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Bases for design of structures — General principles on risk assessment of systems involving structures

Bases du calcul des constructions — Principes généraux sur l'évaluation du risque pour les systèmes comprenant des structures

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Tel. + 41 22 749 01 11
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Contents

Page

Foreword v
Introduction vi
1 Scope 1
2 Normative references 1
3 Terms and definitions 2
4 General framework of risk assessment of systems involving structures 4
4.1 Overview of risk management of systems involving structures 4
4.2 Applicability of risk assessment 6
5 Establishment of structural engineering context 6
5.1 Structural-engineering context 6
5.2 Establishment of design basis 7
5.3 Assessment of existing structures 7
5.4 Assessment of exceptional structures or extraordinary events 7
5.5 Preparation of risk information for decision 7
6 Definition of system 8
6.1 Representation of the system 8
6.2 Identification of the subsystems 8
7 Identification of hazards and consequences 8
7.1 Identification of possible hazards 8
7.2 Identification of extent of scenarios 8
7.3 Identification of consequences 8
7.4 Hazard screening 8
8 Risk estimation 9
8.1 Types of risk estimation 9
8.2 Data for estimation 10
8.3 Risk representation 10
8.4 Estimation of probability 10
8.5 Estimation of consequence 11
8.6 Risk calculation 11
8.7 Sensitivity analysis 11
9 Risk evaluation 11
9.1 Risk acceptance 11
9.2 Risk criteria 12
10 Evaluation of options for risk treatment 12
10.1 General 12
10.2 Determination of options 12
10.3 Assessment of options for risk treatment 13
10.4 Implementation of risk treatment 13
11 Report 13
Annex A (informative) Principles of risk assessment 14
Annex B (informative) Examples of extraordinary events and exceptional structures for risk assessment 18
Annex C (informative) Techniques for treatment of expert opinions 20
Annex D (informative) Examples of quantitative risk representation 23

Annex E (informative) **Equations for risk estimation** 27
Annex F (informative) **Procedure for the estimation of consequences** 31
Annex G (informative) **Examples of measures for risk treatment** 33
Annex H (informative) **Examples of application of risk acceptance and optimization** 36
Bibliography 42

Foreword

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

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

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

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

ISO 13824 was prepared by Technical Committee ISO/TC 98, *Bases for design of structures*, Subcommittee SC 2, *Reliability of structures*.

Introduction

Recently, special attention has been has been focused on risk. Although risk assessment of structures is done with a common basis, it has been implemented under various contexts in diversified ways. Therefore, this International Standard provides a common basis for assessing risk relevant to design, assessment, maintenance and decommissioning of structures. This International Standard accords with the umbrella International Standard of risk management being prepared as ISO 31000 by ISO/TMB.

In a risk assessment, hazard identification and the estimation of consequence are primary major procedures. For these, it is necessary to assess the risk of systems involving structures rather than just the structures, since structural failure has significant consequence for systems, and a failure of systems such as fire protection systems can cause serious consequences. However, actions for risk treatment are taken within the scope of structural design. Such considerations are reflected in the title of this International Standard.

This International Standard is intented to serve as a basic document, along with other relevant standards on risk management, for those assessing risk for systems involving structures.

Annexes A to H of this International Standard are for information only.

INTERNATIONAL STANDARD **ISO 13824:2009(E)**

Bases for design of structures — General principles on risk assessment of systems involving structures

1 Scope

This International Standard specifies general principles of risk assessment for systems involving structures. The focus is on strategic and operational decision-making related to design, assessment, maintenance and decommissioning of structures. This also includes formulation and calibration of related codes and standards. Systems involving structures can expose stakeholders at various levels in society to significant risks. The aim of this International Standard is to facilitate and enhance decision-making with regard to monitoring, reducing and managing risks in an efficient, cost-effective and transparent manner. Within the broader context of risk management, risk assessment provides decision-makers with procedures to determine whether or not and in what manner it is appropriate to treat risks.

This International Standard provides a general framework as well as a procedure for identifying hazards and estimating, evaluating and treating risks of structures and systems involving structures. This International Standard also provides a basis for code writers as well as designers to set reasonable target-reliability levels, such as stated in ISO 2394, based on the result of risk considerations. For existing structures, assessment of the risks associated with the events that were not considered in the original design or with changes in use shall be implemented according to the principles stated in this International Standard. This International Standard can also be used for risk assessment of exceptional structures, the design of which is usually beyond the scope of existing codes.

2 Normative references

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

ISO 2394, *General principles on reliability for structures*

ISO/TS 16732, *Fire safety engineering — Guidance on fire risk assessment*

ISO/IEC Guide 51:1999, *Safety aspects — Guidelines for their inclusion in standards*

ISO Guide 73, *Risk management — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 2394, ISO/TS 16732, ISO/IEC Guide 51 and ISO/IEC Guide 73, together with the following, apply.

3.1
acceptable risk
level of risk that an individual or society accepts to secure certain benefits

3.2
cost/benefit analysis
analysis contributing to decision-making on whether to adopt a project or a plan by quantifying and comparing its costs and benefits

3.3
extraordinary event
event that cannot be anticipated or expected technologically by experts, or an event whose occurrence probability is estimated as extremely low

3.4
hazard
potential source of undesirable consequences

3.4.1
hazard identification
process to find, list and characterize hazards

3.4.2
hazard curve
exceedence probability of a specified hazard magnitude for a specified period of time

3.4.3
hazard screening
process of identifying significant hazards that shall be considered during risk assessment of systems involving the structures

3.5
option
possible measures for managing the risk

NOTE Doing nothing can be a feasible option when other options cannot mitigate the risk against their invested costs.

3.6
reliability
ability of a structure or structural element to fulfil the specified requirements, including working life for which it has been designed

3.7
residual risk
risk remaining after risk treatment

3.8
risk
combination of the probability or frequency of occurrence of an event and the magnitude of its consequence

NOTE From the view point of a strict decision theory, it is the expected value of all undesirable consequences, i.e. the sum of all the products of the consequences of an event and their probabilities.

3.9

risk acceptance

decision to accept a risk

3.10

risk assessment

overall process of establishment of structural engineering context, definition of system, identification of hazards and consequences, risk estimation, risk evaluation and evaluation of treatment options

3.11

risk calculation

act of representing a combination of probabilities and consequences of occurrence of risks as a scalar, in order to compare with risk options

NOTE See 8.6.

3.12

risk communication

exchange or sharing of information about risk among the decision-makers, other stakeholders and engineers

NOTE 1 The information can relate to the existence, nature, form, probability, severity, acceptability, treatment or other aspects of risk.

NOTE 2 Engineers are the main source for risk information and encourage stakeholders to communicate with each other.

3.13

risk control

actions implementing risk-management decisions

NOTE Risk control can involve monitoring, re-evaluation and compliance with decisions.

3.14

risk criteria

criteria against which the results of the risk analysis are assessed

NOTE 1 The criteria are generally based on regulations, standards, experience, and/or theoretical knowledge used as a basis of the decision on acceptable risk.

NOTE 2 Risk criteria can depend on associated costs and benefits, legal and statutory requirements, socio-economic and environmental aspects, the concerns of stakeholders, priorities and other inputs to the assessment.

3.15

risk estimation

process of assigning values to the probability of occurrence of events and their consequences

NOTE Risk estimation can consider cost, benefits, the concerns of stakeholders and other variables, as appropriate for risk evaluation.

3.16

risk evaluation

process of comparing the estimated risk with given risk criteria to determine the significance of the risk

NOTE Risk evaluation can be used to assist in the decision to accept or to treat a risk.

3.17

risk treatment

process of selection and implementation of measures to optimise risk

3.18
scenario
qualitative description of a series of events in time and space and their inter-relationship given the occurrence of a hazard

3.19
structural engineering context
background or reasons why the risk assessment shall be implemented from structural perspectives

3.20
stakeholder
any individual, group, organization or authority that can affect, be affected by, or perceive itself to be affected by, a risk

NOTE The decision-maker is a stakeholder.

3.21
structure
arrangement of materials that is expected to withstand certain actions and to perform some intended function

3.22
system
delimited group of interrelated, interdependent or interacting objects that is assessed for a potential risk

NOTE 1 This definition implies that the system is identifiable and is made up of interacting elements or subsystems, that all elements are identifiable, and that the boundary of the system can be identified.

NOTE 2 A system involving structures includes the structural system defined in ISO 2394 as a subsystem.

NOTE 3 In terms of technological hazards, a system is normally formed from a physical subsystem, a human subsystem, their management and environment.

3.23
undesirable consequence
direct and indirect harm, stated in terms of personal injury, death, environmental damage, and monetary loss

NOTE 1 There can be more than one negative consequence from an event.

NOTE 2 Consequences can be expressed qualitatively or quantitatively.

NOTE 3 Both immediate and long-term consequences should be included.

NOTE 4 “Environmental damage” is based on a versatile point of view and sometimes various kinds of damage can be included, such as social and political damage.

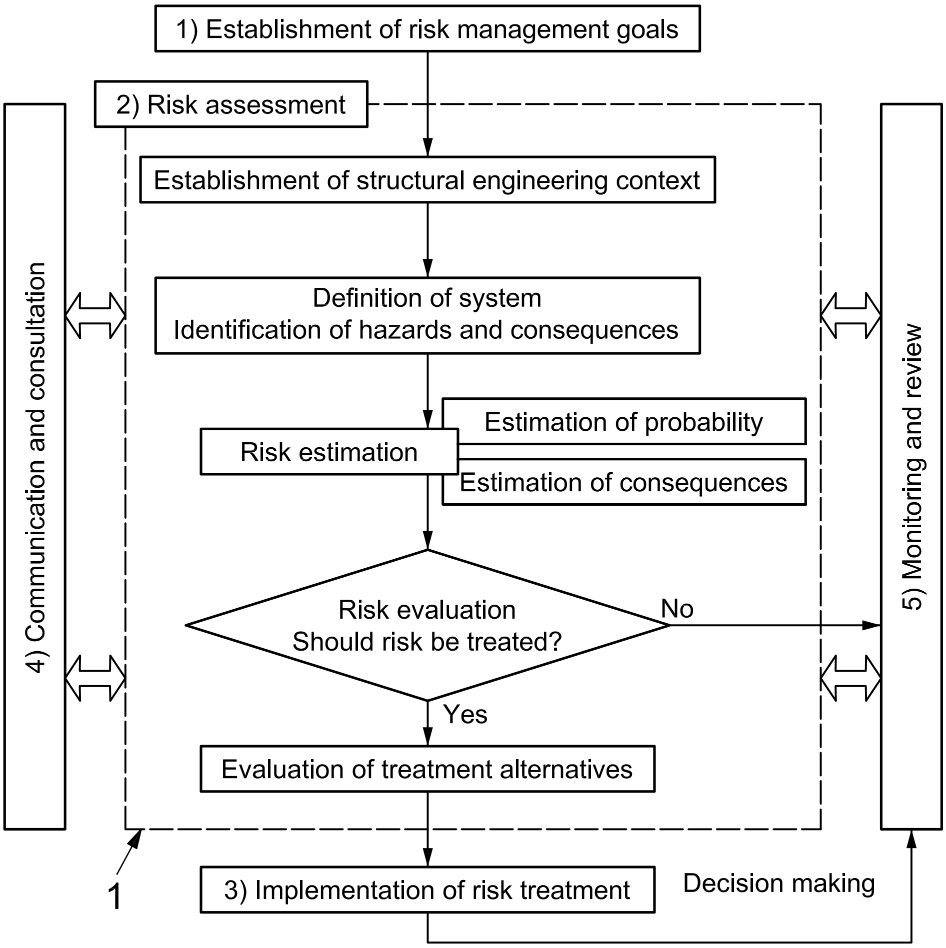
3.24
undesirable event
event that can have undesirable consequences

4 General framework of risk assessment of systems involving structures

4.1 Overview of risk management of systems involving structures

4.1.1 General

The objective of risk management is generally to allocate limited resources “optimally” for the stakeholders such as society, local community, individuals, and various organizations. Risk management typically consists of the establishment of risk-management goals, risk assessment, risk treatment, communication and consultation, and monitoring and review, as illustrated in Figure 1 and described in 4.1.2. Risk management is not a one-way process but shall be an iterative process.



