rules for Classification and Construction – IV Industrial Services, Part 6: Offshore Technologies, Chapter 2: Mobile Offshore Units*", edition 2007

ISO 10418:2003, *Petroleum and natural gas industries – Offshore production installations – Basic surface process safety systems*

ISO 1052:1982, *Steels for general engineering purposes*

ISO 11303:2002, *Corrosion of metals and alloys – Guidelines for selection of protection methods against atmospheric corrosion*

ISO 11306:1998, *Corrosion of metals and alloys – Guidelines for exposing and evaluating metals and alloys in surface sea water*

ISO 11403-1:2014, *Plastics – Acquisition and presentation of comparable multipoint data – Part 1: Mechanical properties*

ISO 11403-2:2012, *Plastics – Acquisition and presentation of comparable multipoint data – Part 2: Thermal and processing properties*

ISO 11403-3:2014, *Plastics – Acquisition and presentation of comparable multipoint data – Part 3: Environmental influences on properties*

ISO 13003:2003, *Fibre-reinforced plastics – Determination of fatigue properties under cyclic loading conditions*

ISO 13373-1:2002, *Condition monitoring and diagnostics of machines – Vibration condition monitoring – Part 1: General procedures*

ISO 13373-2:2016, *Condition monitoring and diagnostics of machines – Vibration condition monitoring – Part 2: Processing , analysis and presentation of vibration data*

ISO 14125:1998, *Fibre-reinforced plastic composites – Determination of flexural properties*

ISO 14126:1999, *Fibre-reinforced plastic composites – Determination of compressive properties in the in-plane direction*

ISO 14688-1:2002, *Geotechnical investigations and testing – Identification and classification of soil – Part 1: Identification and description*

ISO 19901-1:2015, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 1: Metocean design and operation considerations*

ISO 19901-2:2004, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 2: Seismic design procedures and criteria*

ISO 19901-3:2014, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 3: Topsides structure*

ISO 19901-5:2016, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 5: Weight control during engineering and construction*

ISO 19901-7:2013, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 7: Stationkeeping systems for floating offshore structures and mobile offshore units*

ISO 19904-1:2006, *Petroleum and natural gas industries – Floating offshore structures – Part 1: Monohulls, semi-submersibles and spars*

ISO 19905-1:2016, *Petroleum and Natural Gas Industries – Site-specific Assessment of Mobile Offshore Units – Part 1: Jack-ups*

ISO 19906, *Petroleum and natural gas industries – Arctic offshore structures*

ISO 22965-1:2007, *Concrete – Part 1: Methods of specifying and guidance for the specifier*

ISO 6934 (all parts), *Steel for the prestressing of concrete*

ISO 6935 (all parts), *Steel for the reinforcement of concrete*

IEC 60092-301, *Electrical installations in ships – Part 301: Equipment – Generators and motors*

IEC 60204 (all parts), *Safety of Machinery – Electrical equipment of machines*

IEC 61400-3:2009, *Wind turbines – Part 3: Design requirements for offshore wind turbines*

IEC 61508 (all parts), *Functional safety of electrical/electronic/programmable electronic safety-related systems*

IEC 60721-2-1:2013, *Classification of environmental conditions – Part 2-1: Environmental conditions appearing in nature – Temperature and humidity*

IEC TS 62600-201, *Marine energy – Wave, tidal and other water current converters – Part 201: Tidal energy resource assessment and characterization*

ISO 12944 (all parts), Paints and varnishes – *Corrosion protection of steel structures by protective paint systems*

ISO 1940-1, *Mechanical vibration – Balance quality requirements for rotors in a constant (rigid) state – Part 1: Specification and verification of balance tolerances*

ISO 19499, *Mechanical vibration – Balancing – Guidance on the use and application of balancing standards*

ISO 9000, *Quality Management systems – Fundamentals and vocabulary*

ISO 9001, *Quality Management systems – Requirements*

Others

Andersen, T.L.; Frigaard, P.; Damsgaard, M. L.; De Vos, L.: *Wave Run-up on Slender Piles in Design Conditions: model tests and design rules for offshore wind*, Coastal Eng. Vol. 58, p. 281-289, 2011

AULT, J Peter, *The Use of Coatings for Corrosion Control on Offshore Oil Structures*, Journal of Protective Coatings and Linings, Volume: 23, Issue Number: 4, Technology Publishing Company, 2006

Barltrop, N. D. P., and Adams, A. J., *Dynamics of Fixed Marine Structures*, Butterworth Heinemann, ISBN 0 7506 1046 8, available from the Energy Institute, London, UK, 1991.

