DATE: 2013 MAY 23

ICESTRUCT JOINT INDUSTRY PROJECT (JIP) REPORT:

COMMENTARY ON ISO 19906

Contents

Page

Note: The present Commentary makes use of the following colour codes:

Gaps identified. Additional comments provided in the present document, as *basis for potential* ***amendments*** to ISO 19906. The **ICESTRUCT GUIDELINE** may provide specific guidance.

Potential source of misunderstanding. Additional comments provided in the present document, as suggested ***alternatives*** to ISO 19906. The **ICESTRUCT GUIDELINE** may provide specific guidance.

Item not considered specifically in the ICESTRUCT JIP, but some relevant comments are provided.

Item not addressed in the ICESTRUCT JIP.

Introduction

ISO 19906:2010(E), '*Petrochemical and Natural Gas Industries: Arctic Offshore Structures*', belongs to the ISO 19900 series of International Standards on normative design requirements for offshore structures. The general requirements are given in ISO 19900:2002(E), and the intention of ISO 19906 is to supplement ISO 19900 by considering ***specific*** requirements relevant for ***Arctic*** offshore structures.

The objective of ISO 19906 is to:

> '[...] *ensure that offshore structures in arctic and cold regions provide an appropriate level of reliability with respect to personal safety, environmental protection and asset value to the owner, to the industry and to society in general*'.

Thus, it aims to specify and to provide:

> '[...] *requirements and* [...] *recommendations and guidance for the design, construction, transportation, installation, and removal of offshore structures, related to the activities of the petroleum and natural gas industries, in arctic and cold regions environments*'.

With these objectives, ISO 19906 aims to address a large variety of offshore design aspects other than just those associated with the activity of determining ice actions due to ice-structure interaction.

ISO 19906 represents present-day industry consensus and best practice on protection of personnel, environment and assets when operating under Arctic conditions. The normative sections in the standard set *requirements* for performance while the informative sections include specific *recommendations* for meeting the normative requirements.

However, there are gaps in the Standard and, given its present form, one would expect that offshore structural designers with limited or no Arctic experience will require advisory services from experienced ice mechanics specialists on how the Standard is to be applied for design.

The aim of the present ICESTRUCT COMMENTARY ON ISO 19906, which is a result of the ICESTRUCT Joint Industry Project (JIP), is to supplement ISO 19906 and to assist the offshore designer in the use of ISO 19906. Selected gaps identified therein are addressed herein and commented on.

In some cases references are made to the ICESTRUCT GUIDELINE. That document provides additional information on selected topics and additional guidance, via step-by-step instructions, on estimating *characteristic ice actions* and ice action effects, *in conformance with the normative requirements of ISO 19906.*

References are also made to the Barents 2020 report (2012), which has presented a critical review of issues in ISO 19906 concerning design of *floating structures in ice* in particular. The reader is strongly encouraged to read the Barents 2020 phase 4 report. The Barents 2020 reports are available from DNV.

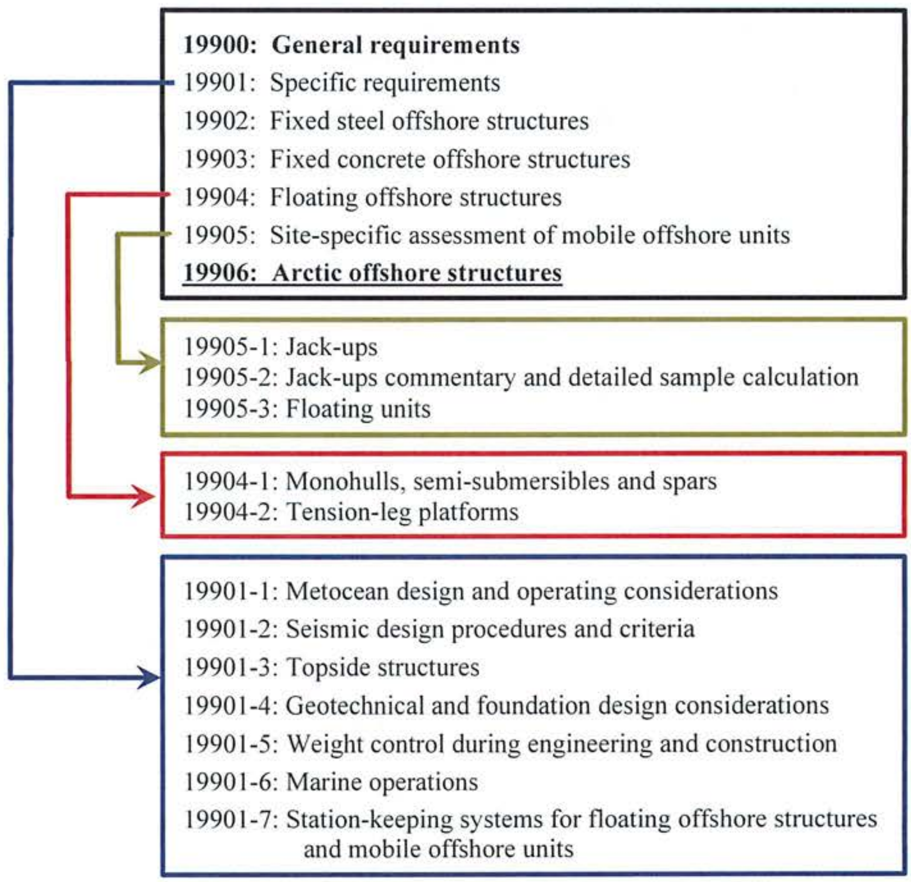
The 19990 Series of International Standards for Offshore Structures

Figure 1 below shows the family of relevant documents in the 19900 Series of International Standards for Offshore Structures. As stated in the introduction to ISO 19900:

> '*The offshore structures International Standards ISO 19900 to ISO 19906 constitute a common basis covering those aspects that address design requirements and assessments of all structures used by the petroleum and natural gas industries worldwide. Through their application the intention is to achieve reliability levels appropriate for manned and unmanned offshore structures* [...].'

ISO 19906 should therefore be used together with other relevant documents of that series.

Figure 1: The ISO 19900 series of standards of normative requirements for offshore structures.



Brief Overview of ISO 19900 and ISO 2394

The ISO 19900 series of documents should be read together with ISO 2394:1998(E), which outlines the general principles of structural reliability assessments on which ISO 19900 is based. As stated therein,

> '*ISO 19900 applies to offshore structures and is in accordance with the principles of ISO 2394* [...]. *It includes, where appropriate, additional provisions that are specific to offshore structures*'.

ISO 19900 is essentially an adaptation of ISO 2394: while ISO 2394 concerns the general principles of structural reliability assessments, ISO 19900 concerns their applications to offshore structure design.

ISO 19900 contains 10 main clauses, as listed in Table 1 below. The similarity with the structure and content of ISO 2394, as outlined in Table 2 and Table 3 below, may be noted.

It may also be noted that ISO 2394 contains additional technical information that should be of interest to the designer who has an interest in developing a deeper understanding of the underlying principles and methodologies which, through ISO 19900, are also relevant for ISO 19906. For example, ISO 2394 provides specific guidance on how actions might be combined to obtain appropriate design values.

Table 1 (left): The 10 main clauses of ISO 19900.

1	Scope
2	Terms and Definitions
3	Symbols and Abbreviated Terms
4	General Requirements and Conditions
5	Principles of Limit States Design
6	Basic Variables
7	Analyses – Calculations and Testing
8	Design Format of Partial Factors
9	Quality Control
10	Assessment of Existing Structures

Table 2 (right): The 10 main clauses of ISO 2394.

1	Scope
2	Definitions
3	Symbols
4	Requirements and Concepts
5	Principles of Limit States Design
6	Basic Variables
7	Models
8	Principles of Probability-Based Design
9	Partial Factors Design
10	Assessment of Existing Structures

Table 3: The 8 annexes of ISO 2394.

A	Quality Management & Quality Assurance
B	Examples of Permanent, variable and Accidental Actions
C	Models for Fatigue
D	Design Based on Experimental Models
E	Principles of Reliability-Based Design
F	Combination of Actions and Estimation of Action Values
G	Examples of a Method of Combination of Actions
H	Index of Definitions

Brief Overview of ISO 19906

As shown in Table 4 below, ISO 19906 contains 18 normative clauses, supplemented by two informative annexes.

The clauses of the first annex mirror the main clauses but aim to offer additional information and guidance on the use of the normative clauses.

The second annex presents guidance on regional information on metocean characteristics and ice conditions at selected geographical locations.

The clauses and sub-clauses given below (starting on page 16), in the present COMMENTARY, provide additional information and guidance on the clauses given by ISO 19906 Annex A.

Table 4: The 18 normative clauses of ISO 19906.

1 Scope
2 Normative References
3 Terms and Definitions
4 Symbols and Abbreviated Terms
5 General Requirements and Conditions
6 Physical Environmental Conditions
7 Reliability and Limit States Design
8 Actions and Action Effects
9 Foundation Design
10 Man-Made Islands
11 Fixed Steel Structures
12 Fixed Concrete Structures
13 Floating Structures
14 Subsea Production Systems
15 Topsides
16 Other Ice Engineering Topics
17 Ice Management
18 Escape, Evacuation and Rescue
Annex A (*Informative*): Additional Information and Guidance
Annex B (*Informative*): Regional Information

Summary of Main Clauses of ISO 19906

Scope, Normative References, Terminology and Symbols (clauses 1 to 4):

The first two clauses state the scope of the document and list the normative references to which the document is related and together with which it should be read (i.e. those listed in Figure 1 above). Although most of the terms and symbols concern the particular subject of Arctic technology, ISO 19906 makes use of the general terms defined in ISO 19900, *which therefore should be consulted.*

General Requirements and Conditions (Clause 5):

Clause 5 concerns the overall requirements for the design, construction, transportation and installation of Arctic offshore structures. References are made to the other ISO 19900 document, and ISO 19906 supplements those by providing special considerations relevant for arctic environments.

Physical Environmental Conditions (Clause 6):

Clause 6 concerns the requirements for the evaluation of meteorological conditions, oceanographic conditions, sea ice and iceberg conditions, and seabed conditions.

Reliability and Limit State Design (Clause 7):

Clause 7 concerns the overall design philosophy adopted in ISO 19906, which essentially is based on the '*limit state*'-based partial load and resistance factor design (LRFD) method, given specified target reliability levels to be satisfied by the design. The specified target reliability levels are given in Table A.7-1 (Annex A of ISO 19906). Clause 7 really should be read together with the relevant provisions of the other ISO 19900 documents and of ISO 2394.

Actions and Action Effects, and Foundation Design (Clauses 8 & 9):

The two clauses on ice actions and action effects (clause 8) and on foundation design (clause 9) are those which concern the actions (imposed by the relevant ice features) and associated reactions (imposed by the foundation), as experienced by the fixed offshore structure and the moored floating offshore structure. Clause 8 on ice actions and action effects, where the focus is on requirements for the establishment of appropriate design values for the actions arising from ice-structure interaction, represents the core material covered by the document. Clause 9 concerns particular requirements for geotechnical analysis and foundation design, which are important for two reasons: (i) the ice actions on an offshore structure can be of such magnitudes that conventional offshore geotechnical practice may not be sufficient, and there may therefore be geotechnical issues that need to be investigated further; (ii) the establishment of Arctic soil conditions may require additional effort and expertise than that required for conventional offshore foundation design.