Key

1 scope of risk assessment

Figure 1 — Risk-management process and the scope of risk assessment of systems involving structures

4.1.2 Steps in the risk-management process

4.1.2.1 Establishment of risk-management goals

Procedures for establishing risk-management goals are outside the scope of this document. For the risk management of either a new structure or an existing structure, the risk associated with the proposed design specification(s) or current condition(s) is estimated objectively by an engineering approach within the process of risk assessment. It is expected that risk-management goals related to a risk assessment be expressed in terms of the protection of assets, maintaining health and safety level, environmental protection, regulatory requirements, functional changes/requirements, etc. These goals are typically determined by comparison of 1) cost/benefit of optional solutions or 2) various risks, for example, those known as acceptable to society.

4.1.2.2 Risk assessment

Risk assessment consists of the establishment of the structural engineering context, the definition of structural system, identification of hazards and consequences, risk estimation, risk evaluation and evaluation of options for risk treatment where it is decided that the risk shall be treated. Although the establishment of a structural-engineering context and the evaluation of options for risk treatment are generally considered as outside the scope of risk assessment, they are included within the scope of this International Standard in order to make the outcome of the risk assessment meaningful.

4.1.2.3 Implementation of risk treatment

In the process of risk treatment, decisions are made about the implementation of risk-reducing measures based on cost-effectiveness considerations or other social value judgements. Based on their sense of values, their social and cultural perspective, etc., the stakeholders can decide to accept a risk that the evaluation has found to be too high.

4.1.2.4 Communication and consultation

There shall be thorough communication and appropriate consultation with the stakeholders for each element of the risk-management process and for the process as a whole. After the risk assessment is complete, its results shall be conveyed in a suitable manner so that the stakeholders can understand them and make appropriate decisions.

4.1.2.5 Monitoring and review

The level of risk shall be monitored in order to keep it under a target level, regardless of whether or not the risk is treated. Also, the effectiveness of all elements of the risk-management process shall be reviewed in order to ensure continuous improvement of the process. For each element of the risk-management process, records shall be kept for future reference to guarantee that decisions are understood and to assist in the continuous improvement of the process.

4.2 Applicability of risk assessment

Risk assessment is useful in circumstances when an event is very rare yet its consequences are very severe, or where frequent events result in medium to large consequences. A huge earthquake occurring in an urban area is a typical example of the former circumstance, whereas a road accident is an example of the latter.

Risk assessment is also useful in circumstances where the size of a structure is very large or the number of people or amount of goods inside a structure is very large. High-rise buildings are a typical example of this circumstance.

Risk assessment is essential when the uncertainty of input parameters has a significant impact on the structural behaviour and the consequences resulting from such behaviour.

Risk assessment is also essential when damage and total loss of the function of a structure has significant influence on a community. Hospitals, fire rescue and police stations, power-generating and distribution networks and structures containing highly toxic materials are typical examples of such structures.

5 Establishment of structural engineering context

5.1 Structural-engineering context

The structural-engineering context defines the role of risk assessment in the framework of risk management for structures. The typical structural engineering contexts are the following:

a) establishment of design basis;

b) assessment of existing structures;

c) assessment of exceptional structures and/or extraordinary events; see Annex B;

d) preparation of risk information for decision.

Stakeholders shall be identified based on the established structural-engineering context.

5.2 Establishment of design basis

5.2.1 A design code prescribes a series of criteria for the design of structural members. The criteria are often based on target reliability levels that can be predetermined based on risks associated with exceedance of relevant limit states. Results of risk assessment can provide a rational basis for determining the target reliability levels.

5.2.2 Risk assessment can be carried out to check the target reliability level of existing structural design codes.

5.3 Assessment of existing structures

5.3.1 The risk associated with existing structures, including heritage structures, should be assessed when the structure is damaged, its use is changed or it is in other relevant situations. If the risk is too large, results from the risk assessment shall be reported to the stakeholders.

NOTE ISO 13822 can be used for risk estimation.

5.3.2 It is necessary to assess the risk due to extraordinary events beyond the design-based events and to verify that the results should be within the acceptable level. It is recommended, where practicable, that the acceptable level should be equivalent to that for newly designed structures; however, the level for existing structures can be determined with cost/benefit consideration.

In many cases for old buildings, it is challenging or practically impossible to assess the reliability and compare it to that of a new-built structure because it is not possible to apply modern design rules to old buildings and structures. Materials and construction techniques are used for which design rules no longer exist. Also, detailing can be in conflict with present detailing rules without representing necessarily an increased and unacceptable risk. In situations where an existing structure is difficult to assess accurately, emphasis should be put on the option of mitigating the risk.

5.4 Assessment of exceptional structures or extraordinary events

Exceptional structures are those whose design is beyond the scope of existing codes. Risk assessment of such structures shall be carried out if their failures can have serious consequences. Risk assessment shall also be implemented for some extraordinary events (see Annex B), such as fires and some critical event scenarios.

5.5 Preparation of risk information for decision

When several optional strategies or concepts are available, the optimum strategy shall be determined based on the result of risk assessment. Risk-based optimization can have two principal objectives:

a) to minimize risk given limited economic resources;

b) to determine the optimal level of investment in risk reduction.

In both situations, the optional use of economic resources should be considered to examine whether they contribute to optimal risk reduction.

Options should be compared according to net utility, cost/benefit or cost-effectiveness; see Annex H. If the aim of decision-making is to minimize risk within economic restraints, any of these criteria may be used provided that all technical solutions are consistent with best practice.

6 Definition of system

6.1 Representation of the system

Fundamentally, the system representation shall facilitate decision-making and, thus, shall be adapted to the structural engineering context described in Clause 5. The definition of the system involving structures shall include a clear identification of the functions provided by the structures and how these functions are supported by the structural components. The extent of the system that is considered in risk assessment shall be clearly identified based on the structural engineering context.

6.2 Identification of the subsystems

The characteristics of each subsystem, such as type of structure(s), codes and standards used in the design of the structure(s), use, importance, location and working life, shall be identified. The limit states of the system shall also be specified.

7 Identification of hazards and consequences

7.1 Identification of possible hazards

During their service lives, structures can be exposed to various natural hazards and man-made hazards. The hazards that can cause undesirable events shall be identified. For hazards that can cause a series of events in time and space (e.g., fire), scenario analysis shall be performed. For the detailed procedure on scenario analysis for fire, see ISO/TS 16732 and ISO/TS 16733.

7.2 Identification of extent of scenarios

Having identified a possible hazard, scenarios shall be identified as the sequences or combinations of events or processes necessary for system failure and resulting undesirable consequences for the system involving structures. The essential techniques used for schematic representation of scenarios are fault trees and event trees. A scenario should include collapse or damage of the structure(s), loss of functionality, human death or injury and other economic and/or social losses caused by or to the stakeholders.

7.3 Identification of consequences

Consequences resulting from the hazards and following events shall be identified. They should be described in terms of several measures, e.g., monetary loss, human fatalities and environmental damage. Some consequences can be identified by scenario analyses considering the extent of influences due to failure of the structural systems in time and space.

7.4 Hazard screening

7.4.1 General

Although all possible hazards should be taken into consideration, hazards important to a system shall be selected on the basis of their significance and incorporated in the risk assessment. As each hazard has its inherent characteristics and possible consequences, it is recommended to categorize hazards by the original cause, the degree of quantification, and the significance of consequences. The screening of hazards in accordance with their importance for risk assessment can then be performed based on experience and expertise of the engineer. The results of the hazard screening shall be documented.

7.4.2 Hazard screening criteria

Preliminary risk estimation (see 8.1) shall be carried out to identify the significant risks. The criteria for the hazard screening are, in principle, based on the magnitude of the risk from the preliminary risk estimation. Frequency of the hazard and/or significance of the relevant consequences can also be useful criteria. Hazards with obviously negligible risk compared with the acceptable risk level may be screened out.

The hazard screening criteria shall be clearly described in terms of frequency of the event and magnitude of its consequence. They may be based on the past experience, human perception and relevant values specified elsewhere.

8 Risk estimation

8.1 Types of risk estimation

8.1.1 General

Risk estimation shall be undertaken according to the purpose of the estimation, required degrees of details, information, data and resources available. The types of estimation fall into three broad categories, i.e., qualitative, semi-quantitative and quantitative, depending on the circumstances. In practice, qualitative estimation is often used, as a preliminary risk estimation, to obtain a general indication of the level of risk and to reveal the risks that shall be considered. Later, it can be necessary to undertake more specific or quantitative estimation on the revealed risk.

8.1.2 Qualitative estimation

In qualitative estimation, risk is subjectively estimated and ranked in a descriptive manner. Qualitative estimation should be used

a) as an initial screening activity to identify risks that require more detailed estimation;

b) where the qualitative estimation provides sufficient information for decision-making;

c) where the numerical data or resources are insufficient for a quantitative estimation.

8.1.3 Semi-quantitative estimation

In semi-quantitative estimation, a ranking scale more expanded than the one usually achieved in qualitative estimation shall be adopted. It should be noted that the numbers chosen cannot properly reflect relativities and this can lead to inconsistent, anomalous or inappropriate outcomes.

8.1.4 Quantitative estimation

In quantitative estimation, numerical values rather than descriptive scales shall be used in qualitative and semi-quantitative estimation for both consequences and probability using data from a variety of sources. The quality of the estimation depends on the accuracy and completeness of the numerical values and the validity of the models used.

8.2 Data for estimation

Data for estimation shall be taken from appropriate sources of information. The most pertinent information sources and techniques should be used when estimating probability. Information sources can include the following:

a) past records;

b) practice and relevant data (field data collection);

c) relevant published data (incident data);

d) experiments and prototypes;

e) engineering or other models;

f) specialist and expert judgment (expert opinions).

8.3 Risk representation

The results obtained in risk estimation shall be presented to stakeholders with maximum clarity, for example by converting the results to a common scale, such as potential fatalities; see Annex H. These can, then, be related to the probability of occurrence of various hazards and can be compared with other hazardous activities or another risk level.

In qualitative risk representation, risk shall be rated as being, for example, of high, moderate or low importance. In quantitative representation, risk shall be presented by a combination of probability and consequence. The expectation of consequence can be used for risk representation; see Annex F.

8.4 Estimation of probability

8.4.1 General

Probability estimates can be obtained from any or all of the following three approaches:

a) direct estimation from data;

b) inference from a model that relates the probabilities of interest to other probabilities;

c) engineering judgment.

Where no reliable or relevant past data are available, subjective estimates can be made that reflect an individual's or group's degree of belief that a particular event or outcome will occur.

In particular, to combine limited amounts of data from different types of sources, Bayesian Inference techniques are recommended.

For the purposes of risk communication, it is preferable to differentiate between uncertainties due to inherent natural variability, model uncertainties and statistical uncertainties. Whereas the first type of uncertainty is often denoted aleatory uncertainty, the latter two are referred to as epistemic uncertainties.

8.4.2 Probability of occurrence of hazard

The probability of occurrence of each hazard shall be estimated based on the past data, if available. If the data are not available, expert judgement should be incorporated; see Annex C. Note that it is important to reflect the characteristics of the hazard, although a hazard is often represented simply in terms of a hazard curve.

8.4.3 Limit state probability

The limit state probability shall be estimated using the following procedures:

a) modelling of action;

b) modelling of resistance;

c) structural analysis (response analysis).