Battjes, J. A. and Groenendijk, H. W., "*Wave height distributions on shallow foreshores*", Coastal Engineering, Volume 40, Issue 3, June 2000, Pages 161-182

Caires, S., and van Gent, R.A., "*Wave Height Distribution in Constant and Finite Depths*", Coastal Engineering, 2012

Chakrabarti, S. K., "*Hydrodynamics of Offshore Structures*", Springer-Verlag, 1987

Clough, R.W. and J. Penzien, *Dynamics of Structures*, 3ed. Computers and Structures, Inc. 1995.

Code for the Construction and Equipment of Mobile Offshore Drilling Units – IMO MODU Code

Damsgaard, M.L.; Gravesen, H.; Andersen, T.L.: *Design loads on platforms on offshore wind turbine foundations with respect to vertical wave run-up*, Proceedings of the European Offshore Wind Conference 2007

Danmeier, D.G.; Seah, R.K.M.; Finnigan, T.; Roddler, D.; Abault, A.; Vacke, M. and Imamura, J.T.: *Validation of wave run-up calculation methods for a gravity based structure*, Proc. 27th Int. Conf. Offshore mechanics and Arctic Eng., OMAE2008, Estoril, Portugal, June 15-20 (2008) paper OMAE2008-57625

Dean, R.G., and Dalrymple, R.A., "*Water Wave Mechanics for Engineers and Scientists*", World Scientific, 2010

Faltinsen, O. M., *Sea loads on ships and offshore structures*, Cambridge University Press, 1990

Guide to Wave Analysis and Forecasting, WMO-No.702, World Meteorological Organization, Geneva, Switzerland, 1988.

Guidelines on design and operating wave energy converters, May 2005

Huges, S.A., "*Physical Models and Laboratory Techniques in Coastal Engineering*", World Scientific, 1993

MaCamy, R.C., R.A.Fuchs, "*Wave forces on piles: a diffraction theory*", US Army Beach Erosion Board, Tedch.Memo., 69, Dec. 1954.

Mai, S., Wilhelmi, J., and Barjenbruch,U., "*Wave Height Distributions in Shallow Waters*", Coastal Engineering, 2010

McCormick, M.E., *Ocean Engineering Mechanics with Applications*, Cambridge University Press, 2010

TurbSim User's Guide Version 1.06.00, NREL

Milne, I. A., R. N. Sharma, R. G. J. Flay and S. Bickerton, “*Characteristics of the Onset Flow Turbulence at a Tidal-Stream Power Site*”, Philosophical Transactions of The Royal Society, 2013.

MODU Code 2009, “*Code for the Construction and Equipment of Mobile Offshore Drilling Units, 2009*”, Res. A.1023(26) adopted 2009

Morison, J.R., O’Brien, M.P., Johnson, J.W., and Schaf, S.A., “*The Forces Exerted by Surface Waves on Piles*”, Petroleum Transactions, AIME, Vol.189, pp.149-157, 1950.

Ochi, M. K., *Ocean Waves – The Stochastic Approach*, Cambridge University Press, 1998.

Osalusi, Emmanuel, “*Analysis of Wave and Current Data in a Tidal Energy Test Site*”, Herriot Watt University, 2010.

Patel, M.H., “*Dynamics of Offshore Structures*”, Butterworths, 1989

Sarpkaya and Isaacson, *Mechanics of wave forces on offshore structures*, Van Nostrand Reinhold, 1981

The Carbon Trust – Marine Energy Challenge / DNV, “*Guideline on assessment and application of Standards and Recommended Practices for Wave Energy Conversion Devices*”, draft version, November 2004

The International convention for the Safety of Life at Seas – SOLAS

Wienke, J.: *Druckschlagbelastung auf schlanke zylindrische Bauwerke durch brechende Wellen.* Dissertation, Technische Universität Carolo-Wilhelmina Braunschweig, 2001

Wu, X-J and Price, W. G., “*An equivalent box approximation to predict irregular frequencies in arbitrarily-shaped three-dimensional marine structures*”, Applied Ocean Research, Vol. 8, No. 4, 1986, pp 223-231

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