Offshore Structures, Subsea Production Systems and Topsides Facilities (Clauses 10 to 15):

Clauses 10 to 15 concern the particular requirements for the design of offshore structures, subsea production systems and topsides facilities:

(i) Clause 10 on offshore man-made islands;
(ii) Clause 11 on fixed steel structures;
(iii) Clause 12 on fixed concrete structures;
(iv) Clause 13 on floating structures;
(v) Clause 14 on subsea production systems;
(vi) Clause 15 on topsides facilities.

Clause 11 (on fixed steel structures) concerns requirements specific to the design of Arctic offshore *steel structures* and which are additional requirements to those specified in ISO 19902 (and also some in ISO 19901-3). Clause 12 (on fixed concrete structures) concerns requirements specific to the design of Arctic offshore *concrete structures* and which are additional requirements to those specified in ISO 19903. Clause 13 (on floating structures) concerns the requirements specific to the design of *floating* Arctic offshore structures but not restricted to steel hulls. These requirements supplement those specified in ISO 19904-1 and in ISO 19901-7 (on station keeping systems), which therefore must be consulted. Regarding the structural design of floating structures, Clause 13 generally refers to relevant Recognized Classification Society Guidelines, although none are listed specifically, and to IMO guidelines and to national requirements.

Other Ice Engineering Topics (Clause 16):

ISO 19906 Clause 16 contains requirements and guidelines for a wide variety of special topics within ice engineering, such as bearing capacity as relevant for Arctic infrastructure (i.e. ice roads), protection barriers, measurements of ice pressure/actions, ice tank modelling and offloading systems.

Ice Management (Clause 17):

Although concerned with operational procedures, the subject of ice management is relevant to offshore structure design, as the levels of ice actions experienced by a structure in managed ice are usually smaller than those associated with unmanaged ice. Thus, the use of ice management in the selected approach to risk management, for a particular structure at a given location, may significantly influences the choice of overall system and structure design.

Escape, Evacuation and Rescue (EER, Clause 18):

The final clause concerns the governing principles for the design of the escape, evacuation and rescue (EER) system, as well as for the required risk assessment on which the overall design requirements shall be based.

Annex A:

The informative clauses of Annex A mirror the normative clauses but aim to offer additional information and guidance on the use of the normative clauses. The present COMMENTARY focuses on the material covered by ISO 19906 Annex A.

Annex B:

Annex B aims to provide regional descriptions of the physical environment of ice covered regions on the northern hemisphere. Commentaries are provided on the general meteorological and oceanographic conditions as well as on sea ice conditions and iceberg properties and occurrences. Further, included tables indicate:

> '[...] *estimates of the highest (or lowest) values which are expected to be exceeded on average every year*'.

Regarding the applicability of the given data, it is stated in Annex B that:

> *'The regional descriptions are meant to provide interested parties with an overview of the region but are not meant to provide parameter values appropriate for the design of offshore structures.'*

Further, it is stated that:

> '*While the parameters described are to be considered in the design, some might not be important for the design of particular facilities. A full description of the appropriate parameters can require review and analysis of available data, collection of new data, interpretation of parameters found in nearby regions or similar ice regimes, and statistical evaluation of the data. Appropriate specialists should be consulted in the determination of physical environmental parameters for use in the design* [...].'

Hence, detailed investigations into the local site-specific metocean characteristics are needed, and this work requires assistance from specialists.

Safety Philosophy

The Fundamental Safety Requirement

The underlying safety philosophy throughout the entire ISO 19900 series of standards is based on the principle of *reliability differentiation* of structures (see ISO 2394, clause 4.2), by which:

(i) two offshore structures located in the same regional area may be referred to as being *nominally* equally and sufficiently safe, if they both have been designed to fulfil the same standard set of performance requirements with similar degrees of reliability (see Table 5 below) as specified by the relevant standard, although it is important to note that '*Different regional areas have different requirements with regard to reliability level*' (ISO 19900, clause 8.6, Note 1);

(ii) the required degree of reliability, as specified by the relevant standard, increases with increasing severity of the consequences of structural failure.

The fundamental safety requirement is then that the structure is to be designed such that it fulfils its specified performance requirements with *appropriate degrees of reliability* (see Table 5 below; see also ISO 19906, clause 7.1.1, and ISO 19900, clause 4.1).

Regarding the required reliability, ISO 19906 adopts the philosophy whereby:

> '*The required reliability depends on the exposure level, which is determined by the life-safety category and the environmental and economic consequence category of the structure or component*' (ISO 19906, clause 7.1.1).

The term '*exposure level*' is defined by ISO 19900 clause 2.15 as a:

> '[...] *classification system used to define the requirements for a structure based on consideration of life safety and of environmental and economic consequences of failure.* [...]. *The method for determining exposure levels are described in ISO 19902. An exposure level 1 platform is the most critical and exposure level 3 the least.* [...].

In ISO 19906 (and in ISO 19902) there are three different exposure levels, L1, L2 and L3, where a structure associated with L1 requires the highest level of reliability; L2 and L3 are associated with a structure for which the safety requirements can be relaxed. In ISO 19906 (and in ISO 19902) the required reliability levels are not specified directly, but the appropriate exposure levels are specified. These depend on assigned '*failure consequence categories*' and '*life-safety conditions*', which must be specified for the structure at the outset (for example, in the governing design basis):

> '*The exposure level applicable to a structure or a component shall be determined by the owner prior to the design of a new structure or the assessment of an existing structure, and be agreed by the regulator where applicable*'. (ISO 19906 clause 7.1.4, and ISO 19902 clause 6.6.4.)

Once the structure is categorized according the appropriate exposure level, the design assessment involves design equations that require the use of *exposure level dependent action factors*, referred to as partial factors. The numerical values of these partial factors have been (or *are intended to be*) calibrated such that '*appropriate reliability*' is considered to be achieved by using these factors in the relevant design equations:

> '*The format of partial factors* [...] *is intended to be the normal method for the design procedure. In this format, the appropriate level of structural reliability is obtained through partial factors* [...]'. (ISO 19900, clause 8.6.)

ISO 19906 Table A.7-1 (taken from ISO 19902 clause 6.6.4, Table 6.6-1 therein) shows how an exposure level is to be determined, given appropriate categories of consequence and life-safety conditions. As far as the designer is concerned, the predefined exposure levels should therefore be given *a priori* in the governing design basis. From the given exposure levels, the associated target reliability levels may be deduced from ISO 19906 Table A.7-1. This allows the safety associated with a particular design to be *quantified*, and it allows the safety of two different designs to be compared, to some extent, all *provided* that the load and resistance factors have been calibrated appropriately given prescribed target reliability levels.

Appropriate Degrees of Reliability and Exposure Levels

ISO 2394 and ISO 19900 do not specify what the appropriate reliability levels should be, as this is to be determined by other standards specific to structure and location (see ISO 19900, clause 8.6, Note 1). However, ISO 2394 (appendix E) suggests the *three annual nominal failure probabilities 10^{-5}, 10^{-4} and 10^{-3}* as suitable indicators relevant for high consequence structures, where the smallest failure probability is associated with the highest degree of nominal reliability.

For Arctic offshore structures, one should expect ISO 19906 to specify appropriate reliability levels. Although these only appear in the Annex of ISO 19906 (and are therefore not normative), these three target failure probabilities have in fact been used in the development of the particular design equation action factors (i.e. the partial action factors) given in ISO 19906:

> '*The partial action factors for environmental actions* [...] *have been calibrated to the reliability targets given in Table A.7-1. When these partial action factors are applied to ULS and ALS action combinations for arctic offshore structures and their components within the scope of this International Standard of exposure levels L1 and L2, the reliability targets given in Table A.7-1 are deemed to be achieved.*' (ISO 19906 clause 7.2.4).

ISO 19906 Table A.7-1 shows that the exposure levels L1, L2 and L3 are intended to correspond to the annual nominal target failure probabilities 10^{-5}, 10^{-4} and 10^{-3}, respectively (see Table 6 below, page 13).

Regarding the nominal target failure probabilities, ISO 2394 (clause E.4.3) points out that:

> '[...] *there is a substantial difference between the notational probability of failure in the design procedure and the actual failure frequency (which to a considerable extent is due to human errors). For this reason, target levels for reliability are often based on calibration. Using calibrated reliability values, one should keep in mind that they are related to a specific set of structural and probabilistic models. Using the calibrated values in connection with other models could lead to unintentionally high or low levels of reliability.*'

Reliability, Exposure Levels and Action Factors

The specified target reliability levels are approximate, so that the actual structural reliability level of a given structure may not be exactly equal to the target reliability level used to obtain the action factors (ISO 19906 clause A.7.2.4). This is standard practice and is not unusual. In fact, if it is considered that a more detailed analysis is required, site-specific calibration of the relevant action factors should be performed. It is then the intention of ISO 19906 that such a site-specific calibration exercise shall be based on the target values for the annual nominal failure probabilities listed in Table 6 below (i.e. those given in ISO 19906 Table A.7-1):

> '*This International Standard allows a user to perform a calibration of action factors for use in place of the action factors presented in Table 7-4, to the reliability targets presented in Table A.7-1, for all exposure levels.*' (ISO 19906, Clause A.7.2.4.)

The underlying principle in ISO 2394 is that the design shall satisfy a predetermined target reliability level, given a particular design situation that reflects a particular mode of operation under a given set of environmental conditions. Although the target reliability levels are not to be interpreted as accurate estimates of the expected probability of survival of the actual structure, the reliability levels are considered sufficiently approximate such that the degree to which a given design can be classified as safe may be quantified. In addition, the target reliability level provides a measure of the safety associated with one particular design as compared with another. The key philosophy here is that different designs based on the same requirements should exhibit similar (but not necessarily identical) degrees of safety.

In ISO 19906, action factors have been calibrated based on given target reliability levels, *but these reliability levels are not part of the normative design requirements.* The starting point of the design procedure, according to ISO 19906 (but not according to ISO 2394), is the selection of appropriate consequence categories and life-safety conditions. From these, the appropriate exposure levels follow. The *normative* design requirements then involve the use of *specified* partial action factors associated with the *given exposure levels*.

Table 5: The fundamental safety requirement: fulfilment of a set of performance requirements with appropriate degrees of reliability.

ISO 19906 (Clause 5.1):   *'Offshore structures for use in arctic and cold regions **shall be** planned, **designed**, constructed, transported, installed and decommissioned **in accordance with ISO 19900** supplemented by this International Standard.'*   ***ISO 19906 (Clause 7.1.1):***   *'The structure and its components shall be designed so that they **function with adequate reliability** for all physical environmental, accidental and operational actions and conditions to which the structure can be subjected during all phases of the design service life, including construction, transportation, installation and removal.'*
ISO 19900 (Clause 4.1):   *'A structure and its structural components shall be designed, constructed and maintained so that it is suited to its intended use. In particular, it **shall, with appropriate degrees of reliability, fulfil** the following **performance requirements**:*   *a) it shall withstand actions liable to occur during its construction and anticipated use (ULS requirement);*   *b) it shall perform adequately under all expected actions (SLS requirement);*   *c) it shall not fail under repeated actions (FLS);*   *d) in the case of hazards (accidental or abnormal events), it shall not be subsequently damaged disproportionately to the original cause (ALS);*   *e) appropriate degrees of reliability depend upon:*   *— the cause and mode of failure;*   *— the possible consequences of failure in terms of risk to life, environment and property;*   *— the expense and effort required to reduce the risk of failure;*   *— different requirements at national, regional or local level.'*
ISO 2394 (Clause 4.2):   *'Structures and structural elements shall be designed, constructed and maintained in such a way that they are suited for their use during the design working life and in an economic way. In particular they **shall, with appropriate degrees of reliability, fulfil** the following **requirements**:*   *— they shall perform adequately under all expected actions (serviceability limit state requirement);*   *— they shall withstand extreme and/or frequently repeated actions occurring during their construction and anticipated use (ultimate limit state requirement);*   *— they shall not be damaged by events like flood, land slip, fire, explosions, impact or consequences of human errors, to an extent disproportionate to the original cause (structural integrity requirement).*   ***The appropriate degree of reliability** should be judged with due **regard to the possible consequences of failure** and the expense, level of effort and procedures necessary to reduce the risk of failure (see 4.2).'*

Table 6: Exposure Levels and Target values of the annual failure probability.