Based on the statistical data of the above, the limit-state probability can be estimated by means of either theoretical approaches or statistical approaches such as Monte Carlo simulations.

To represent a conditional limit state probability, a fragility curve can be defined as a function whose argument is the magnitude of the hazard; see Annex D.

8.5 Estimation of consequence

Consequences shall be determined by modelling the outcomes of an event or a set of events, or by judging from experimental studies or past data. A scenario analysis is performed from the occurrence of an initial event with regard to the extent of consequences, as specified in 7.2. Tools like fault tree analysis and event tree analysis are recommended.

A quantitative estimation of consequence should be expressed numerically to define the extent of human fatality and injuries and/or environmental damage and economic loss.

8.6 Risk calculation

The probability distribution of consequences is a quantitative representation of the whole profile of a risk, which is a combination of probability and consequence as defined in this International Standard. The probability distribution can be expressed by a cumulative distribution function, CDF. It can also be expressed by a probability mass function, PMF, when the consequence is a discrete value, or by a probability density function, PDF, when it is continuous.

For the convenience of risk comparison, a risk is sometimes represented with a scalar. Traditionally, one of the most frequently used representations is $E[C]$, the expectation of consequences.

These are described in D.2 and E.1.

8.7 Sensitivity analysis

Since some of risk estimation results are not sufficiently accurate to lead to a rational decision, a sensitivity analysis should be carried out to investigate the effect of uncertainty in assumptions, models and data. A higher sensitivity suggests that more care and/or effort is required in obtaining data or estimates for the variables concerned. Sensitivity analysis is also a way of examining the appropriateness and effectiveness of possible risk controls and risk treatment options.

9 Risk evaluation

9.1 Risk acceptance

After the risk is estimated, it shall be determined whether the risk level is acceptable or not by comparing it with predetermined criteria. If the risk is unacceptable, it shall be treated appropriately.

9.2 Risk criteria

Risk criteria shall be developed prior to the risk estimation as a part of establishing the risk-management goals. They can be determined based on regulations, standards, cost/benefit considerations or net utility.

Risk criteria may be modified after risk estimation based on the cost/benefit analysis and optimization; see Annex A. Although risk criteria are initially developed as a part of the risk management, they can be further developed and refined subsequently as particular risks are identified and as procedures for risk estimation are chosen.

Risk criteria shall be consistent with the risk-management goals, and shall reflect the values of society and/or the decision-maker. The tolerable risk level of the parties who do not benefit from the series of activities shall be considered rather than the organization that does benefit. Risk criteria shall be determined based on characteristics of risks, such as whether they are natural or man-made, voluntary or involuntary, related to specified or unspecified people, well known or new. More conservative criteria are usually set for the latter characteristic of each of the pairs listed above.

10 Evaluation of options for risk treatment

10.1 General

If the risk level is higher than the acceptable level, the risk shall be treated and brought to be below the acceptable level. Risk treatment involves identifying the range of options for treating a risk, assessing these options and preparing and implementing a treatment plan.

10.2 Determination of options

10.2.1 General

In order to reduce a risk effectively, more than one risk treatment option should be considered. Options can generally be sorted into the following four categories described in 10.2.2 to 10.2.5.

10.2.2 Risk avoidance

The risk can be avoided by deciding not to proceed with the activity likely to generate the risk. Since another risk can arise by avoiding the activity or substituting an optional activity, such risk shall be estimated when this option is considered.

10.2.3 Reduction of probability and/or consequences

The probability of hazardous events can be reduced, for example, by relocating the structure to a less hazardous site. The consequences can be reduced, for example, by a revision of the structural design. The associated costs and other effects of such optional measures shall be estimated.

10.2.4 Risk transfer

Insurance is a typical instance of transfer of risk. An organization can reduce a risk by involving another party to share some part of the risk with a trade-off of fixed cost, i.e. risk premium. By transferring the risk, the original organization can reduce the risk, but the total amount of the risk does not change for the whole society.

10.2.5 Risk retention

When a risk level is below the acceptable level, the residual risk can be retained by an organization. The organization should submit to the consequence expected in the residual risk and, thus, should cope with the loss through some means of financing (such as allowable financial reserve).

10.3 Assessment of options for risk treatment

The most appropriate treatment options should be selected based on the assessment of the options in terms of cost and benefit.

The cost/benefit ratio and values of not only the decision-makers but also of the other stakeholders and possibly the society should be considered. All direct and indirect costs, gains and losses, whether tangible or intangible, financial or otherwise, should be considered within the established context. Legal and social responsibility requirements should also be considered in the assessment.

If the budget for risk treatment is constrained, the assessment should be carried out while considering the priority order in which individual risk treatments should be implemented. It is important to compare the cost of not taking action against the budgetary saving. It also shall be taken into consideration that infrequent but severe consequences require treatment actions not justifiable on strictly economic grounds.

The effectiveness of each option should be tested by sensitivity analysis.

10.4 Implementation of risk treatment

After the assessment of options for risk treatment, the most appropriate treatment option shall be selected and implemented. Since new risks can be introduced by the risk treatment, they shall be identified, assessed, treated and monitored.

Several options can be applied in combination.

After treatment, a decision shall be made on whether to retain the residual risk or repeat the risk treatment process.

11 Report

The assessment of systems involving structures shall produce a report, which shall include the following items:

a) definition of the system;

b) identified hazard(s);

c) conclusions of the assessment and acceptable or unacceptable risk for the system;

d) recommendations for risk treatment (cost/benefit consideration);

e) monitoring plan on and around the system;

f) documented information.

All of these items shall include sufficient information for decision-makers. The final results shall be translated into an appropriate form that allows the stakeholders to make decisions within the framework of risk management.

Annex A
(informative)

Principles of risk assessment

A.1 Statement of the problem

Risk analyses are performed in many fields in order to provide input to different decisions ranging from simple technical problems to managerial strategy making. The decision-makers and stakeholders vary in number and degree of knowledge. The variety of decision situations constitutes a challenge to the risk analyst concerning how to represent risk in a way that serves the decision-makers and makes risk analysis a useful tool in the decision-making process.

It adds to the complexity that decisions normally are multi-purpose tasks being solved within strict economical and organizational boundaries. In a political setting (where upper-level decisions belong), the decision-making process is more or less based on negotiation and consensus-seeking processes with agendas that are not always supported by mathematical rationality.

The theoretical representation of risk, such as the expected value of all undesirable consequence, can simply not be a sufficient answer to decision-makers in complex decision contexts. More information is necessary to answer questions like the following:

- What groups of people gain or suffer from the solution?
- Does a probability of 10^{-5} fatalities per year imply a high risk?
- Can risk be reduced: how and to what expense?
- What are the optional solutions?

The influence of risk analysis on decisions depends on the credibility of the risk analysis results and their relevance to the decision problem. While characteristics like consistency and transparency contribute to credibility, it is necessary to have knowledge about the analysed system for a relevant risk representation. To achieve credibility and relevance in the risk analysis, it is necessary to establish a common understanding between the decision-maker and the analyst at an early stage of the analysis. This understanding should include the following:

a) concept of risk:	What aspects of risk are being included? What kind of knowledge should the analysis be based on?
b) scope of the risk analysis:	systems understanding, definition and limitations
c) purpose of the analysis:	What are the decision problem and the decision options?
d) risk representation:	What is a useful representation of risk to decision-makers and stakeholders?
e) risk evaluation and decision-making:	interpretation of the risk results, evaluation criteria and the role of the risk analysis in the decision-making

The issues above are epistemologically connected and it is necessary that they be consistent. There is no sense in discussing risk representation without considering the other issues. This annex elaborates the above points in order to advise decision-makers and risk analysts on risk communication.

A.2 Concept of risk

Different professional traditions have different conceptions of risk and risk assessment that can lead to confusion and communication problems. Some concepts of risk are

- the decision-theoretic risk concept based on probabilities and consequences of undesirable events;
- the economic risk concept concerning uncertainty of outcome;
- the psychological understanding of risk as individual or group perceptions;
- the societal interpretation of risk as a multi-dimensional problem involving political as well as technical aspects.

The concepts are grounded in different epistemological assumptions that it is necessary to clarify prior to the risk analysis: What kind of knowledge provides a credible and relevant base for the risk analysis? It is necessary that the analyst and decision-maker agree on this in order to “speak the same language”.

Several epistemological problems are connected to risk analyses. In addition to different professional views on risk, there are different opinions on the use of quantitative versus qualitative data in risk analysis. A significant epistemic challenge due to the nature of risk analysis is the time gap between available historical data and the focus of the analysis: the future. No one can observe the future. How do we use present and past observations to predict the future? The final problem concerning knowledge being mentioned here is that of the different views on the nature of knowledge or epistemological stances.

The two main epistemological directions are objectivism and subjectivism. The objectivists assume that facts can be objectively observed and analysed without being influenced by the analysts' subjective interpretations and judgments. Science is based on the “the principle of neutrality”. Objectivism is the epistemological basis for engineering science.

The subjectivists claim that facts cannot be “objectively” observed as far as someone is observing. Neutrality is impossible. The observations are judged and assigned meaning by the analyst; thus, they are social and cultural constructions. While the relativists say risk is solely a perception without reality, the constructionists say risk is a subjective interpretation of reality. Most social sciences belong to the subjectivist camp.

One can “blame” both the relativists and the objectivists for reductionism: the relativists for overlooking the knowledge that we do have and the objectivists for their naïve faith in neutral science. Schrader-Frechette, 1991, suggests a third approach, scientific proceduralism, saying that credible knowledge can be obtained by scientific methods and not by “objective” data. She presents a set of procedural rules to obtain scientific, valid results in risk analyses by, for example, logical argumentation, full disclosure and critical testing.

In the engineering field, more flexible modelling frameworks have received increased attention over the last decade. One such framework is the use of Bayesian network models and similar influence diagram methods designed for reasoning with uncertain knowledge. Expert judgment, as well as statistical data, is used to estimate the parameters in these models. The framework takes performance of human and organizational factors into consideration and treats them in a precise quantitative way (Langseth and Portinale, 2007; Røed *et al.*, 2006).

Obviously, the epistemic assumptions influence our approach to risk assessment. Our view on risk determines the choice of process and method for risk analysis (e.g. an analytical expert analysis versus discursive processes), sources of knowledge and use of data, treatment of uncertainty and risk representation. To avoid confusion and disagreement on the format of risk representation, the concept of risk should be discussed and clarified by the analysts and decision-makers preliminary to the risk analysis.

A.3 Scope of the risk analysis

“Systems thinking” in the risk field is growing. The systems approach can be explained as looking at connected wholes rather than separate parts. Design in engineering systems is assumed to have a socio-technical and multi-disciplinary nature and one should attempt a holistic rather than a reductionist thinking by seeing the big picture of the connectivity among elements (Marashi and Davis, 2006). The classical work of Charles Perrow on normal accidents theory (Perrow, 1999) in the 1980s and 90s reminds us that systems thinking about safety is not a new phenomenon.

In a systems approach, safety is regarded as a resulting effect of the complexity in a system with many interactive and adaptive features. The risk connected to structural elements like roads and buildings is assessed in relation to their environment and users. Designing safe hard- and software in complex systems is actually about designing safe use rather than designing safe products (Hale *et al.*, 2007).

While the system description should include all relevant risk factors to provide a proper model for risk assessment, it is also necessary to limit the system and confine the analysis.

What is modelled and what is not have to be explicitly identified and described in order to assess the validity of the risk results.

A.4 Purpose of the risk analysis

Different projects and different phases of a project require different scopes of risk analysis. At the design stage, the purpose is typically to select the best solution among options, judge whether the solution is sufficiently safe and optimize it technically. At the operational stage, the scope of risk analysis normally is to assess safety problems and consider the requirement for risk-mitigation measures. At all levels, different decision options should be established and assessed in order to optimize the final solution.