Exposure level	Target values for the annual nominal failure probability
L1	10^{-5}
L2	10^{-4}
L3	10^{-3}

Additional notes included herein:

(1) Under the given environmental conditions, and in the state of structural behaviour described by the given limit state, the '*annual failure probability*' is the probability of the event that the relevant *annual maximum action effect* exceeds the relevant structural capacity to withstand the imposed action effect.

(2) The 'annual failure probability' is a *nominal target* value:

(i) it is a *nominal* value, because it is usually based on engineering models of structural response that do not take into account all operational aspects (e.g. maintenance) and human behaviour (e.g. gross operational error) which can change the *actual* expected failure probability through the violation of the underlying model assumptions;

(ii) it is a *target* value, because it is not possible to provide an exhaustive list of action factors that are valid for all structures in all environments in such a way that the structure-specific (nominal) failure probability will be identical for all structures. However, through the use of prescribed target values the structure-specific (nominal) failure probabilities will be considered as *similar*, so the degree of safety of two offshore structures designed according to a prescribed set of target reliability levels can be *compared consistently*.

(3) '[...] *there is a substantial difference between the notational probability of failure in the design procedure and the actual failure frequency (which to a considerable extent is due to human errors). For this reason, target levels for reliability are often based on calibration. Using calibrated reliability values, one should keep in mind that they are related to a specific set of structural and probabilistic models. Using the calibrated values in connection with other models could lead to unintentionally high or low levels of reliability.*' (ISO 2394, clause E.4.3)

Design Philosophy

ISO 19906 and ISO 2394, LRFD and Limit State Design

The design philosophy adopted in ISO 19906 is the '*load and resistance factored design*' (LRFD) by the '*limit state*' approach; see ISO 2394 for background and details on the governing principles. The key principle is that satisfactory performance of the design, for a given mode of operation, shall be checked through the fulfilment of a limit state criterion associated with the given mode of operation (ISO 19900, clause 2.11). This is the design criterion.

Limit States

The design criteria are defined in ISO 19900 (clause 2.11) as '*quantitative formulations that describe the conditions to be fulfilled for each limit state*', where the limit state is the '*state beyond which the structure no longer fulfils the relevant design criteria*'. The limit states then represent the explicit formulations of the design criteria, by which satisfactory load-bearing performance of the structure is checked.

Design Situations

A key part of the design basis is that which deals with the set of relevant design situations, or load cases, considered critical for the design assessment of the structure:

> '[...] *set of physical conditions representing a certain time interval for which the design demonstrates that relevant limit states are not exceeded*' (ISO 2394:1998(E)).

The design situations correspond to different operating conditions under which satisfactory performance is to be assessed by the designer.

> '*Design situations as used herein include all the service and operational requirements resulting from the intended use of the structure and the environmental conditions that can affect the design of the structure in accordance with ISO 19900.* [...]. *Criteria that are to be met by the design are directly related to the specific formulation of the design situations. Therefore, design situations and design criteria shall not be separated from one another.*' (ISO 19902, clause 6.2.4.)

The Fundamental Design Requirement

The fundamental design requirement may be summarized as follows:

> '*Design shall be in accordance with the limit states approach* [...]. *This requires that action effects arising from factored action combinations shall not exceed factored resistances.* [...]. *Partial factors for action combinations associated with ULS and ALS shall be in accordance with 7.2.4 or, if adequate data are available, may be specifically calibrated to achieve the reliability target (see 7.2.6) for the structure or component.*' (ISO 19906, clause 7.1.1.)

In this framework, the limit state function is evaluated for a design resistance and a set of design actions, on which the limit state function depends; here the design action factor is the action effect arising from design actions. The design actions are obtained by multiplying characteristic actions by particular factors, whose numerical values have been calibrated such that they correspond to a given target reliability level.

Characteristic Actions and Characteristic Action Effects

The characteristic action is the annual maximum action expected to occur no more than once during a given return period (e.g. 100 years); larger actions are not expected to occur within this return period. Characteristic action effects are defined similarly. As an example, ISO 19904 (clause 6.4.2) specifies that '*For ULS conditions, representative metocean actions shall be established with the intention of resulting in the most onerous metocean action effects with the return period of 100 years*'.

The Fundamental Types of Limit States, and Characteristic Actions

There are really only two fundamental limit states (ISO 2394, (clauses 2.2.10 and 2.2.11):

(i) the Ultimate Limit State (ULS), which is '*a state associated with collapse, or with other similar forms of structural failure [...]. This generally corresponds to maximum load-carrying resistance of a structure or structural element but in some cases to the maximum applicable strain or deformation*'.

(ii) the Serviceability Limit State (SLS), which is '*a state which corresponds to conditions beyond which specified service requirements for a structure or structural element are no longer met*'.

ISO 2394 does not refer to an Accidental Limit State (ALS): this is fundamentally a *ULS under an accidental situation* (i.e. exceptional condition of use or exposure for the structure). However, for design purposes, it is convenient to refer to the ALS explicitly. In ISO 19906, the emphasis is on ULS and ALS as far as reliability and appropriate exposure levels (ISO 19906 clause 7.1.5) are concerned. ISO 19906 specifies the required return periods of the characteristic actions as 100 year and 10,000 years for ULS and ALS design, respectively (ISO 19906 clauses 7.2.2.3 and 7.2.2.4).

Limit State Criteria, Characteristic Actions and Partial Action Factors

ISO 19906 Table 7-4 lists the required partial action factors to be used in the design equations:

> '*The action combinations specified in Table 7-4 shall be used in design. For each action combination, the representative value of an action or combined environmental action shall be multiplied by a partial action factor not less than that specified in Table 7-4, except that, alternatively, action factors for permanent and variable actions may be taken from ISO 19902, ISO 19903 or ISO 19904-1 for the respective structure types. These action factors apply to both local and global actions.*' (ISO 19906 clause 7.2.5)

In particular, the environmental action factor to be used, *according to ISO 19906*, for ice actions, is:

(i) 1.35 for L1 structures under ULS (*NB: see comments under clause A.7.2.4 below*);
(ii) 1.10 for L2 structures under ULS (*NB: see comments under clause A.7.2.4 below*);
(iii) 1.00 for all structures under ALS (*NB: see comments under clause A.7.2.4 below*).

The Limit State Criteria and Characteristic Action Effects

The fundamental design principle of ISO 19906 clause 7.1.1 applies equally to floating structures and fixed structure. Within the framework of ISO 19906, the overall challenge of designing floating structures in ice appears to be the application of appropriate '*ice actions*' on the structure such that appropriate *ice action effects* associated with ULS and ALS are obtained. The particular challenge is to establish appropriate '*ice actions*' that result in the *required characteristic ice action effect*: an annual maximum ice action effect with such a magnitude that it occurs, on average, no more than once in 100 years (in the case of ULS).

However, it is generally not correct to simply *apply* an 'external' 100-year global ice action and to expect to obtain the 100-year ice action effect on a floating structure in ice, as required by the ISO 19906 design requirements. The ice failure process, when considered as a random process, can be strongly non-stationary, and the ice actions depend implicitly and non-linearly on the instantaneous configuration of the structure, which again depends on the ice actions. What *is* possible, provided a suitable numerical ice-interaction global response model is available, is to define an ice environment and to compute the response (i.e. ice action effects) of the structure in that ice environment. In other words, the ice action effect associated with a prescribed ice environment is obtained directly. Characteristic action effects may then be obtained from probabilistic analyses. Here, the global ice action is *not* quantified explicitly and independently, as they may be in the case of fixed structures.

The required remedy is to reformulate the design criterion such that the design check involves a comparison of a factored resistance against an action effect arising from a combination of *factored ice action effects* and other factored actions and/or action effects. Here, the ice action effect which is to be factored is a *prescribed characteristic action effect*.

Comments are also given below under clauses A.7.2.2, A.7.2.5, A.8.1, A.8.2.2.1, A.13.2 and A.13.4.

ADDITIONAL INFORMATION AND GUIDANCE ON ISO 19906, ANNEX A

(Informative)

The clauses and sub-clauses given below provide additional information and guidance on the clauses given by ISO 19906 Annex A, based on the results of the ICESTRUCT Joint Industry Project (JIP). In order to ease the cross-referencing between the present document and ISO 19906, the present ICESTRUCT COMMENTARY uses the format, numbering system and heading titles used in ISO 19906. References are also made to relevant sections of the ICESTRUCT GUIDELINE.

Note the colour codes referred to on page 2.

A.1 Scope

Item not addressed in the ICESTRUCT JIP.

A.2 Normative references

Item not addressed in the ICESTRUCT JIP.

A.3 Terms and definitions

Item not addressed in the ICESTRUCT JIP.

A.4 Symbols and abbreviated terms

Item not addressed in the ICESTRUCT JIP.

A.5 General requirements and conditions

A.5.1 Fundamental requirements

The fundamental requirements for *any* offshore structure are specified in ISO 19900, and these are normative also for Arctic offshore structures. ISO 19900 is essentially an implementation of ISO 2394 (which concerns general principles of reliability of structures) applied to offshore structures. This clarification is considered as basis for a potential ***amendment*** to ISO 19906.

The underlying safety philosophy throughout the entire ISO 19900 series of standards is based on the principle of *reliability differentiation* of structures (see ISO 2394, clause 4.2), and this is summarized above on page 10 under 'Safety Philosophy: The Fundamental Safety Requirement'. The fundamental safety requirement essentially involves the check of fulfilment of specified performance requirements (via the limit state criteria) with appropriate degrees of reliability (see Table 5 and Table 6 above, pages 12 and 13). ISO 19900 does not explicitly specify target reliability levels, because it is acknowledged that different structures in different environments at different geographical locations may require different levels of reliability. However, the underlying philosophy clearly implies that (i) location specific or (ii) structure specific standards in the series should address the appropriate reliability levels relevant for the structures to which these standards apply. ISO 19906 is an example of such a location and/or structure specific standard, and one should therefore expect that the normative part of ISO 19906 specifies the appropriate reliability levels relevant for Arctic offshore structures. This clarification is considered as basis for a potential ***amendment*** to ISO 19906.

In ISO 19906:2010(E) these required reliability levels (listed above in Table 6, page 13, for completeness) appear in the *informative* Annex A (Table A.7-1 therein) rather than in the *normative* part. In draft versions of ISO 19906, e.g. ISO/FDIS 19906, this table appeared in a simpler form as Table 7-5 in the normative section of the standard. However, before the release of ISO 19906:2010(E), that table was taken out of the normative section and placed in the informative section as Table A.7-1. This is considered as a fundamental gap in ISO 19906, in its present form, because without these normative requirements in ISO 19906, the fundamental safety philosophy in ISO 19900 (and ISO 2394) is not adhered to. It is recommended here that future versions of ISO 19906 include this table in the normative part. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

Moreover, in the case where site-specific design assessments are made based on a site-specific environmental description, there may be a need to obtain site-specific action factors to be used in the limit state criteria, and these site-specific action factors must be obtained based on normative requirements on the target reliability levels with which the action factors are to be associated, by requirement (ISO 19900). This issue is not considered any further in the ICESTRUCT GUIDELINE, but highlighted here for the purpose of addressing a critical gap in ISO 19906. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

Also related to clause A.5.1, the summary above on '*Safety Philosophy*' (page 10) is relevant here, addressing:

- *The Fundamental Safety Requirement (see also Table 5, page 12).*
- *Appropriate Degrees of Reliability and Exposure Levels (see also Table 6, page 13).*
- *Reliability, Exposure Levels and Action Factors.*

That summary is considered as basis for a potential ***amendment*** to ISO 19906.

A.5.2 Design methods

Although ISO 2394, ISO 19900 and ISO 19902 all refer to design situations, ISO 19906 introduces the *ice-structure interaction scenarios*. A set of design situations is essentially a sub-set of a given ice-structure interaction scenario, where each design situation is associated with a set of values of environmental input parameters relevant for the given scenario. In short, an ice interaction scenario is defined by:

(1) the governing conditions for limiting ice actions;
(2) the structural configuration;
(3) the type of ice feature involved in the ice-structure interaction; and
(4) the assumed failure mode of the ice.

ISO 19906 requires that the ice-structure interaction scenarios are identified explicitly. For a given ice interaction scenario, there may be different design situations (or load cases) associated with, for example, different ice characteristics such as thickness and temperature or different structural characteristics such as structural width and slope angle. The ICESTRUCT GUIDELINE, in section 6, provides a list of ice-structure interaction scenarios that should be considered. This is considered as basis for a potential ***amendment*** to ISO 19906.

Also related to clause A.5.2, the summary above on '*Design Philosophy*' (page 14) is relevant here, addressing:

- *ISO 2394, LRFD and Limit State Design*
- *Limit States*
- *Design Situations*
- *The Fundamental Design Requirement*
- *Characteristic Actions and Characteristic Action Effects*
- *The Fundamental Types of Limit States, and Characteristic Actions*
- *Limit State Criteria, Characteristic Actions and Partial Action Factors*
- *The Limit State Criteria and Characteristic Action Effects.*

That summary is considered as basis for a potential ***amendment*** to ISO 19906.

In particular, the last section of the summary above on page 15 concerns the unsatisfactory recommendation in ISO 19906 by which appropriate 'ice actions' are to be applied on a floating structure in ice to check for ULS and ALS criteria (clause 13.5.3); see also the comments below under clauses A.7.2.2, A.7.2.5, A.8.1, A.8.2.2.1, A.13.2, A.13.4 and A.13.5.

A.5.3 Site-specific considerations

A. 5.3.1 General

This clause stresses the normative requirement for obtaining site-specific environmental data. A reference to clause 5.1 of ISO 19901-1 should have been made. That clause provides normative requirements for '*the determination and use of meteorological and oceanographic (metocean) conditions for the design, construction and operation of offshore structures of all types* [...]', and it is therein stated that:

> '*The owner of a platform is responsible for selecting the appropriate environmental conditions applicable to particular design and operating situations. The selection shall take regulatory requirements into account, where these exist*'.

Note that ISO 19901-1 identifies the owner of the installation as the responsible for the design basis, while a more common understanding is that this responsibility lies with the operator. The reference to ISO 19901-1 clause 5.1 and the present comments are considered as basis for a potential ***amendment*** to ISO 19906.

The ICESTRUCT JIP has considered methodologies for estimating characteristic ice actions and ice action effects on fixed and floating structures in ice, for *preliminary design assessments*. These are presented in the ICESTRUCT GUIDELINE. They are based on a generic but simplified probabilistic environmental model developed in ICESTRUCT, where geographical differences in environmental conditions *are* taken into account. However, they are not necessarily site-specific, and any detailed design assessment must be based on site-specific data. This comment is considered as basis for a potential ***amendment*** to ISO 19906.

A. 5.3.2 Long-term climate change

Item not addressed in the ICESTRUCT JIP.

A. 5.3.3 Structural configuration

Item not addressed in the ICESTRUCT JIP.

A. 5.3.4 Winterization

Item not addressed in the ICESTRUCT JIP.

A.5.4 Construction, transportation and installation

Item not addressed in the ICESTRUCT JIP.

A.5.5 Design considerations

It should be noted that the general normative design requirements for offshore structures are given in ISO 19900, which are specific applications of the general requirements of ISO 2394, as relevant to offshore structures. As far as design considerations are concerned, the purpose of ISO 19906 is then to *supplement* ISO 19900 if there are considerations particular to *Arctic* offshore structures that must be made. The most important example of such a consideration particular to Arctic offshore structures is the ***compliance with required target reliability levels specific for operations in the Arctic***, and it is the role of application-specific standards in the ISO 19900-series, of which ISO 19906 is an example, to specify appropriate reliability targets. This is essentially the philosophy presented in ISO 19900 and ISO 2394, but it is not made clear in ISO 19906. The issue is not considered any further in the ICESTRUCT GUIDELINE, but highlighted here for the purpose of addressing a fundamental gap in ISO 19906. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A.5.6 Environmental protection

Item not addressed in the ICESTRUCT JIP.

A.5.7 Vibrations and crew comfort

Item not addressed in the ICESTRUCT JIP.

A.6 Physical environmental conditions

A.6.1 General

ISO 19906 does not offer guidance on '*the number of years of measured data required to develop the basis for design parameters*', instead suggesting that it is to be agreed by the owner and the appropriate regulatory agency. In the present document it is suggested that a recommended industry practice is established for the required sampling period and sampling rate. The ICESTRUCT GUIDELINE, in section 3.2.1.1, suggests appropriate sampling periods for ice thickness and air temperature. This is considered as basis for a potential ***amendment*** to ISO 19906.

Sampling periods for other parameters are not considered in the ICESTRUCT GUIDELINE.

A.6.2 Daylight hours

Item not addressed in the ICESTRUCT JIP.

A.6.3 Meteorology

A. 6.3.1 Air temperature

As stated in clause A.6.3.1, air temperature '*is a critical parameter not only in the design of an offshore structure, but also in its day-to-day operation*'. For design, air temperature statistics are sometimes important for obtaining cumulative freezing degree-days statistics, which can be used to estimate level ice thickness growth during the freezing season. Also, air temperature statistics may be used to estimate ice temperatures. Hence, it is important to obtain sufficient amounts of site-specific air temperature recordings, but ISO 19906 does not indicate any requirement or recommendation on the minimum sampling period and sampling rate (e.g. once per hour per day over 10 years).

In the present document it is recommended that air temperature data, as used as input to structural design assessments, *should be based on 20 years of measurements*. This is addressed in the ICESTRUCT GUIDELINE, section 3.2.1.1. This is considered as basis for a potential ***amendment*** to ISO 19906.

A. 6.3.2 Wind

Item not addressed in the ICESTRUCT JIP.

A. 6.3.3 Wind chill

Item not addressed in the ICESTRUCT JIP.

A. 6.3.4 Precipitation and snow

Item not addressed in the ICESTRUCT JIP.

A. 6.3.5 Ice accretion

Item not addressed in the ICESTRUCT JIP.

A. 6.3.6 Visibility

Item not addressed in the ICESTRUCT JIP.

A. 6.3.7 Polar lows

Item not addressed in the ICESTRUCT JIP.

A.6.4 Oceanography

Item not addressed in the ICESTRUCT JIP.

A.6.5 Sea ice and icebergs

A. 6.5.1 General

A. 6.5.1.1 Nomenclature and modelling

Analysis of limited site-specific data sets should be performed using standard statistical inference techniques. The uncertainty in the parameters of the assumed underlying distribution should be quantified (e.g. by confidence limits on the mean and standard deviation associated with prescribed probabilities). Probabilistic models (i.e. a joint probability distribution) of environmental parameters should be constructed, and these formulations should include uncertainty in the model parameters (e.g. by a Bayesian formulation). The uncertainty in the model parameters is reduced by increasing the amount of data available. These issues are not addressed in the ICESTRUCT GUIDELINE, but mentioned here because ISO 19906 is considered insufficiently informative about these issues. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

The WMO sea ice nomenclature has not been reviewed in the ICESTRUCT JIP.

A. 6.5.1.2 Ice growth

Equation (A.6-3) in clause A.6.5.1.2 shows the typical form of a growth equation for first-year level ice thickness h, given as $h = a\ C_{FDD}^{\ b}$, where C_{FDD} represents the cumulative freezing degree-days, and where a and b are site-specific constants related to the growth process during the freezing season. This form agrees with several empirical relations reported in the literature (see Figure 1 below), and it also agrees overall fairly well with the thickness values reported in ISO 19906 Annex B. However, ISO 19906 only indicates the general form of the equation, without specifying useful values of the parameters of the equation, although it is suggested that $b = 0.5$ may be used based on heat conduction considerations.

The ICESTRUCT GUIDELINE, in section 3.2.2, explicitly provides a simple equation that can be used to estimate level ice as a function of cumulative freezing degree-days, as useful for preliminary design assessments. The equation is of the same form as ISO 19906 Eq. (A.6-3), including $b = 0.5$, but also suggesting $a = 0.026$ (see Figure 1 below). This is considered as basis for a potential ***amendment*** to ISO 19906.

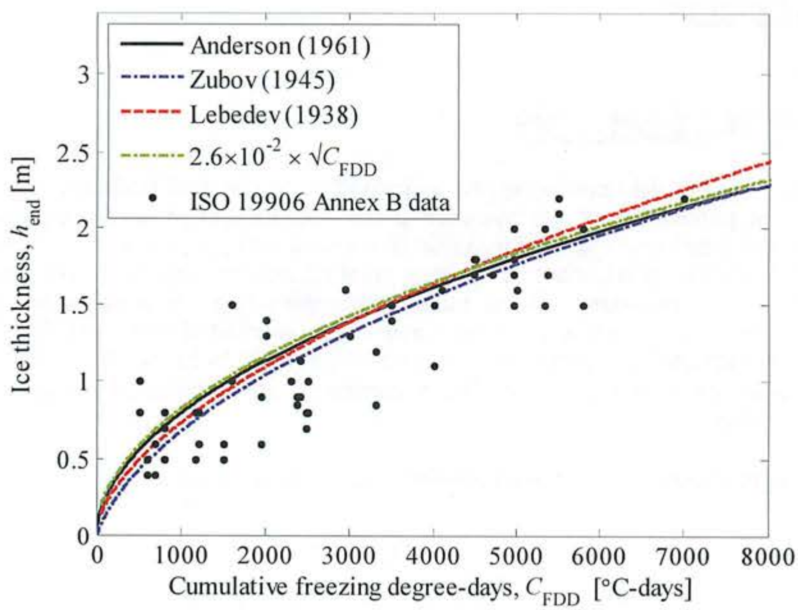


Figure 1: Average end-of-freezing-season first year level ice thickness versus average end-of-season cumulative freezing degree-days.

A. 6.5.1.3 Sea ice salinity

ISO 19906 Eq. (A.6-4) provides an estimate of the average salinity of first-year sea ice. The equation expresses the salinity S as a bi-linear function of ice thickness h, where the change in behaviour occurs at $h = 0.34$ m. This equation is strictly not correct, as it is based on a mixture of first year data and multiyear data.

Section 3.2.4 of the ICESTRUCT GUIDELINE provides another equation for first year ice salinity and which is preferred over Eq. (A.6-4). The alternative equation is based on a database of measured data more extensive than that on which Eq. (A.6–4) is based. This is considered as basis for a potential ***amendment*** to ISO 19906.