The decision problem and the purpose of the risk analysis should be consciously considered and described as a starting point for the analysis. Experience tells that the purpose of the risk analysis too often is taken for granted and not sufficiently oriented toward the specific decision problem.

Hale *et al.*, 2007, suggest specific risk-management activities within each phase of the design process: at an early stage, to develop options and select the best solution with respect to project objectives by performing conceptual risk analysis. The options should be evaluated according to explicit and implied risk criteria. On a more detailed level, the selected solution should be optimized and judged as to whether the inherent safety barriers are adequately implemented by performing risk analysis.

Formulating different options highlights the differences in risk between possible solutions rather than just judging whether the risk is acceptable or not. Also, in detailed design and in the operation phase, the solution can be optimized by formulating options. A risk analysis without optional decision possibilities is a verification of risk and not a tool for improvement.

A.5 Risk evaluation and decision-making

A number of methods for risk evaluation are in use today. The evaluation of quantified risk can be in terms of absolute criteria of various kinds, e.g. frequency and number, F-N, criterion lines, expressing an upper limit of “acceptable risk” or number of fatalities. Other kinds of absolute evaluation criteria are technical standards and legislative and regulatory requirements. Only recently, economy-inspired criteria like cost/benefit and maximum expected utility considerations have come into focus as a means for more comprehensive risk evaluation. Risk evaluations are also performed by using qualitative methods such as comparing with “best practice” and professional judgments.

Absolute criteria benefit from simplicity; they are clear-cut and seemingly easy to use. But while simplifying the evaluation and decision-making, they do not necessarily lead to a commonly accepted solution. One can argue that no-one can decide the level of risk that it is necessary for another to accept. Risk perception is not mathematically rational: for instance most people accept the risk connected to driving a car, but they don't accept rock falls or fires in tunnels. The degree of controllability and benefits connected to the risk influence the level of acceptance.

Neither do F-N criterion lines necessarily lead to optimal solutions. Kroon and Maes, 2007, illustrate the problem by calculating the risk inherent to seven F-N curves. The inherent risk was seen as strongly dependent on the shape of the F-N curve. The calculations demonstrate that a certain F-N curve, which is not acceptable by application of the criterion line, can be much safer than a competing system, which is acceptable using the criterion line. The use of F-N criteria can, therefore, result in unreasonable decisions, and they might not be as suitable as they appear for evaluating and comparing risk.

Absolute risk-acceptance criteria can be convenient for decision-makers who want to avoid the responsibility of taking unpopular or expensive decisions. Blaming the risk analysis for difficult decisions is not unusual and can be avoided by not making mechanical decisions based on absolute criteria.

Acceptable risk cannot be theoretically pre-defined or considered without regard to the options. Decisions on risk should consider all the pros and cons of the decision options, including not doing anything.

This suggests a risk-based decision-making process as follows:

a) establishing a common understanding of the risk concept, the scope and purpose of the risk analysis, representation of risk, risk evaluation and decision-making;

b) generating optional solutions;

c) assessing the options by performing risk analysis;

d) comparing and ranging the options based on explicit criteria such as optimizing utility or cost-effectiveness;

e) discussing whether the selected option is safe enough, the need for technical optimization and the effects on other objectives.

While the risk analyst is responsible for steps 3 and 4, the decision-maker is responsible for step 5. The first two steps should involve the analyst as well as the decision-maker — and preferably also the stakeholders and users of the analysed system.

Annex B
(informative)

Examples of extraordinary events and exceptional structures for risk assessment

B.1 Extraordinary event

B.1.1 An extraordinary event is a very rare event that causes very severe consequences.

B.1.2 Extraordinary events can be put into two major categories with regard to causes: natural and man-made events.

B.1.3 Some examples of natural extraordinary events are as follows: huge earthquake, tsunami, hurricane, violent windstorm, extraordinary ocean wave, methane hydrate eruption, volcanic eruption, landslide, shallow debris flow, rock fall, avalanche, flood, heavy snowstorm, ice accretion, atmospheric icing, etc.

B.1.4 Man-made extraordinary events can be intentional or unintentional. Causes of these events are different but consequences can be similar. The examples of man-made extraordinary events include the following: severe fire; gas explosion; bomb blast; impact from projectile, vehicle, ship, helicopter or aircraft; impact from collision of trains or trucks; mining ground deformation; catastrophic erosion; cardinal human error; and others.

NOTE 1 Some events that can occur due to natural causes, such as landslides and rock falls, can also be the result of human activity.

NOTE 2 Some events, such as erosion, can occur due to natural causes.

B.2 Exceptional structure

B.2.1 An exceptional structure is one designed beyond the scope of existing codes, e.g. historical monuments and super-long-span bridges and roofs.

B.2.2 An exceptional structure is one for which the loss of the function has extremely negative and very important influences on a community, e.g. nuclear power plants, structures containing highly toxic materials.

B.3 Situations recommended for risk assessment

B.3.1 Risk assessment is useful in circumstances where extraordinary events can happen or/and exceptional structures are considered.

B.3.2 Risk assessment is essential where the socially acceptable level of risk to human life and health as well as to assets, environment and historical heritage can be exceeded.

B.3.3 Some examples of situations recommended for risk assessment are the following:

- super-long-span bridges, in particular suspension and cable-stayed bridges, taking into consideration some possible extraordinary events, such as ship impact from river or canal traffic or from seagoing vessels; impact from road vehicles, trains, helicopters or aircraft; hurricanes or wind storm; catastrophic corrosion;
- long-span roofs, especially lightweight structures of exhibition, sport and concert halls, stadiums and courtyards, with regard to one or some of the potential hazardous events, such as extreme snow load, hurricane or violent windstorm, internal fire, catastrophic corrosion, and cardinal human error;

- nuclear power plants, which are particularly exposed to huge internal explosions and fire, earthquakes, impact from projectiles, helicopter or aircraft, and terrorist attacks;
- structures containing highly toxic materials and hazardous waste, storage tanks for liquid natural gas, petroleum and natural-gas transmission pipelines, taking into consideration some possible extraordinary events, such as earthquake, landslides, mining ground deformations, internal explosion and fire, impact from projectiles and terrorist attacks;
- major natural and industrial disasters in urban areas, among the most important of which are huge earthquakes, tsunami, volcanic eruption, flooding from rivers and the sea, hurricanes, and large industrial accidents from nuclear power plants, large chemical plants and storage structures for highly toxic or explosive materials.

Annex C
(informative)

Techniques for treatment of expert opinions

C.1 A risk assessment requires probabilistic information for the quantification of epistemic or aleatory uncertainties. Such uncertainties are best quantified from analysis of large statistical databases derived from operating experience and field or experimental studies. However, for many situations, the data can be of insufficient extent or quality to provide useful and credible quantitative measures for use in a risk assessment. In such cases, it is often necessary to rely on the use of expert opinions where quantitative information obtained from people associated with the parameter being measured can be solicited. Such information relies heavily, of course, on the expert's experience, knowledge, judgment and communication skill. In general, however, an expert can be defined as a very skilful person who has a good deal of training, experience and knowledge in some special field. It is necessary to take great care in the selection of experts, and at least some of their opinions should be calibrated against known information. A simple criterion for selection of an expert is that the person is recognized by others as such.

Winkler *et al*., 1992, provides the following guidance for selection of experts: Experts can be identified through literature searches and/or registries of professional organizations, consulting firms, research laboratories, government agencies and universities. A formal nomination process is sometimes used, particularly when controversy is possible. The nomination process should be designed to preclude bias in selection. The first step is to invite stakeholders and interested parties to nominate experts. The second step is to use an independent external selection panel to evaluate the nominees.

The criteria for selection should be specific and documented, including the following:

- evidence of expertise, such as publications, research findings, degrees and certificates, positions held, awards, etc.;
- reputation in the scientific community, such as knowledge of the quality, importance and relevance of the nominee's work and ability to judge the issue(s) at stake;
- availability and willingness to participate;
- understanding of the general problem area;
- impartiality, including the lack of an economic or personal stake in the potential findings;
- inclusion of a multiplicity of viewpoints.

C.2 An expert opinion has been defined as a “subjective assessment, evaluation, impression or estimation of the quality or quantity of something of interest that seems true, valid or probable to the expert's own mind” (Ayyub, 2001). The opinion for the matter of interest (or issue) is often based on uncertain or incomplete information. It follows that an expert can unintentionally provide information that is false. A number of elicitation and assessment techniques exist that essentially aggregate expert opinions so that a relatively high degree of “consensus” or consistency among experts is attained.

Expert opinions can be obtained from the following approaches (Ayyub, 2001; Paté-Cornell, 2002):

a) aggregated individual method: weighted average of expert-provided data;

b) iterative methods: varying levels of interaction among elicited experts before rendering opinions, followed by review of results with opportunity for revision of expert opinions. This process is repeated until complete consensus is achieved. The expert responses are anonymous so that independence of responses is preserved. Typical methods include

- Delphi method,
- nominal group technique;

c) interactive methods: meeting of experts to identify and structure the probabilistic data required;

d) analytical methods: Bayesian integration of expert opinions based on the confidence of each expert.

C.3 The elicitation of expert opinions can be from personal interview or written questionnaires. The questions can be qualitative or quantitative in nature, for example, qualitative questions can be used to check the validity of available pertinent experimental or field data or modelling assumptions. Quantitative questions can include probability estimates such as mean, median, variance, upper and lower bounds, confidence limits and probability distribution type. Such elicitation can be in the form of

- absolute probability judgement;
- pair comparisons;
- rankings;
- indirect numerical estimates.

C.4 The aggregation of expert opinions is dependent on a variety of factors (Chhibber *et al.*, 1992). Arithmetic and geometric averaging assume that all experts are equally weighted, which is unlikely to always be true and so can be an unrealistic assumption as this ignores expert biases. Weighting factors, based on the ranking of experts or on biases exhibited by the expert by calibrating their responses with known probabilistic data, can be used. Bayesian methods are often better suited for considering expert biases as they also allow for the explicit modelling of dependence among experts. The following is taken from Chhibber *et al.*, 1992:

$$P\left(X\middle|E\right)=P\left(X\middle|E\right)P\left(X\right)\Big/K \tag{C.1}$$

where

$P(X)$ is an analyst's belief about the variable quantity, X, before any expert judgment is revealed to him or her;

$P(X|E)$ is the analyst's belief about the variable quantity, X, after the revelation of expert judgment, E;

K is a normalizing constant that ensures that the area enclosed by the posterior distribution $P(X|E)$ is unity.

This theorem states that if the analyst's belief about the variable quantity, X, before any expert judgment is revealed to him or her is $P(X)$, then upon the revelation of expert judgment(s), E, the analyst can revise his or her belief to obtain $P(X|E)$. If the analyst is unsure about X prior to hearing from the experts, then $P(X)$ is diffuse and non-informative, and so $P(X|E)$ is completely determined by $P(E|X)$, also known as the likelihood function. The likelihood function allows the analyst to calibrate or make corrections for the various biases present in the experts' subjective probability assessments and also to account for the inter-expert dependence. The analyst does so by defining the likelihood function.

The Bayesian methods, thus, follow two steps.

a) First, the experts make their judgments, independent of the analyst.

b) Second, the analyst assesses the likelihood that the experts' judgments, given the known biases of the experts, are influencing the other experts in the process.

This gives the analyst the desirable ability to nuance the experts' opinions and give more importance to experts of his or her choice. See Chhibber *et al*., 1992; and Winkler and Clemen, 1992, for more details.

The following are example applications of expert opinions:

- seismic-hazard curves (Cummings, 1986);
- seismic-fragility curves (Grossi, 2000);
- seismic-loss models (Kircher *et al*., 2006);
- unavailability of fire-suppressant systems (Siu and Apostolakis, 1988);
- human-error probabilities (Kirwin, 1994).