A. 6.5.1.4 Brine volume and total porosity

The relative brine volume ν_b in the ice is an important parameter, because it is used to estimate mechanical properties of sea ice, such as the flexural strength, the compressive strength and the effective elastic modulus. ISO 19906 (Eq. A.6-5 therein) recommends the use of the empirical Frankenstein-Garner equation (Frankenstein and Garner, 1967) for estimating the relative brine volume ν_b in the ice. The Frankenstein-Garner equation is simpler but less accurate than the standard Cox-Weeks equations (Cox and Weeks, 1983), and it is in the present document recommended to use the Cox-Weeks equations if the relative brine volume needs to be computed accurately. However, for the purpose of obtaining a nominal value, an even more simple and easily remembered equation can be used, and this is given in the ICESTRUCT GUIDELINE section 3.2.4.4. This is considered as an *alternative* to ISO 19906.

Sometimes effective mechanical properties of sea ice are given in terms of the total porosity, rather than just the relative brine volume. The total porosity ν in the ice is the sum of the relative brine volume ν_b, the relative air volume ν_a and the relative volume of solid salts, ν_{ss}. ISO 19906 implicitly recommends that the total porosity may be obtained by considering the sum of the relative brine volume ν_b and the relative air volume ν_a only; however, no equation is given for estimating ν_a. Again, this quantity can also be estimated from the Cox-Weeks equations (Cox and Weeks, 1983), but there is a simple and easily remembered equation also for ν_a, and this is given in the ICESTRUCT GUIDELINE section 3.2.4.6. This is considered as basis for a potential ***amendment*** to ISO 19906.

For both ν_a and ν_b, nominal values are also suggested in the ICESTRUCT GUIDELINE, sections 3.2.4.5 and 3.2.4.7. This is considered as basis for a potential ***amendment*** to ISO 19906.

A. 6.5.1.5 Ice decay and melting

Item not addressed in the ICESTRUCT JIP.

A. 6.5.2 Ice types

Not addressed in the ICESTRUCT JIP; only first year ice considered therein.

A. 6.5.3 Ice morphology

A. 6.5.3.1 General concepts

Item not addressed in the ICESTRUCT JIP.

A. 6.5.3.2 Level and pack (broken) ice

The morphology of level and pack ice was not considered as a topic in the ICESTRUCT JIP. However, simple growth models were considered; see comments under clause A.6.5.1.2 above.

A. 6.5.3.3 Ridged and rafted ice (deformed ice)

The morphology of ridged and rafted ice was not considered as a topic in the ICESTRUCT JIP. However, simple models for predicting the ridge keel draught in terms of the surrounding level ice thickness were considered. A simple model is given in section 3.3.1 of the ICESTRUCT GUIDELINE. This is considered as basis for a potential ***amendment*** to ISO 19906.

Moreover, the ICESTRUCT GUIDELINE, in sections 3.3.2, 3.3.3, 3.3.4, provide clear guidance on estimating the thickness and density of the consolidated layer of the ridge, as well as the physical properties of the ridge keel. This is considered as basis for a potential ***amendment*** to ISO 19906.

Section 3.5 of the ICESTRUCT GUIDELINE provides clear guidance on estimating the mechanical properties of ice ridge keels, such as the effective keel cohesion and the effective angle of internal friction. This is considered as basis for a potential ***amendment*** to ISO 19906.

A. 6.5.3.4 Hummocks and rubble fields

Item not addressed in the ICESTRUCT JIP.

A. 6.5.3.5 Landfast ice

Item not addressed in the ICESTRUCT JIP.

A. 6.5.3.6 Icebergs

Item not addressed in the ICESTRUCT JIP.

A. 6.5.3.7 Shelf ice

Item not addressed in the ICESTRUCT JIP.

A. 6.5.4 Ice movement

Item not addressed in the ICESTRUCT JIP.

A. 6.5.5 Ice properties

ISO 19906 here refers to clause A.8.2.8; see comments under clause A.8.2.8 below.

A. 6.5.6 Ice monitoring

Item not addressed in the ICESTRUCT JIP.

A.6.6 Seabed considerations

Item not addressed in the ICESTRUCT JIP.

A.7 Reliability and limit states design

A.7.1 Design Philosophy

A. 7.1.1 Governing principles

This clause is very important, and the first and third paragraphs highlight, by references to '*underlying reliability targets*' and '*site-specific conditions'*, the need for normative reliability targets in the normative part of ISO 19906. The lack of such normative targets is considered as a critical gap in in the standard. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A. 7.1.2 Life-safety categories

Item not addressed in the ICESTRUCT JIP.

A. 7.1.3 Consequence categories

Item not addressed in the ICESTRUCT JIP.

A. 7.1.4 Exposure levels

Apart from the comments made above in the summary of the Safety Philosophy (see Tables 5 and 6 above, pages 12 and 13), this item was not addressed in the ICESTRUCT JIP.

A. 7.1.5 Limit states

A reference should have been made to ISO 2394 or ISO 19900. This is considered as basis for a potential ***amendment*** to ISO 19906.

A. 7.1.6 Alternative design methods

Design assessments may of course be made without the use of the LRFD limit state design approach, provided they are based on full probabilistic analyses, and *provided there are normative requirements for the appropriate target reliability levels*. This clarification is considered as basis for a potential ***amendment*** to ISO 19906.

A.7.2 Limit states design method

A. 7.2.1 Limit states

Item not addressed specifically in the ICESTRUCT JIP.

A. 7.2.2 Actions

This clause primarily discusses the Extreme Level Ice Event (ELIE) and the Abnormal Level Ice Event (ALIE). In 7.2.2.1 (in the normative part of the standard), it is clearly stated that:

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

Further,

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

It is then important note that the *normative* requirements in 7.2.2.3 ('Extreme-level ice events') and 7.2.2.4 ('Abnormal-level ice events') *clearly* specify that the required characteristic loads *shall* be determined based on prescribed annual probabilities of exceedance. For ULS design (for which ELIEs are relevant), it is stated that:

> '*The representative value for actions arising from extreme-level ice events (ELIE) shall be determined based on an annual probability of exceedance not greater than* 10^{-2}';

while for ALS design (for which ALIEs are relevant), it is stated that:

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

In other words, the normative requirements in 7.2.2 *clearly* specify the required representative actions as *characteristic actions*, based on prescribed annual exceedance probabilities. This is important to note, because *the advice in A.8.2.2.1 (see comments below) appears to be non-compliant with this normative requirement.* these comments are considered as basis for a potential ***amendment*** to ISO 19906.

The topics of ELIE and ALIE were not addressed in detail in the ICESTRUCT JIP, however, they have been critically addressed in the Barents 2020 (2012) project (see list of references; project reports are available from DNV). The statements made therein should be considered as basis for a potential ***amendment*** to ISO 19906.

See also the comments below under A.13.2 and A.13.4.

A. 7.2.3 Principal and companion environmental actions

Item not addressed in the ICESTRUCT JIP.

A. 7.2.4 Combinations of actions and partial action factors

This item was not considered specifically in the ICESTRUCT JIP, but note that this clause is the informative clause in which the target reliability levels are given (see Table A.7-1 in ISO 19906, page 151).

Table 7-4 in the normative part of the Standard (see 7.2.4, page 24 and 25) provides ULS and ALS action factors to be used in design checks. However, regarding the action factors, reference should be made to the Barents 2020 report (2012, page 70):

> '*When considering design of floating structures in ice, the environmental action factors as specified in table 7-4 should be reconfirmed by project specific calibration analysis, since the underlying calibration cases did not account for:*
>
> - *flexibility of the mooring system;*
> - *the degrees of freedom of a floating structure;*
> - *the non-linear interaction between a moored structure and ice;*
> - *the change in direction of the incoming ice for a turret-moored ship-shaped floater;*
> - *relevant operational procedures, such as physical ice management and disconnection, and their uncertainty.*'

These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A. 7.2.5 ULS and ALS design

The first sentence in A.7.2.5, which states that '[...] *the total design action effect in a limit state is derived from an analysis of appropriate combinations of the factored representative values of the actions'* is considered acceptable for fixed structures in ice. For floating structures in ice, however, *the statement is considered unsatisfactory*. The focus should be on the combination of factored ice action effects and other action effects (or causing actions, if they are linearly related to the action effects they cause). This is discussed above on page 15, under the section on '*Design Philosophy*', under the heading '*The Limit State Criteria and Characteristic Action Effects'*.

Figure A.7.2 is somewhat misleading in indicating the shaded area denoted therein as 'C' as the '*domain of possible failure*'. The 'domain' of failure is all-inclusive; the only criterion for failure is that the random realization of the resistance is smaller than the random realization of the action effect. The key point of the figure is to highlight that by the limit state criterion design method, the factored resistance (indicated by the right-most line at E in the figure, to the left of F) must be at least as great as the factored action effect (indicated by the left-most line at E, to the right of D).

These comments are considered as basis for a potential ***amendment*** to ISO 19906.

This subject is not addressed further in the ICESTRUCT GUIDELINE.

A.8 Actions and action effects

A.8.1 General

It is stated in clause 8.1 that:

> '*The actions and action effects necessary to consider for design depend on the physical environment into which the structure will be placed, as well as the reliability expected of the structure*'.

It should be added that the actions and action effects necessary to consider are the ***characteristic actions on fixed structures and characteristic action effects on floating structures***, associated with ***prescribed return periods*** (e.g. 100 years for ULS design and 10,000 years for ALS design). This is considered as basis for a potential ***amendment*** to ISO 19906.

Characteristic values are found from obtaining, from site-specific measured data, a *distribution of the annual maximum action or annual maximum action effect*, and hence by inferring:

the upper 1% point, $x_{0.99}$,

(i.e. the point $x_{0.99}$ for which the exceedance probability is 1%, i.e. $\Pr\{X > x_{0.99}\} = 10^{-2}$)

and the upper 0.01% point, $x_{0.9999}$.

(i.e. the point $x_{0.9999}$ for which the exceedance probability is 0.01%, i.e. $\Pr\{X > x_{0.9999}\} = 10^{-4}$).

Characteristic ice action effects for floating structures can only be found from computational modelling of the highly non-linear ice-structure interaction, where of course the computational model must include all other relevant (and possibly response dependent) actions. The computational model must then involve a probabilistic analysis of the response, given a probabilistic description of the environment. The analysis must be sufficiently extensive to cover all environmental conditions that result in numerically similar action effects. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A.8.2 Ice actions

A. 8.2.1 General principles for calculation ice actions

Generally, the content of A.8.2 is strictly valid only for fixed structures in ice; it is not valid for floating structures in ice, for which characteristic ice action *effects* must be determined. This clarification is considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.2 Representative values of ice actions

A. 8.2.2.1 Representative values

ISO 19906 states that:

> '*In this International Standard, representative ice actions are determined for ELIE (extreme-level ice event) and ALIE (abnormal-level ice event) with relevant annual exceedance probability levels, for each ice scenario under consideration and for all scenarios considered together*'.

As a result of the ICESTRUCT JIP, doubts are cast on the validity of this statement: it is not clear that the results obtained from using ISO 19906 really provide characteristic ice actions and ice action effects associated with prescribed exceedance probabilities, especially since several of the ice parameters are to be assigned *nominal* values that are not specified explicitly by the standard. For example, it is stated that:

> '[...] *representative ice actions can be estimated using deterministic methods, in which extreme (e.g. thickness, for sea ice) or abnormal (e.g. mass or kinetic energy, for icebergs) and nominal values (e.g. pressure) of ice parameters are combined to yield the ELIE and ALIE actions*'.

This is an unfortunate statement, because the designer may obtain any arbitrary number by mixing nominal values and 'extreme' values, whatever 'extreme' means. This appears to be in violation of the normative requirements in 7.2.2.3 and 7.2.2.4 (see the comments above under A.7.2.2), because it is not necessarily true that the mixed use of nominal values and extreme values in the given ice action equations results in the required *characteristic* actions. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

It should have been stated that if characteristic values or methods for obtaining them cannot be provided to the designer, via e.g. a design basis based on site-specific measured data, then all resulting actions and action effects are to be considered as ***nominal*** actions and action effects, *and it is not possible to associate these with prescribed return periods*. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

Further, it should have been stated that characteristic ice actions on fixed structures and characteristic ice *action* effects on floating structures need to be determined *according to* prescribed *return periods* (e.g. 100 years for ULS design and 10,000 year for ALS design). These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.2.2 Probabilistic approach

A. 8.2.2.2.1 Analysis of individual scenarios

ISO 19906 states that:

> '*Generally, the main parameters should be characterized such that their combination does not lead to overly conservative or unconservative estimates of representative ice actions. Proper attention should be drawn to the tails of the distributions in question since they have a strong effect on ice loads at small exceedance levels.*'

It is also stated that:

> '*When nominal values are used, care should be exercised to ensure that the resulting action approximates the ELIE or ALIE level, as required. To ensure this, nominal values should represent the most likely ones associated with the representative actions*'.

In practice, such a careful quantitative assessment of appropriate nominal values is neither (i) possible to expect from a designer, nor (ii) possible to document without a statistical analysis of measured site-specific data. Only a limited number of ice experts are likely to be able to exercise such '*care*'. The aforementioned statement is thus not satisfactory as guidance to designers. This is considered as a critical deficiency in ISO 19906. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

The ICESTRUCT GUIDELINE provides the designer with simplified equations for estimating characteristic actions on fixed offshore structures in ice. In using these equations, there is no need for the designer to perform probabilistic analyses. The simplified equations have been based on a simplified but generic probabilistic environmental model that takes into account geographical differences in ice conditions and their variations during the winter season. This has been based on, among other factors, air temperature statistics and freezing degree-days considerations. If the designer has available information on ice thickness or on ice ridge keel draught, say, these may be used as input parameters directly. This is considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.2.2.2 Combining different scenarios

This item was not considered in the ICESTRUCT JIP. However, note that one should expect, within the framework of ISO 19900 and ISO 2394, that different ice interaction scenarios may give rise to different characteristic actions and action effects, which therefore must be checked separately for the same limit state design criterion. Further, it may be that site-specific environmental data requires different action and action effect factors for different ice action scenarios. In this case, the recommendation in A.8.2.2.2.2 appears to be not entirely in conformance with the philosophy of ISO 19900 and ISO 2394. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.2.3 Deterministic approach

ISO 19906 states that:

> '*Nominal values of the parameters, $X_{j,N}$, should generally be selected to result in conservative values of the actions. To ensure this, the nominal value of each parameter should be a conservative upper bound where it contributes to increase the ice action and a lower bound where it decreases the action*'.

It is not realistic to expect such judgements to be made by the designer. The statement above is thus considered as a critical deficiency in ISO 19906.

The ICESTRUCT GUIDELINE recommends nominal values for selected ice parameters, which yield a nominal ice action; this nominal ice action is then scaled into an appropriate characteristic ice action. This is achieved through a multiplication factor, itself a function of the governing ice parameters and structural parameters. The ICESTRUCT GUIDELINE provides the necessary equations. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.2.4 Monte Carlo simulations

This item was not considered in the ICESTRUCT JIP as a topic relevant for *the designer*.

A. 8.2.2.5 Encounter frequency

This item was not addressed in detail in the ICESTRUCT JIP, although the quantity was used therein. In the equations for estimating characteristic ice actions on fixed structures in ice, as provided in the ICESTRUCT GUIDELINE, the annual average number of action events is required as an input parameter and assumed available to the designer. For discrete ice features, such as ice ridges, this is identical to the encounter frequency referred to by ISO 19906.

For crushing in large floes, or crushing in continuous level ice, a different approach may be used. This involves a characteristic length of an ice-interaction event (associated with the measured data on which the crushing equation is based), and this is described in the ICESTRUCT GUIDELINE, section 7.3.6. This is considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.2.6 Updating distributions for encounter

Topic not considered in the ICESTRUCT JIP.

A. 8.2.2.7 Determination of probability distributions

In terms of topics of relevance to the *designer*, this particular topic was not addressed in detail in the ICESTRUCT JIP, in which the philosophy has been that the designer should not perform probabilistic analyses. The topic is thus not addressed in the ICESTRUCT GUIDELINE.

However, it could have been stated in ISO 19906 that proper statistical inference techniques should be applied to any limited data set, *taking into account parameter uncertainties* in the inferred probabilistic models. The result of these techniques is that the characteristic actions or the characteristic action effects increase with increasing parameter uncertainty, which does lead to conservative estimates; but this is only a natural and usually desirable consequence of having a limited data set. If the results are considered 'overly conservative', the recommended remedy here is to increase the sample size of the data set, rather than to apply 'judgement' in adjusting the characteristic action or action effect into a more desirable result.

Further, with the use of statistical inference techniques taking into account uncertainty in the probabilistic models, one would generally not expect that '*extrapolation to extreme or abnormal values from limited datasets can [...] lead to unsafe [...] designs*', because the result should generally lead to *larger* characteristic actions or characteristic action effects. However, *erroneous tail distribution extrapolation*, focusing on data points in which there is a large but natural uncertainty, may well lead to 'unsafe designs' by underestimating characteristic actions or action effects; but that is not a result of a statistical inference technique taking into account uncertainty in the probabilistic model.

A. 8.2.2.8 Ice action data

In terms of topics of relevance to the *designer*, this particular topic was not addressed in detail in the ICESTRUCT JIP, in which the philosophy has been that the designer should not perform statistical analysis of measured data. This is the area of expertise of the metocean specialists compiling the design basis *for* the designer. The topic is thus not addressed in the ICESTRUCT GUIDELINE.

However, it should be emphasized that any analysis of full-scale data should either result in an equation for the average action in terms the environmental parameters, or result in an equation for a defined characteristic action associated with a prescribed return period. The former can be used to obtain (or construct) the latter. 'Upper bounds', as referred to in ISO 19906, should be avoided.

A. 8.2.3 Ice action scenarios

ISO 19906 provides general information but no specific guidance for different structures and scenarios. Additional specific guidance should be provided to the designer on how to use ISO 19906 Table A.8-2 for different structures: for example, how is it intended that a designer should use A.8.2.4.4 for a moored, floating structure with a conical surface in the waterline? These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.4 Global ice actions

A. 8.2.4.1 Limiting mechanisms

The different limiting conditions for ice actions were not addressed in detail in the ICESTRUCT JIP, which only focused on the interaction scenarios associated with the limit stress condition. See the ICESTRUCT GUIDELINE, section 7.

A. 8.2.4.2 Ice failure modes

Different ice failure modes were not addressed in detail in the ICESTRUCT JIP: the informative sections in ISO 19906 were adopted, using the crushing equation for level ice, the Ralston/Croasdale equations for level ice flexural failure, and the Dolgopolov-Kärnä-Nykänen equation (see Dolgopolov et al., 1975) for ice ridge failure. See the ICESTRUCT GUIDELINE, section 7.

A. 8.2.4.3 Vertical structures

A. 8.2.4.3.1 Compression failure of an ice sheet

Item not addressed in detail in the ICESTRUCT JIP, in which the principles behind the level ice crushing equation were adopted.

A. 8.2.4.3.2 Global actions due to ice crushing

Equations (A.8-19) and (A.8-20) were adopted in the ICESTRUCT JIP; these equations reflect the typical convention adopted in the ice engineering community of expressing global ice action in terms of a global ice pressure, averaged over a nominal contact area. However, in the context of *characteristic actions,* it is important to note the difference between a *characteristic ice force (or load)* and a *characteristic ice pressure*; although force is obtained as the product of ice pressure, ice thickness and structural width, it does not follow that the required characteristic global ice action (interpreted as force) can simply be obtained from combining a characteristic ice thickness with a characteristic ice pressure. This is, in effect, what is recommended in ISO 19906, and it is generally not correct, unless the expression for the ice pressure has been specially formulated for that purpose, based on a probabilistic analysis. However, it may appear that this is not the case, based on discussions with experts involved in the development of ISO 19906 (see comments under A.8.2.4.3.3 below). The clarification of the difference between characteristic global ice action (interpreted as force or load) and characteristic global ice pressure is considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.4.3.3 Global pressure for sea ice

For the purpose of estimating characteristic ice actions associated with prescribed return periods, equations (A.8-20) and (A.8-21) are problematic, because it is not clear how to obtain the required *characteristic* global ***action*** (interpreted as force or load; e.g.: what value of thickness should be combined with the global pressure, which also involves thickness?). It would be better to formulate directly the expression for the action (interpreted as force or load), and indicate how to obtain a characteristic action. The ICESTRUCT GUIDELINE provides equations for this purpose. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

Equation (A.8-21) represents an '*upper bound ice pressure*' for crushing of level ice against a vertical structure. The present form of the equation is inappropriate: it is based on an 'upper bound' analysis of a selected data set, but that 'upper bound' analysis was not a rigorous statistical analysis and there is no prescribed probability exceedance level associated with the 'upper bound'. Moreover, the form of the equation has been adjusted so that it provides results similar to those obtained from another equation given in the Canadian Standard CAN/CSA S471-04. Also, the equation does not take into account different amounts of exposure, so it does not differentiate between two structures experiencing very different amounts of passing ice; hence, the 'design action' would be the same for both. This is considered unsatisfactory. Furthermore, it is not clear how to combine Eqs. (A.8-20) and (A.8-21) to obtain a characteristic action (e.g. 100-year action);

that is, which thickness value should be used in this combination to obtain the 100-year action, rather than the 100-year pressure. The 100-year action is not obtained by multiplying a 100-year pressure with a 100-year area. The ICESTRUCT GUIDELINE provides an alternative equation for this purpose. The alternative equation allows the characteristic actions to be estimated directly, given a prescribed return period and a prescribed number of interaction events per year. For crushing, the latter is associated with the amount of passing level ice. This is considered as basis for a potential ***amendment*** to ISO 19906.

The statement '*Equations (A.8-20) and (A.8-21) can be used in a probabilistic analysis by first determining probability density functions for the ice thickness and the strength parameter CR. A characteristic value of the global ice action can then be determined by using guidelines described in A.8.2.2*' is incorrect. Information has been made available to DNV indicating that there is no quantitative basis behind this statement. In any case, given that the equation is an 'upper bound', the statistical basis of which is unclear, it is also not clear how to interpret the results of such a probabilistic analysis. It is recommended here that the equation, in its present form, is *not* used in a probabilistic analysis. This comment is considered as basis for a potential ***amendment*** to ISO 19906.