Expert opinions are subject to a number of issues and problems and so should be used with caution, however, Paté-Cornell, 1986, concludes that “experts' opinions are indispensable given the scarcity of unquestionable data sets”.

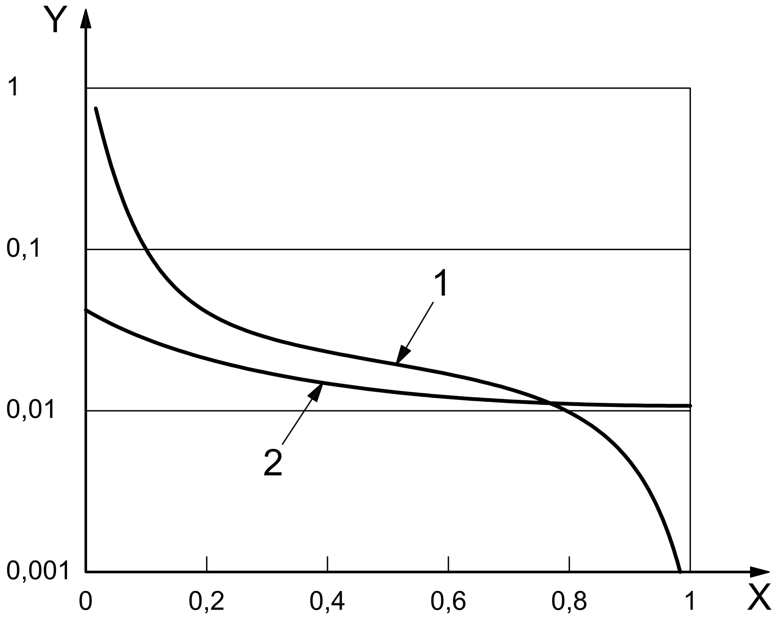
Annex D
(informative)

Examples of quantitative risk representation

D.1 Probability distribution of consequences

The probability distribution of consequences is a quantitative representation of the whole profile of a risk, which is a combination of probability and consequence, as defined in this International Standard. The probability distribution can be expressed by a cumulative distribution function, CDF. It can also be expressed by a probability mass function, PMF, when the consequence is a discrete value, or by a probability density function, PDF, when it is continuous.

A frequent complementary function of the CDF, which is sometimes designated as a risk curve, is to show the probability of consequences exceeding a defined limit during a reference period. Figure D.1 shows an example of risk curves representing earthquake and fire risks for a building. In Figure D.1, the reference period is taken as fifty years and the consequence is represented by a damage factor that is defined as the ratio of repair cost to replacement cost.



Key

X damage factor

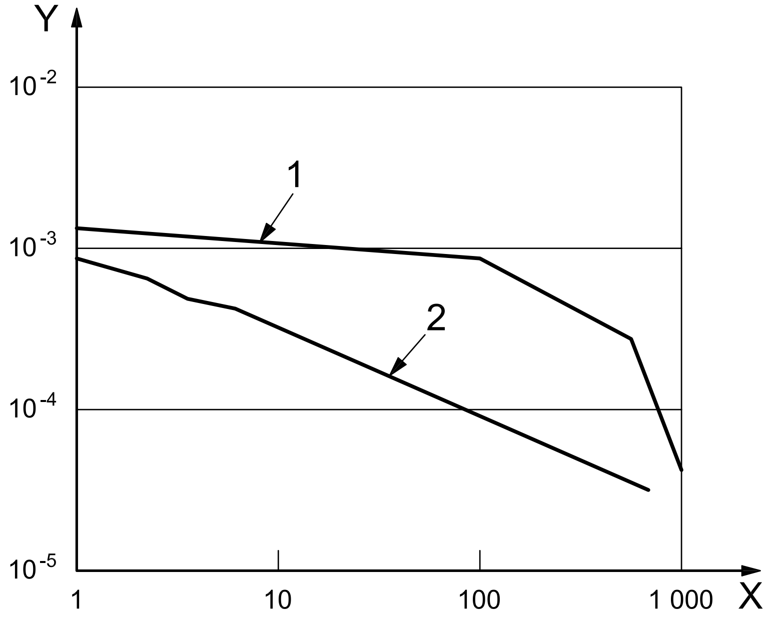
Y annual frequency of exceeding a defined limit during a period of fifty years

1 curve for earthquake risk

2 curve for fire risk

Figure D.1 — Example of risk curves

When the number of casualties is taken as representing the consequences, the function is called as an F-N (frequency and number) curve. Figure D.2 illustrates examples of F-N curves for two fictitious disasters.



Key

X number of causalities

Y annual frequency of exceeding the pre-defined limit during a period of fifty years

1 curve for earthquake risk

2 probability of a once-yearly occurrence

Figure D.2— Example of an F-N curve

Risk matrixes and similar tables are widely used in the less-detailed, semi-quantitative or qualitative risk analyses. Risk matrixes are based on the same principle as F-N curves, expressing risk as a combination of frequencies or probabilities and consequences. But unlike F-N curves, risk matrixes use intervals of probabilities and categories of consequences. Risk matrixes do not pretend to express the exact level of risk, but are useful to highlight the different contributions to risk from the underlying hazards. Risk matrixes and similar tables can be feasible tools during risk meetings aimed at identifying and evaluating hazards in a direct manner.

As an illustrative example, the matrix shown in Figure D.3 presents the assessors' judgement of probabilities and consequences of the three undesirable events UE1, UE2 and UE3 addressed in the analysis. The colours indicate the levels of risk according to the assessors and can be interpreted as levels of the need for risk reduction measures.

Risk matrixes can be used in preliminary hazard analysis and as a first step in more detailed quantitative analyses to decide what hazards to elaborate. Risk matrixes can also serve as a secondary, compound presentation of risk results from detailed analyses to the client or decision-maker. The matrix presents the big picture and is intuitively easy to understand. The connected assumptions, causal factors and possible risk mitigation measures should be represented in tables and diagrams, or verbally.

Probability	Consequence		
	Minor injuries	**Severe injuries**	**Fatalities**
Very high (at least once per year)	▒ UE3	▓	▓
High (once in 2 to 9 years)	░ UE2	▓ UE3	▓
Low (once in 10 to 50 years)	░ UE1	▒ UE2	▓
Very low (less than every 50 years)	░	░ UE1	▒ UE3, UE2

░ risk mitigation measures not necessary
▒ risk mitigation measures should be considered (as low as reasonably practicable)
▓ risk mitigation measures necessary

Figure D.3 — Example of risk matrix

Klinke and Renn, 2002, suggest a broad societal representation of risk, including social and psychological aspects in addition to the physical, due to the “the dual nature of risk”. The authors introduce new criteria to represent and evaluate risk based on characteristics of the hazards. Additional to “extent of damage” and “probability of occurrence”, they suggest measures such as incertitude, ubiquity, persistency, reversibility, delayed effects, violation of equity and potential of mobilization. This comprehensive risk description was developed by in order to analyse global environmental risks.

Extreme subjectivists do not make any attempt at all to represent risk. They say that perceptions of risk are established through power play and negotiation. Risk is about arguments and positions and not about expected values.

D.2 Scalar representation

For the convenience of risk comparison, a risk is sometimes represented with a scalar.

Traditionally, one of the most frequently used representations is $E(C)$, the expectation of consequences, which can be calculated using Equation (D.1) if the consequences are discrete or Equation (D.2) if consequences are assumed to be continuous:

$$E(C)=\sum_{i=1}^{n} c_i \cdot p_i \tag{D.1}$$

where

n is the number of assumed consequences;

c_i is the ith consequence;

p_i is the probability of occurrence of the ith consequence.

When only a single consequence is assumed, i.e., i is equal to 1, Equation (D.1) reduces to c times p.

$$E(C)=\int_{0}^{\infty} c \cdot f_{\mathrm{C}}(c)\,\mathrm{d}c \tag{D.2}$$

where

c is the consequence;

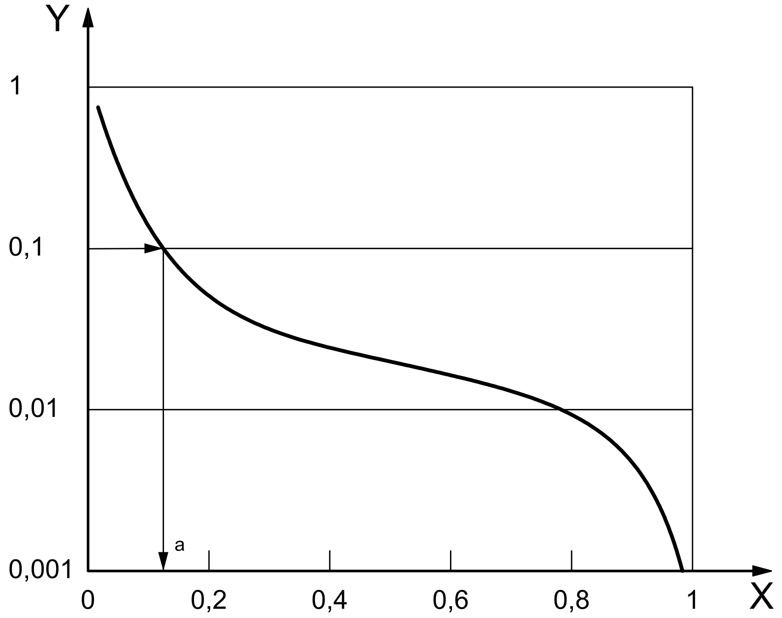
$F_C(c)$ is the probability density function of consequence.

It is recommended to confirm the condition of p_i or $F_C(c)$ when the expectation is calculated with the equations above.

Some expectations are used as risk indicators, e.g., the fatal accident rate (FAR) the expected number of fatalities in the activity per hundred million person-hours, and potential loss of life (PLL) the expected number of fatalities in the activity during one year.

Another type of scalar representation uses one of the two arguments in the CDF of the consequence (i.e., probability or consequence) as a variable, with the other fixed with respect to the risk-management goal. Representation with a probability can be effective to evaluate a risk when an unacceptable level of consequence(s) is obviously determined. This concept is similar to a failure probability for a limit state used in structural design. Namely, it is an expanded concept of failure from a physical phenomenon, such as collapse, to any kind of undesirable consequences caused by a structural problem.

On the contrary, the consequence of an occurrence at a specified probability is also used to represent a risk. This concept is designated as “value at risk” in the fields of economics and finance. For structural design/analysis, the probable maximum loss, PML, which is one of the commonly used measurements, is usually defined as the ratio of the maximum loss to the replacement cost at a certain level of probability: 10 % in 50 years is most widely used. Figure D.4 shows the relationship between a risk curve and the PML defined such as stated above. In this case, PML is estimated as 13 %.



Key

X damage factor

Y probability of exceeding the defined limit during a period of fifty years

[a] PLM is equal to 0,13.

Figure D.4 — Relationship between risk curve and PML

Annex E
(informative)

Equations for risk estimation

E.1 General formulation

As a quite general expression for the risk estimation for a time interval, T (e.g. one year or the life time), a risk curve, $P(C > c)$, which is the complementary cumulative distribution function of consequence, C (see Annex D), is given by Equation (E.1):

$$P(C > c) = P\left\langle \sum_{i=1}^{N_\mathrm{S}} C(S_i)\left\{1 - \exp\left[-\sum_{k=1}^{N_\mathrm{H}} \int_T \nu_k P(S_i \mid H_k)\,\mathrm{d}T\right]\right\} > c \right\rangle \tag{E.1}$$

where

k	is the designated number of an individual hazard to which the structure is subjected; $k = 1$ to N_H;
N_H	is the total number of hazards;
i	is the designated number of an individual scenario; $i = 1$ to N_S;
N_S	is the total number of different scenarios leading to limit states with corresponding consequences, $C(S_i)$;
ν_k	is the occurrence rate of the kth hazard;
$P(S_i \mid H_k)$	is the conditional probability of the ith scenario for the kth hazard.

The expectation of consequence, R, which is one of the most frequently used scalar representations of risk (see Annex D), can be expressed as given in Equation (E.2):

$$\begin{aligned} R &= E_\mathrm{R}(C) \\ &= E_\mathrm{R}\left\langle \sum_{i=1}^{N_\mathrm{S}} C(S_i)\left\{1 - \exp\left[-\sum_{k=1}^{N_\mathrm{H}} \int_T \nu_k P(S_i \mid H_k)\,\mathrm{d}T\right]\right\}\right\rangle \end{aligned} \tag{E.2}$$

where E_R is the expectation over all non-time-invariant variables, like resistance, self-weight and so on.

NOTE 1 Hazards H_k, for different values of k, can be of different types, e.g. earthquake and fire, but also of the same type but different origin, e.g. different earthquake zones.

NOTE 2 $P(S_k|H_k)$ and $C(S_k)$ can be dependent on time.

NOTE 3 For the evaluation of the limit-state probability $P(S_i|H_k)$, action models, resistance models, and structural as well as non-structural response analysis are usually required.

If the exponent is always small compared to unity and frequencies are time-independent, Equation (E.2) can be simplified to Equation (E.3):

$$R = E_{\mathrm{R}}\left[\sum_{i=1}^{N_{\mathrm{S}}}\sum_{k=1}^{N_{\mathrm{H}}}(\nu_k T)P(S_i \mid H_k)\,C(S_i)\right] \tag{E.3}$$

E.2 Formulation on the basis of hazard curves and fragility curves

E.2.1 Formulation

When only a single hazard is considered but the occurrence of a certain intensity of hazard is expressed in a probabilistic manner, Equation (E.3) can be rewritten as Equation (E.4):

$$R = E_{\mathrm{R}}\left\{\sum_i C(S_i)\int_\gamma\left[-\frac{\mathrm{d}P_0(\gamma)}{\mathrm{d}\gamma}\right]P(S_i \mid \Gamma = \gamma)\,\mathrm{d}\gamma\right\} \tag{E.4}$$

where

$P(S_i \mid \Gamma = \gamma)$ is the conditional probability that the actual damage state, S_i, is reached given that load intensity, Γ, is equal to γ(fragility curve);

$P_0(\gamma)$ is the probability that the load intensity, γ, is exceeded at least once during the time interval, T (hazard curve).

NOTE 1 The variable γcan also be a vector.

NOTE 2 The formulation on the basis of hazard curves and fragility curves is less suitable if it is necessary to combine various hazard types.

E.2.2 Example of seismic risk estimation

E.2.2.1 Seismic hazard curve

In conventional seismic hazard analysis, it is assumed that earthquakes occur randomly and statistically independently. Then, the probability that the random intensity, Γ, at a specific site exceeds a certain value, γ, is expressed as given in Equation (E.5):

$$P_0(\gamma) = 1 - \exp\left[-\sum_{k=1}^{n}\int_T \nu_k q_k(\gamma)\,\mathrm{d}T\right] \cong \sum_{k=1}^{n}\nu_k T q_k(\gamma) \tag{E.5}$$

where

n is the number of potential earthquake zones around the site;

ν_k is the rate of occurrence of earthquakes with upper and lower bound magnitudes m_{uk} and m_{lk}, respectively, at source k;

$q_k(\gamma)$ is the probability of $\Gamma > \gamma$, given that an earthquake occurs at source k, and can be expressed as given by Equation (E.6):

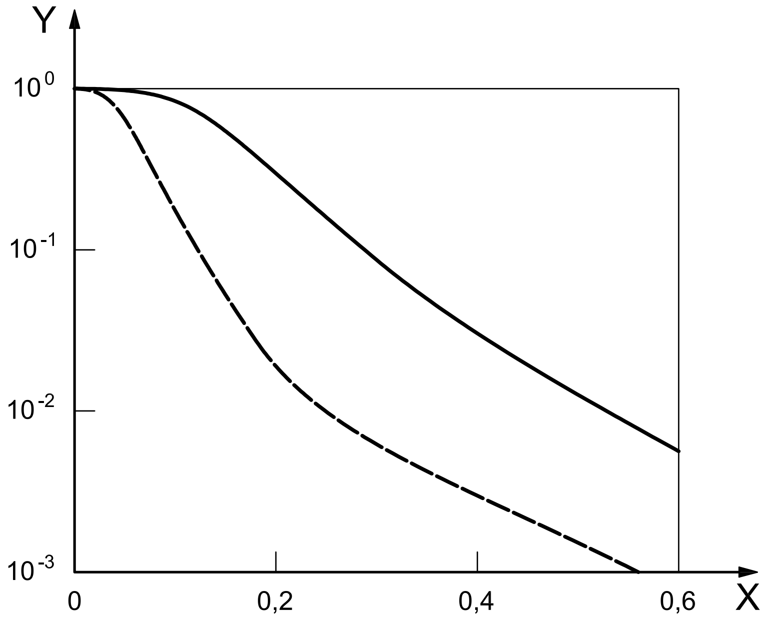
$$q_k(\gamma) = \int_{m_{\mathrm{lk}}}^{m_{\mathrm{uk}}}\int_{r_{\mathrm{lk}}}^{r_{\mathrm{uk}}} P(\Gamma > \gamma \mid m, r)\, f_{\mathrm{Mk}}(m)\, f_{\mathrm{Rk}}(r)\,\mathrm{d}m\,\mathrm{d}r \tag{E.6}$$

where

$f_{\mathrm{Mk}}(m)$	is the probability density function of magnitude, M, of an earthquake occurring at source k;
$f_{\mathrm{Rk}}(r)$	is the probability density function of distance, R, having upper and lower values of r_{uk}, and r_{lk}, respectively, from the site to the rupturing fault at source k;
$P(\Gamma > \gamma \mid m, r)$	is the probability of $\Gamma > \gamma$ given $M = m$ and $R = r$.

An extension of Equation (E.4) can be necessary when a model uncertainty is included.

The seismic hazard curve is obtained from Equation (E.3) for various values of γ. Figure E.1 shows an example of a seismic hazard curve.



Key

X maximum velocity, expressed in metres per second

Y annual probability of exceedance, P_0

——— city A

- - - - - - - city B

Figure E.1 — Example of a seismic hazard curve

E.2.2.2 Fragility curve

A fragility curve describes the probability that the actual damage to a structure, D, exceeds a damage criterion, d_i, when the structure is subjected to a specified load intensity, γ.

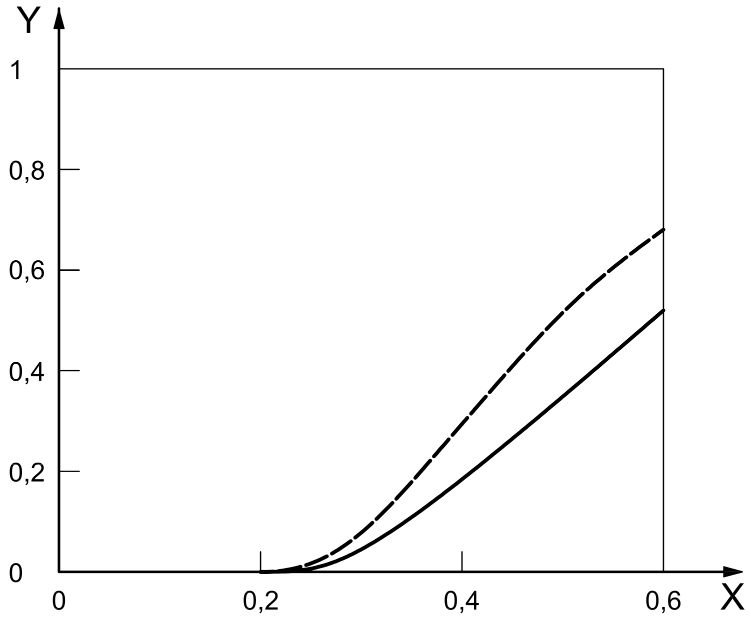
$$P\left(S_i \mid \Gamma=\gamma\right)=P\left(D\geqslant d_i \middle| \Gamma=\gamma\right)=P\left(\frac{S_\mathrm{d}}{S_\mathrm{c}}\geqslant 1{,}0\right) \tag{E.7}$$

where

S_c is the structural capacity, e.g. inter-story drift ratio at a collapse threshold;

S_d is the structural demand.

Fragility curves can be derived empirically or by theoretical analysis. Figure E.2 shows an example of a fragility curve for an earthquake, where γ represents the ground peak velocity.



Key

X maximum velocity, expressed in metres per second

Y conditional probability

——— damage state: collapse

------- damage state: severe

Figure E.2 — Example of a fragility curve

Annex F
(informative)

Procedure for the estimation of consequences

F.1 General

F.1.1 Estimation of consequences represents a systematic procedure to identify and estimate outcomes of a decision related to desirable or undesirable events. Consequences can range from positive to negative values. There can be more than one consequence from a single event. Moreover, some of the consequences can occur immediately after the event, some of them later after a certain time has elapsed. There are generally three types of consequences that are identified:

- fatalities and injuries;
- ecological effects;
- economic outcomes.

Some consequences, such as political and social damage and the loss of unique, heritage-related items, can be difficult, even impossible, to quantify appropriately.

For the whole procedure of the risk assessment of complex engineering systems, the estimation of consequences is often a key, or even the most important, step. To determine the extent of human fatalities and injuries or ecological effects and economic outcomes, the verbal (qualitative, descriptive) or numerical (quantitative) expressions can be used.

Consequences are generally multi-dimensional quantities. However, in a particular case, they can be simplified and described by a single indicator, say in terms of a monetary unit. Then the consequences of the events, E_{ij}, can be described by costs components, $C_{ij,k}$, where the subscript “ij” denotes event “j” of scenario “i”. Subscript “k” denotes the individual components associated with the number of lost lives, extent of human injuries, ecological effects and economic outcomes that are expressed in a certain “currency”.

F.1.2 The following recommendations should be considered when estimating consequences of desirable or undesirable events.

a) All consequences should be related to well defined hazard scenarios and relevant events.

b) Possible series of consequences resulting from an event should be taken into account.

c) Mitigation measures applied to reduce or eliminate adverse consequences should be taken into account.

d) Both immediate and later consequences should be considered.

F.1.3 Three optional methods may be applied for the estimation of consequences:

- estimation from loss experience;
- estimation using models;
- estimation based on engineering judgment.

In relevant cases, the options mentioned above may be used simultaneously.

F.2 Consequence estimation from loss experience

Estimation of consequences from loss experience is based on previous knowledge provided by observed events of relevant buildings or engineering systems. Loss experience used to estimate consequences can be applicable to

a) the specific existing structure and relevant engineering system being studied, e.g. in the case of the modification or renovation of an existing system;

b) all systems of a common type sharing a common location or owner, e.g. in the case of a fire-risk estimation for similar administrative buildings;

c) all systems of a common type up to a national or an international level, e.g. in the case of risk estimation for bridges or power plants.

In each case considered, the relevance and level of available data, their accessibility and magnitude should be critically verified.

F.3 Consequence estimation using models

Estimation of consequences using appropriate models has one important advantage. It provides insight into the system being investigated, better understanding of mutual links between system units, and relevant incentives for effective mitigation measures that can be applied to reduce or eliminate unfavourable consequences. For example, a model for the evacuation of a building or a tunnel in case of fire can provide evidence supporting appropriate arrangements and the relevant number of escape routes.