The crushing equation, in its present form, can strictly only be used to estimate a nominal action. This is considered as a critical gap in ISO 19906. The ICESTRUCT GUIDELINE provides alternative equation for estimating characteristic actions. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.4.3.4 Influence of local ice conditions on ice pressures

A key parameter in the crushing equation is the strength parameter, C_R, and it can be determined from ISO 19906 Eq. (A.8-22), but this requires the determination of another strength index σ appropriate for the specific site under consideration. ISO 19906 then recommends a method, as given by Eq. (A.8-23) and the associated Table A.8-3, for obtaining the strength index σ based on local 'strength' measurements. Now, it has *not* been made clear in ISO 19906 that this table (Table A.8-3) has been taken from SNiP (1995) and is a table of *uniaxial compressive strength*, obtained as a function of relative brine volume, for *small scale specimens*. In other words, ISO 19906 relates the strength in the crushing equation to small scale uniaxial compressive strength. This clarification is considered as basis for a potential ***amendment*** to ISO 19906.

In section 7.3.4, the ICESTRUCT GUIDELINE provides an alternative method for estimating a nominal strength index. This method takes into account geographical differences in terms of the cumulative freezing degree-days relevant for the geographical location under consideration. This is considered as an *alternative* to ISO 19906.

A. 8.2.4.3.5 Global ice pressures from ship ramming tests

Item not addressed in the ICESTRUCT JIP.

A. 8.2.4.3.6 Points of action

The content of this item was not addressed in detail in the ICESTRUCT JIP, but the point of application of a global level ice action on a vertical structure is addressed in the ICESTRUCT GUIDELINE section 7.3.1.3.

A. 8.2.4.4 Sloping structures

A. 8.2.4.4.1 Description of the failure process

This item was not addressed in detail in the ICESTRUCT JIP, which simply adopted the recommended ice failure models given in ISO 19906. However, further work must be carried out with the purpose of improving the engineering models of ice failure under ice-structure interaction and their implementation in industry.

A. 8.2.4.4.2 Plastic method for cones

ISO 19906 is not sufficiently clear on providing guidance on how to determine appropriate values of the input parameters in the Ralston ice action equations. This is considered as a critical gap in ISO 19906. The ICESTRUCT GUIDELINE, in sections 3.2 and 3.4, provide nominal values of ice parameters relevant for Ralston's equation. This is considered as basis for a potential ***amendment*** to ISO 19906.

The ICESTRUCT GUIDELINE, in section 7.5.5, provides *alternative forms* of the Ralston equations for estimating actions on conical structures. The alternative formulations, which provide identical results to those of the original equations, aim to assist the designer in obtaining correct results in *a consistent way* without the need for a computer spreadsheet. This is considered as an *alternative* to ISO 19906.

ISO 19906 does not provide guidance on how to determine *characteristic* ice actions on conical structures, associated with a prescribed return period and an annual number of failure events. This is considered as a critical gap in ISO 19906. The ICESTRUCT GUIDELINE, in section 7.5.3, provides guidance on how to obtain estimates of characteristic ice actions on conical structures. This is considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.4.4.3 Model based on elastic beam bending

ISO 19906 is not sufficiently clear on providing guidance on how to determine appropriate values of the input parameters in the Croasdale ice action equations. This is considered as a critical gap in ISO 19906. The ICESTRUCT GUIDELINE, in sections 3.2 and 3.4, provide nominal values of ice parameters relevant for Croasdale's equation. This is considered as basis for a potential ***amendment*** to ISO 19906.

The ICESTRUCT GUIDELINE, in sections 7.4.4 and 7.4.5, provides *alternative forms* of the Croasdale equations for estimating actions on planar sloping structures. The alternative formulations, which provide identical results to those of the original equations, aim to assist the designer in obtaining correct results in *a consistent way* without the need for a computer spreadsheet. This is considered as an *alternative* to ISO 19906.

ISO 19906 does not provide guidance on how to determine *characteristic* ice actions on conical structures, associated with a prescribed return period and an annual number of failure events. This is considered as a critical gap in ISO 19906. The ICESTRUCT GUIDELINE, in section 7.4.3, provides guidance on how to obtain estimates of characteristic ice actions on planar sloping structures. This is considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.4.4.4 Effect of ice rubble

In ISO 19906, the effect of rubble pile-up in front of a sloping structure is addressed only for planar sloping structures, via the rubble-terms in Croasdale's equation. However, the effect of rubble pile-up in front of a *conical* structure is not addressed. This is considered as a critical gap in ISO 19906.

The ICESTRUCT GUIDELINE, in section 7.5.13, provides equations for estimating the effects of rubble pile-up in front of conical structures. This is addressed via the *ride-up thickness* over the surface of the cone, which is one of the parameters in Ralston's equation. In particular, an equation for estimating the *equivalent ride-up thickness* over the surface of the cone is given, in terms of the rubble volume, which is again given in terms of the rubble pile height. This is considered as basis for a potential ***amendment*** to ISO 19906.

The ICESTRUCT GUIDELINE, in section 3.6, provides guidance on estimating the rubble pile height. This is considered as basis for a potential ***amendment*** to ISO 19906.

Also, the ICESTRUCT GUIDELINE, in section 3.6, provides clear guidance on how to obtain nominal values of various ice rubble properties; in particular, the ICESTRUCT GUIDELINE provides two different equations for the angle of repose, depending on whether the structure is planar sloping or conical. This is considered as basis for a potential ***amendment*** to ISO 19906, which only considers the angle of repose for planar structures.

A. 8.2.4.4.5 High speed interactions

Item not addressed in the ICESTRUCT JIP.

A. 8.2.4.5 Ice rubble and ridges

A. 8.2.4.5.1 First-year ridges

The ICESTRUCT GUIDELINE, in sections 3.3 and 3.5, provides guidance on determining nominal values of the input parameters in the ice ridge action formulation (the Dolgopolov-Kärnä-Nykänen equation) recommended in ISO 19906. This is considered as basis for a potential ***amendment*** to ISO 19906.

The ICESTRUCT GUIDELINE, in sections 7.8 and 7.9, also provides alternative equations for estimating ridge actions on *sloping* structures, which is not addressed in ISO 19906. This is considered as basis for a potential ***amendment*** to ISO 19906.

The equations given in the ICESTRUCT GUIDELINE take into account *surcharge effects* associated with underwater rubble build-up. This is considered as basis for a potential ***amendment*** to ISO 19906. Reference should also be made to the Barents 2020 report (page 89).

ISO 19906 does not provide guidance on obtaining characteristic ice ridge actions, associated with a prescribed return period and annual number of interaction events (i.e. encounter frequency). This is considered as a critical gap in ISO 19906. Characteristic ice ridge actions are addressed in the ICESTRUCT GUIDELINE, in sections 7.7.4 (vertical structures), 7.8.4 (planar sloping structures) and 7.9.4 (conical structures). This is considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.4.5.2 Multi-year ridges

Item not addressed in the ICESTRUCT JIP.

A. 8.2.4.6 Limit force actions due to the ridge building process

Item not addressed in the ICESTRUCT JIP.

A. 8.2.4.7 Limit energy global ice actions

Item not addressed in the ICESTRUCT JIP.

A. 8.2.4.8 Floating structures

This clause refers to ice actions on floating structures, which is misleading; what matters are ice action *effects* on a floating structure in ice, in a given ice environment (see also comments under A.13.4 below; reference may also be made to the Barents 2020 report and to ISO 19904 and to, for example, DNV-OS-C101). The reference to ice actions on floating structures should be changed in future revisions of ISO 19906. Also, if it is considered that the action equations given in ISO 19906 can be used as formulations for the instantaneous action on a floating structure, in a given configuration (e.g. in a given pitch angle, which affects the instantaneous interaction angle), then guidance should be given on the formulation and use of an appropriate numerical model, the aim of which is to obtain iteratively the final configuration of the structure and the relevant ice action effect, *both* associated with the given ice environment. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

The subject of computational modelling of the structural response of a floating structure in a given ice environment is not addressed in the ICESTRUCT GUIDELINE.

A. 8.2.4.9 Multi-leg structures

The ICESTRUCT GUIDELINE, in section 7.3.7, provides guidance on the use of ISO 19906 Eq. (A.8-60) to estimate the global action on a multi-leg structure. This is considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.4.10 Adfreeze action effects

Item not addressed in the ICESTRUCT JIP.

A. 8.2.4.11 Thermal action effects

Item not addressed in the ICESTRUCT JIP.

A. 8.2.5 Local ice actions

A. 8.2.5.1 Overview of local ice actions

It is clearly stated in ISO 19906 that the local pressure equations provided under A.8.2.5 may be used to obtain ELIE conditions directly, i.e. to obtain the annual maximum local pressure with a return period of 100 years. However, due to (i) the background of the equations, (ii) the exclusion of exposure, and (ii) the public unavailability of the data on which the equations are based, the results should be treated as equations for *nominal values,* not for characteristic values associated with a 100-year return period (for ULS design). These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.5.2 Local actions from thin first-year ice

A. 8.2.5.2.1 Overview

The content of this clause was not addressed in detail in the ICESTRUCT JIP, but it should be noted that the local ice failure associated with the most severe 'actions' is implicitly assumed to be of the ductile type, due to the implementations in ISO 19906 of results by Takeuchi et al. (2004). This is considered appropriate at low ice velocities. Future work may establish velocity dependent local pressures.

A. 8.2.5.2.2 Representative values of local actions

ISO 19906 Equation (A.8-62) is essentially derived from Eqs. (A.8-63) and (A.8-64) but only considered valid when the thickness exceeds the local design height by a factor of 2.5.

See ICESTRUCT GUIDELINE, section 7.2.

A. 8.2.5.2.3 Full thickness local pressure

ISO 19906 Eq. (A.8-65) is presented as a 'design' equation for estimating 100-year pressure, based on analysis of measured data. However, the equation does not take into account exposure, so the same '100-year' pressure is obtained for two structures located in different geographical locations experiencing different amounts of passing ice. This appears unreasonable and is considered here as a gap in ISO 19906. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

Also, it appears from Figure A-8-19 that the equation is a result of a simple but arbitrary '*mean plus three times the standard deviation*' consideration. It does not appear that the equation represents a characteristic pressure, associated with a prescribed return period (e.g. 100 years), or a prescribed exceedance probability of 0.01 of the annual maximum pressure. This is considered here as a gap in ISO 19906. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

In the present document it is advised against using ISO 19906 Equation (A.8-65) for anything but obtaining a *nominal* value, and the equation appears in section 4.2.1 in the ICESTRUCT GUIDELINE. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

See also ICESTRUCT GUIDELINE, section 7.2.

A. 8.2.5.2.4 Local design at discontinuities in the structure

Item not considered in the ICESTRUCT JIP.

A. 8.2.5.2.5 Probabilistic local design

It is clearly implied in ISO 19906 that the local pressure equations given in A.8.2.5.2 may be used within a probabilistic framework, given a suitable probability density function for the ice thickness. This statement is considered herein as contradictory against the statement about the equations yielding ELIE conditions directly. It is not considered good practice to carry out probabilistic analyses with equations that already have been formulated to quantify 'characteristic' values (which themselves should be obtained from probabilistic analyses); note here that Eq. (A.8-63) is presented as an '*upper bound*' equation. Based on discussions with experts involved in the development of ISO 19906, it appears that this '*upper bound*' has no established statistical basis. The statement about using the presented equations in a probabilistic framework is considered unsatisfactory and is a critical gap in ISO 19906. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

Further progress here would require detailed insight into the background of Eq. (A.8-63), which is not possible without access to the complete data set on which it was originally based. In the ICESTRUCT GUIDELINE, ISO 19906 Eq. (A.8-63) is used as basis for providing guidance on obtaining *nominal* values (see section 7.2.1 in the GUIDELINE).

Also, it should be recalled that Eq. (A.8-63) has been determined from field measurements at the Norströmsgrund lighthouse, which has a diameter of 7.48 m and is located in the Baltic Sea. The validity of this equation for other areas remains to be documented.