However, use of models does not entirely remove the requirement for experiential and subjective data. In the case of models, the estimation of consequences can be less difficult when such a requirement is transferred to a more specific variable. Thus, the model comprises a trade-off between advantages of the sophisticated model (in terms of better understanding of the system) and the uncertainty associated with the data required by the model (as compared with the uncertainty of data used directly).

F.4 Estimation of consequences based on engineering judgment

Estimation of consequences based on engineering judgment can result in a point estimate or, preferably, in a range estimate. The latter is usually sufficient for use in a risk matrix or other qualitative assessment procedure. In the case where relevant data are nearly or completely non-existent, a risk matrix can be used. Estimates of consequence are then concentrated into a small number of values. It can be useful to separate consecutive values by one or two orders of magnitude and to specify the lowest, middle and highest value with a special meaning, such as fatalities, or environmental or economic loss.

Engineering judgment can be made more systematic and consistent through the use of Delphi methods or other procedures for reducing bias and improving the quality of estimates. These methods consist of a series of repeated interrogations, usually by means of questionnaires, of a group of experts whose opinions or judgments are of interest. After the initial interrogation of each individual, each subsequent interrogation is accompanied by information regarding the preceding round of replies, usually presented anonymously. The individual is thus encouraged to reconsider and, if appropriate, to change his previous reply in light of the replies of other members of the group. After two or three rounds, the group position is determined by averaging.

Annex G
(informative)

Examples of measures for risk treatment

G.1 Introduction

There are four approaches to risk treatment.

- Avoidance: aimed at avoiding the risk by not undertaking or discontinuing an activity that can generate it (i.e., preventing occurrence of hazard). In order to use this approach, it is necessary to identify the particular hazards.

- Reduction: aimed at reducing the likelihood/probability of the hazard and/or its consequences if it occurs. Reducing the likelihood of the hazard does not eliminate the risk if it is inherent to a particular process associated with the structure use.

- Transfer: aimed at passing some of the risk to other parties. It can be achieved via insurance or finding (a) partner(s) to share the burden of the risk.

- Retention: aimed at accepting the risk and being ready to deal with its consequences if the hazard occurs.

The approaches are not mutually exclusive and in most cases their combination can provide the most efficient solution. Examples illustrating the approaches are given in Clauses G.2 to G.5. It is important to stress that the measures for the structural risk treatment should be addressed as part of the initial risk assessment during the planning, design and commissioning stages. Many of the practical engineering or structural risk-treatment measures can be impossible or costly to implement once the structure has been commissioned. It should be verified that measures undertaken against certain risks do not inadvertently increase others.

G.2 Risk avoidance

Measures associated with this approach can include changes in the structure site or access to it (e.g., not building near a seismic fault or imposing a minimum stand-off distance by placing barriers or other similar devices), or by preventing the use or storage of hazardous substances within or near the structure (e.g., not using natural gas). Although such measures are often the most simple ones and usually do not require special structural engineers' services, it is important to stress that avoiding the risk also prevents achieving the benefits associated with it.

G.3 Risk reduction

G.3.1 Measures associated with this approach are divided into those aimed at reducing the likelihood of the hazard and others that can reduce the consequences in the case that the hazard occurs.

Measures from the first group may include the following:

- personnel training;

- review of structural design specifications and requirements;

- quality control at the stages of design and construction;

- regular inspection of the structure during its service life;
- control for processes associated with the structure use;
- preventative maintenance (e.g., repair, replacement of damaged components);
- strengthening and retrofit of existing structures;
- structural protective measures (e.g., protection of columns);
- non-structural protective measures (e.g., installing a fire sprinkler system);
- improving techniques for structural design, construction and maintenance through research and development.

G.3.2 Measures from the second group can include the following:

- provision of evacuation routes;
- training building occupants on how to behave in emergency situations;
- response planning;
- confinement of the hazard (e.g. the prevention of fire spread by compartmentalization);
- limiting the extent of failure (e.g. by robustness-related measures).

G.3.3 For response planning, the time frame available for it is a critical issue. In some cases, there is sufficient time to carefully plan the response. However, there are situations that require emergency responses (Flin, 1996):

- rapid onset of the risk;
- little warning or preparation time;
- high level of hazard;
- those responding to the risk are affected by the risk;
- high level of harm, such as numbers of casualties or financial loss;
- wide variety of people involved with the response to the risk;
- stage of development of the risk;
- major risk, one involving high loss of life;
- high demand on the decision-makers;
- limited resources compared to the size of the threat;
- lack of knowledge of the situation;
- time of onset, e.g. can be worse at night or during a holiday period;
- a remote or inaccessible location.

G.3.4 In the case of an emergency, the issue is not only the planning but also that it is necessary for the planning to be adapted to the situation. The response is more immediate and passes through three stages:

- response phase (evaluation and containment);
- resolution phase (contingency planning);
- recovery phase (restoration of normality).

The response phase is the initial phase where it is necessary for the team involved to be able to evaluate the risk by assessing the size of the problem and considering whether it is possible to contain or limit the spread of the emergency. Once this has been carried out, the next stage is the implementation of the contingency plan by bringing into place the skill of the fire, police, ambulance and rescue services involved. Finally, there is the recovery phase. This final stage can be lengthy and is dependent on the type and extent of the incident that has occurred.

G.4 Risk transfer

Measures associated with this approach involve reduction of risk through financial treatments with real monetary transactions, such as purchasing insurance or derivative financial instruments. Stakeholders responsible for the risk pay for the insurance cost in exchanging the probabilities of risk reduction with insurance payments. If a loss event doesn't occur, the cost is no more than a expense; but if it does occur, the loss is reduced in accordance with the payment conditions.

There are two popular measures as risk transfer. One is insurance and the other is a derivative. In case of seismic risk, there is securitization, called a “catastrophe bond”, hereinafter called a CAT bond.

Earthquake insurance is not always utilized effectively from the viewpoint of the reinsurance market conditions. Therefore, attention is focused on the CAT bonds as another measure, called an alternative risk transfer (ART), to transfer the risk.

A CAT bond helps risk-management entities to establish an efficient risk-transfer scheme that can include earthquake insurance. On the other hand, it incorporates additional risks that insurance does not cover, as typified by basis risk in the case that they incorporate a CAT bond. Basis risk can be defined as the difference between the amount paid for the CAT bond and the actual loss that the risk-management entities want compensated. Basis risk is controllable; ignoring it, however, can have the undesirable result that the compensation is not sufficient to cover actual loss or the increased cost of risk transfer.

Meanwhile, in cases when the stakeholders invite co-operators from outside and gain the members who take the basis risk, the previous risk can be reduced. This is an example of risk transfer.

G.5 Risk retention

Risk retention involves accepting the consequences when a loss event occurs. It is necessary that plans be prepared for dealing with the consequences of taking the risk, including identifying possible sources for covering the losses. All risks that are not avoided or transferred are retained by default. Risk retention can be a viable option for small risks where the cost of insuring against the risk can be greater over time than the total potential losses. This can be assessed by cost/benefit analysis. This also includes risks that are so large or catastrophic that they either cannot be insured against or for which the premiums would be disproportionately expensive. War is an example, since most property and risks are not insured against it. Any amount of potential loss (consequences) over the amount insured is included as part of the risk.

Annex H
(informative)

Examples of application of risk acceptance and optimization

H.1 Optional strategies for seismic upgrading of existing non-conforming wooden houses in Japan

NOTE 1 See Mori, *et al.*, 2007.

There are about 11 million existing non-conforming wooden houses today in Japan, and upgrading the seismic resistance of such houses is essential for disaster mitigation. Although it is desirable to upgrade all of these houses to the level required by the current design code, this does not seem to be feasible because of the huge cost of upgrading. In Aichi Prefecture, it would cost about one trillion yens, which is more than one third of the annual budget, to upgrade all 570 000 of its existing, non-conforming wooden houses. Furthermore, houses with a very poor structural performance would remain untouched because of the much higher cost, although they should be the first to be upgraded from the viewpoint of saving human lives. As a part of seismic risk management, the effective target level for upgrading the existing non-conforming wooden houses in Aichi Prefecture should be investigated from the viewpoint of both economics and fatalities.

NOTE 2 Representative exchange rates in mid-2009:

- 1 USD = 95 yen to 100 yen;
- 1 euro = 125 yen to 135 yen.

H.2 Definition of the system

H.2.1 Identification of the system involving structures

The system consists of all of the existing wooden houses in Aichi Prefecture and the people living in the houses.

The structural performance level of an existing wooden house is often measured by the index of seismic diagnosis; a seismic grade, I_G, equal to 1,0 is considered conceptually to satisfy the current design code. Considering the modifications of the seismic design code in Japan in 1971 and 1981, wooden houses are classified into three groups depending on their construction periods, as shown in Table H.1. It is assumed that the seismic performance level of the houses is log-normally distributed with parameters as shown in Table H.1 [Japan Upgrading Wooden Housings Business Co-operation (2005)]. As a part of economic activities, some of the old houses will be demolished and reconstructed during the next thirty years. For the sake of simplicity, it is assumed that 17 % of non-confirming wooden houses are randomly picked up, demolished, and reconstructed instantaneously at time zero to be the one of the houses in period III.

Table H.1 — Probabilistic model of seismic grade of existing wooden houses

Period		Mean seismic grade	Coefficient of variation
I	before 1970	0,61	0,29
II	1970 through 1981	0,74	0,36
III	1982 to present	1,31	0,24

H.2.2 Identification of consequences

Only direct loss due to structural failure, i.e., fatality due to collapse, cost for repair or reconstruction, cost for demolition before reconstruction and cost for temporary housing, is considered.

H.3 Risk assessment

H.3.1 Hazard curve

NOTE See Annex E.

The seismic hazard map of Japan recently mapped on a 1 km grid by the Headquarters for Earthquake Research Promotion (2005) is used here.

H.3.2 Fragility curve for damage level

NOTE See Annex E.

The damage level is quantified by a damage index as shown in Figure H.1. It is assumed that the damage index, w, of a wooden house with $I_G = x$ subjected to a ground motion with a maximum peak velocity of v cm/s is estimated by the Weibull distribution expressed as given by Equation (H.1):

$$w = g_1(x,v) \equiv 1 - \exp\left[-\left(\frac{v}{241x^{1,2}}\right)^{1,16}\right] \qquad \text{(H.1)}$$

H.3.3 Economic loss function

Assuming that the reconstruction cost of a house is 120 000 yen/m^2, the economic loss, expressed in thousands of yen per square metre, for each unit floor area, z, of a house with a damage index, w, for $0 \leqslant w < 0{,}7$, is calculated as given in Equation (H.2):

$$w = g_2(z) \equiv 10 \cdot \exp\left(\frac{w - 0{,}384}{0{,}127}\right) - 0{,}058 \qquad \text{(H.2)}$$

For $0{,}7 \leqslant w \leqslant 1{,}0$, the value of the expression is fixed as 120.

It is further assumed that a total of five million yen is required for demolishing a collapsed house and for the temporary houses for the people evacuated from the house. A discount rate is not included in this example.

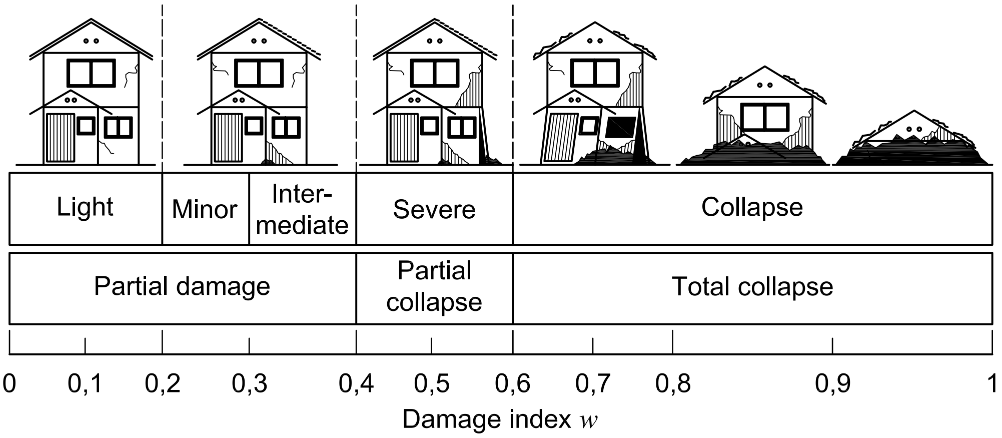


Figure H.1 — Damage level and damage index
(Okada and Takai, 2004)

H.3.4 Fatality rate

Based on the field investigation data after Kobe earthquake, it is assumed that the fatality rate, d, of the people staying in houses subjected to the structural damage with damage index, w, is as given by Equation (H.3):

$$d = g_3(w) \equiv 0{,}000\,1 \cdot \exp(6{,}98 \cdot w) \cdot F(w;\, 0{,}6;\, 0{,}01) \tag{H.3}$$

in which $F(w;\ 0{,}6;\ 0{,}01)$ is a normal conditional probability distribution function, cdf, with a mean equal to 0,6 and standard deviation equal to 0,01.

H.3.5 Cost for upgrading

The incremental cost, $\mathrm{d}C$, expressed in thousands of yen per square metre, for upgrading to increase the seismic grade by an increment, $\mathrm{d}I_\mathrm{G}$, is modelled on the basis of field data for 3 001 wooden houses upgraded in the Aichi Prefecture from 2003 to 2005, as given in Equation (H.4):

$$\mathrm{d}C = 163 \cdot \mathrm{d}I_\mathrm{G} + 5{,}8 \tag{H.4}$$

H.3.6 Estimation of seismic risk

The cdf of the damage index, w, of a house constructed in period j, given that the house is subjected to a ground motion with an intensity of v cm/s, is expressed as given in Equation (H.5):

$$F_{W|V}(W \mid V; j) = F_\mathrm{IG}\left[g_1^{-1}(w;v); j\right] \tag{H.5}$$

where

$F_\mathrm{IG}\left(g_1^{-1}; j\right)$ is the cdf of I_G of a house constructed in period j;

$g_1^{-1}(w;v)$ is the reciprocal of $g_1(w;v)$ from Equation (H.1).

The cdf of the economic loss, Z, expressed in thousands of yen per square metre, for a house constructed in period j given that the house is subjected to a ground motion of intensity v cm/s, can be evaluated from Equations (H.2) and (H.5) as given in Equation (H.6):

$$F_{Z|V}\left(Z \mid V; j\right) = F_{w|v}\left[g_2\left(z\right) \mid v, j\right] \tag{H.6}$$

Similarly, the cdf of the fatality rate, D, of a person in a house constructed in period j given that the house is subjected to a ground motion with an intensity of v cm/s, can be evaluated from Equations (H.3) and (H.5) as given in Equation (H.7):

$$F_{D|V}\left(D \mid V; j\right) = F_{w|v}\left[g_3^{-1}\left(d\right) \mid v, j\right] \tag{H.7}$$

The economic loss, $Z_{\mathrm{T}j}$, for the houses on a 1 km grid constructed during period j and the fatalities, $D_{\mathrm{T}j}$, among people living in those houses can be estimated from Equations (H.8) and (H.9), respectively.

$$Z_{\mathrm{T}j} = Z \cdot A_j \tag{H.8}$$

$$D_{\mathrm{T}j} = D \cdot M_j \cdot m_{\mathrm{p}} \tag{H.9}$$

where

A_j is the total floor area of the wooden houses in the grid constructed during period j;

M_j is the number of people living in the houses;

m_{p} is the probability that a person living in one of the houses is staying in the house at the time of strong ground motion.

A_j is estimated as the number of wooden houses in each grid times the average floor area of a house, which is 125 m^2. M_j can be estimated based on the ratio of the number of wooden houses to the total number of houses in each grid. It is assumed here that $m_{\mathrm{p}} = 0{,}5$

Applying the theorem of total probability, the complementary probability distribution function (the so-called risk curve; see Annex E) of economic loss, $R_{\mathrm{m}}(z)$ and that of fatalities, $R_{\mathrm{d}}(d)$, of a 1 km grid can be evaluated as given by Equations (H.10) and (H.11), respectively.

$$R_{\mathrm{m}}\left(z\right) = 1 - \sum_{j=1}^{3}\left\{\int_0^{\infty}\left[F_{Z|V}\left(\left.{}^{Z}\!/\!{}_{A_j}\right| V; j\right)\right] \cdot f_V\left(V\right)\mathrm{d}V\right\} \tag{H.10}$$

$$R_{\mathrm{d}}\left(d\right) = 1 - \sum_{j=1}^{3}\left\{\int_0^{\infty}\left[F_{D|V}\left(\left.{}^{D}\!/\!{}_{M_j \cdot m_{\mathrm{p}}}\right| V; j\right)\right] \cdot f_V\left(V\right)\,\mathrm{d}V\right\} \tag{H.11}$$

where $f_{\mathrm{v}}(v)$ is the probability density function of the maximum velocity of the grid.

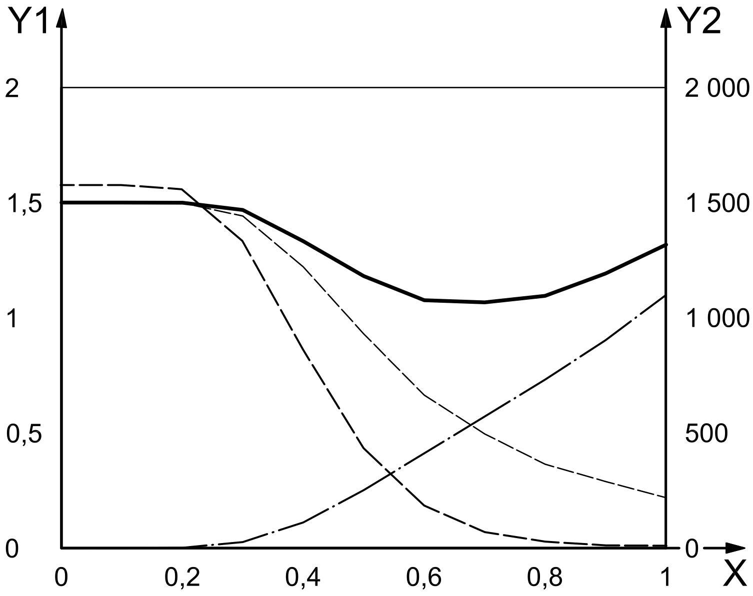
Figure H.2 illustrates the total expected economic loss due to earthquakes during the next thirty years in Aichi Prefecture as the sum of the expected economic loss, $E[C_{\mathrm{f}}]$, and the cost for upgrading, C_{u}, as a function of the target level of upgrading, I_{GT}. The expected number of fatalities, $E[D]$ is also presented in the figure. It is assumed that all houses whose I_{G} is below the target level are upgraded to exactly the target level in Figure H.2.

It is often the case that only some of those houses are upgraded. Figure H.3 illustrates the contours of the expected number of fatalities after upgrading during the next 30 years in Aichi Prefecture as a function of the target level of upgrading and ratio of upgraded houses. The contours of the cost for upgrading are also illustrated in the figure.

H.4 Risk treatment strategies

In Figure H.2, the expected loss decreases with increase of I_{GT} for upgrading; however, the decrease is overcome by the rapidly increasing of cost of upgrading for I_{GT} higher than 0,8. As a result, the total expected economic loss is minimized not by a strategy with an I_{GT} equal to 1,0 but with an I_{GT} equal to between 0,6 and 0,8. The expected number of fatalities, $E[D]$, decreases very rapidly up to an I_{GT} equal to 0,6; above this value, it slows down and the difference is fairly small for I_{GT} values higher than 0,8. From the viewpoint of cost effectiveness, Figure H.2 suggests that it is worthwhile to consider a target level for upgrading lower than the current design requirement.

In Figure H.3, the fatalities decrease as the target level of upgrading and the ratio of upgraded houses increase. The contour of fatalities is nearly parallel to the axis of the ratio of upgraded houses when the target level is low, while it is nearly parallel to the axis of target level when the target level is higher than about 0,7. This suggests that, with respect to fatalities, it is more important and effective to upgrade the houses with a very low seismic performance than to upgrade a small number of houses to the level of current design requirements. Also, in any range of the ratio of upgraded houses, it is not cost-effective to upgrade to an I_{GT} value greater than 0,7; the number of fatalities decreases little with large investment. Rather, as many houses as possible should be upgraded.



Key

X target I_{G} for upgrading

Y1 economic loss, expressed in trillions of yen

Y2 fatalities

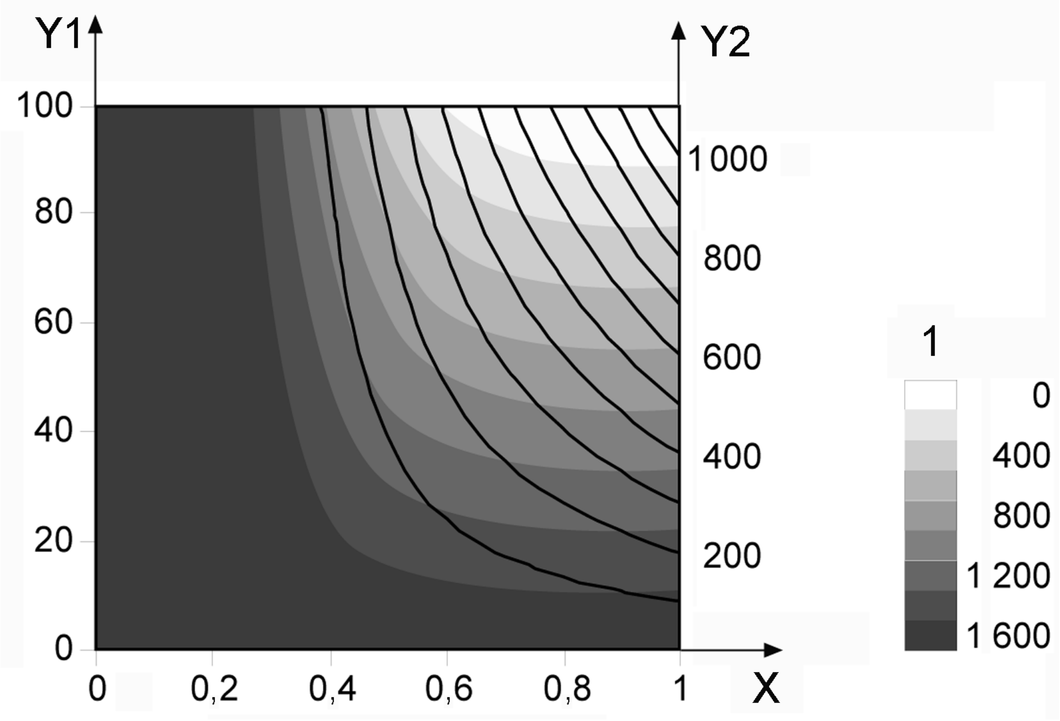
——— $E[C_{\mathrm{f}}] + C_{\mathrm{u}}$

- - - - - $E[C_{\mathrm{f}}]$

— — — · $E[D]$

— · — · - C_{u}

Figure H.2 — Target level and expected loss



Key

X target I_G for upgrading

Y1 ratio of upgraded houses, expressed as a percentage

Y2 cost of upgrading, expressed in billions of yen

1 fatalities

Figure H.3 — Expected number of fatalities as a function of I_{GT} and of the ratio of upgraded houses

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