A. 8.2.5.3 Local pressures for thick, massive ice features

ISO 19906 Eq. (A.8-65) is an equation for the local pressure from multi-year ice features thicker than 1.5 m, and it is a result of data from indentation tests performed in the Beaufort Sea and from direct measurements on the Molikpaq structure during its deployment there.

The equation is intended for use in a deterministic analysis; if 'action' in this case is synonymous with pressure, then it is implied (see A.8.2.5.1) that the equation directly yields a 100-year value for the annual maximum pressure (i.e. an annual maximum pressure with a return period of 100 years) for a given local design area. The equation is based on the 'revised pressure-area curve' (Masterson et al., 2007), which is a curve fit to a set of data points where the logarithm of pressure is plotted against the logarithm of area (see ISO 19906 Figure A.8-19 and Fig. 2 of Masterson et al., 2007). However, the equation is presented as a '*mean plus three standard deviations*' curve; but the implication of this in terms of exceedance probability of the annual maximum is not clear, considering the fact that the data points taken from the Molikpaq measurements only include the 10 largest of several '*pressure events*' (Masterson et al., 2007) recorded for a number of panels of a given area *A* in one particular year. It is not sufficiently clear that the '*mean plus three standard deviation*' result actually represents the 100-year condition. The validity of the equation should be further documented in publically available literature (including the measured data), so that independent statistical analyses can confirm the results. This represents a critical gap in ISO 19906.

In the ICESTRUCT GUIDELINE, section 4.2.1, the equation is included as an equation for an *initial estimate* of a ***nominal*** local pressure from icebergs and from impact with thick multi-year ice thicker than 1.5 m. No return period should be associated with the result of the equation. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.5.4 Probabilistic model for local ice pressures

ISO 19906 Eq. (A.8-66) is an equation for the cumulative distribution function $F_P(p)$ for the maximum annual local pressure p on a single panel, given an annual exposure in terms of the annual number of impacts. The equation is based on results from ship impacts with multi-year ice floes, but the relevant range of ice thickness for which the equation is valid is not given (although for multiyear ice the relevant thickness may be expected to be greater than 1 m). This represents a gap in ISO 19906. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

In the ICESTRUCT GUIDELINE, section 4.2.2, an equation is given for the characteristic pressure associated with a prescribed exposure (in terms of the annual number of impact pressure peaks) and with the required return period. This equation, from which the designer obtains the required characteristic pressure *directly*, has been derived from ISO 19906 Eq. (A.8-66) but is much simpler to use than that equation. This is considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.5.5 Local ice pressure combinations

Item not addressed in the ICESTRUCT JIP.

A. 8.2.6 Dynamic ice actions

A. 8.2.6.1 Dynamic actions on vertical structures

A. 8.2.6.1.1 General

Item adopted in the ICESTRUCT JIP.

A. 8.2.6.1.2 Time-varying interaction processes

This item was generally adopted in the ICESTRUCT JIP. However, in the case of continuous crushing, it could have been pointed out that although the magnitudes of the structural response under a stochastic ice action time series are significantly lower than those associated with frequency lock-in, mainly due to the (i) low brittle failure strength of ice, and (ii) non-simultaneous failure along the structure circumference, continuous crushing may cause accumulated damage to relatively compliant structures. This is considered as a gap in ISO 19906. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

The structural response of relatively compliant structures under continuous crushing should be considered as part of fatigue life assessments. This comment is considered as basis for a potential ***amendment*** to ISO 19906.

ISO 19906 does not provide any guidance on dynamic structural response analysis under continuous crushing, other than suggesting that a spectral approach may be used. Additional guidance on that topic is provided in the ICESTRUCT GUIDELINE, section 8.2.4. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.6.1.3 Dynamic response to intermittent crushing

Item not addressed in the ICESTRUCT JIP.

A. 8.2.6.1.4 Susceptibility to frequency lock-in

Frequency lock-in may occur at one of the natural frequencies of the structure, or at a frequency *close* to a natural frequency. ISO 19906 suggests that an eigenvalue analysis of the structure will determine the lock-in frequency. However, the dynamic interaction between the ice and the structure may affect the *in situ* dynamic characteristics of the structure, by altering the natural frequency, modal mass and modal damping. Therefore, an eigenvalue analysis will *not necessarily* reveal the *actual* lock-in frequency, and the modal damping during lock-in *may not* be identical to the modal damping initially assumed for the structure. Nevertheless, it is generally recommended to perform an eigenvalue analysis in order to identify those structural *modes* of vibration (both global and local) which are considered likely to be excited during ice-structure interaction. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

ISO 19906 recommends that susceptibility to frequency lock-in is assessed by checking whether the modal damping ratio (i.e. ratio of damping to critical damping) ξ_n of the mode being checked for susceptibility to frequency lock-in is greater than a particular critical value, ξ_{crit}. The condition for sufficient damping and therefore dynamic stability is simply

$$\xi_n \geq \xi_{\text{crit}}, \quad \xi_{\text{crit}} = \left(\frac{1}{4\pi f_n}\right)\left(\frac{\phi_{nc}^2}{M_n}\right) h\,\theta, \qquad \text{(A.8-69)}$$

where h is ice thickness, θ is an empirically determined constant ($\theta = 40\times10^6$ kg m^{-1}s^{-1}), and f_n is the natural frequency of the mode being considered; further, ISO 19906 states that ϕ_{nc} '*is the non-normalized modal amplitude*' at the ice action point. and that '*M_n is the true modal mass, expressed in kilograms*'. This is *misleading*, for the following reasons:

Firstly, ϕ_{nc} is not the modal amplitude; it is the value of the mode shape at the ice action point (the 'modal amplitude' is a common term used by structural dynamicists when referring to the generally complex amplitude of each mode shape in a series expansion of the structural response in terms a finite number of mode shapes).

Secondly, mode shapes are *always* normalized, but the sense in which they are normalized is a matter of preference and is therefore not unique. Mass normalization is usually adopted by structural dynamicists, in which case the modal mass M_n is dimensionless and has a value of unity (for *all* modes), but it is also popular to normalize such that the largest value of a given mode shape is unity (for *all* modes). Irrespective of the choice of normalization, however, the term (ϕ_{nc}^2/M_n) is constant (for a given structure) and has the unit of kg^{-1}, and so the experimental coefficient θ has the unit of kg/(ms), or kg m^{-1} s^{-1}. Note also that the unit of the mode shape depends on the choice of normalization.

These comments are considered as basis for a potential ***amendment*** to ISO 19906.

An application example is provided in the ICESTRUCT GUIDELINE, section A.1.1.

A. 8.2.6.1.5 Dynamic response to frequency lock-in

In the ice action time series shown in ISO 19906 Figure A.8-23, to be used for assessing structural response under frequency lock-in conditions, guidance on the appropriate ratio of the duration of positive rate of change of action to the action cycle period T is not given. This is considered a gap in ISO 19906. A suggested ratio is given in the ICESTRUCT GUIDELINE, section 8.2.3.1. This is considered as basis for a potential ***amendment*** to ISO 19906.

The ICESTRUCT GUIDELINE section 8.2.3.4 provides an analytical method for estimating approximately the response of a multi-degree-of-freedom system under a saw-tooth ice action time series, in line with the general recommendations given by ISO 19906 and under the assumption that the recommendations provided by ISO 19906 are correct. An application example is provided in the ICESTRUCT GUIDELINE, section A.1.2.

The methodology suggested in the ICESTRUCT GUIDELINE follows ISO 19906, in that the response amplitude depends on the ratio, denoted as q in ISO 19906 Eq. (A.8-70) therein, of (i) the difference between the maximum and minimum ice action during a single cycle, to (ii) the maximum ice action during a single cycle. ISO 19906 suggests that this ratio should be scaled such that '*the velocity response at the waterline amounts to a value that is 1.4 times the highest ice velocity, v_t, at which a lock-in condition can occur*'. This statement is the governing principle recommended by ISO 19906, and unfortunately it is not made clear in ISO 19906 that *this velocity should be taken from site-specific data*. ISO 19906 then provides an equation, Eq. (A.8-71), for estimating the highest velocity at which lock-in can occur, where the required velocity is given as being proportional to a structural natural frequency. This equation is *incorrect* in the sense that although it may be considered valid from *some* structures, it is not universally valid. In fact, its use results in the incorrect conclusion that *all* structures exhibit identical displacement amplitudes in the waterline (Metrikine, 2010, and Cammaert et al., 2011). ISO 19906 Eq. (A.8-71) should not be used and *should be removed* from ISO 19906, as it has caused unnecessary controversy. The guidance on the factor of 1.4 could be maintained. These comments are considered as basis for a potential but highly required ***amendment*** to ISO 19906.

A. 8.2.6.2 Dynamic actions on conical structures

Clause A.8.2.6.2 provides a description of a particular ice action time series that could be applied to a fixed conical structure for predicting the dynamic response under ice induced vibration. The parameters required to completely specify this time series are not all given in ISO 19906 (e.g. the location of the local temporal peak during a single loading-offloading cycle). An alternative and fully described time series is given in the ICESTRUCT GUIDELINE, section 8.3. This time series is based on full scale ice action data, and it is characterized by instantaneous loading in each loading-offloading cycle. This is considered as basis for a potential ***amendment*** to ISO 19906.

Further, one of the given time series characteristics is the minimum action F_{min}, but ISO 19906 only provides guidance on estimating its numerical value for conical structures with a waterline diameter of 10 m. No explicit guidance is provided in the case of other diameters. The ICESTRUCT GUIDELINE, in section 8.3.2.2, provides additional guidance. This is considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.6.3 Fatigue accumulation due to ice actions

Clause A.8.2.6.3 provides a general philosophy for assessing structural fatigue damage caused by dynamic ice actions, but no further details on a suitable method are provided. The ICESTRUCT GUIDELINE, in section 8.4, proposes a methodology for estimating ice induced fatigue under different scenarios. The methodology requires information about: (i) the joint relative frequencies of key environmental parameters representing different ice conditions, such as level ice thickness, ice velocity and ridge keel depth; (ii) the average number of interactions, (iii) estimated stress ranges. Specific guidance is given therein. This is considered as an *alternative* to ISO 19906. A simple application example is also provided in the ICESTRUCT GUIDELINE, section A.1.4.

A. 8.2.7 Operational procedures to reduce ice actions

Item not considered in the ICESTRUCT JIP.

A. 8.2.8 Physical and mechanical properties of ice

A. 8.2.8.1 Overview of physical and mechanical properties of ice

The mechanical properties of sea ice depend on the temperature, density and salinity of the ice, and ISO 19906 Eq. (A.8-75) provides an estimate of the relative brine volume v_b, as a function of the average salinity S and the average ice temperature T. The given equation may be referred to as the Frankenstein-Garner equation (Frankenstein and Garner, 1967). The Frankenstein-Garner equation is simpler but less accurate than the Cox-Weeks equations (Cox and Weeks, 1983), and it is here generally recommended to use the Cox-Weeks equations if the relative brine volume needs to be computed. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

However, for the purpose of obtaining a nominal value of the brine volume ν_b, an even more simple and easily remembered equation can be used, and this is given in the ICESTRUCT GUIDELINE section 3.2.4.4. This is considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.8.2 Compressive strength

A. 8.2.8.2.1 General

It is pointed out in ISO 19906 that one should consider tri-axial compressive strength of sea ice, rather than simply uniaxial compressive strength. However, ISO 19906 provides no further guidance on this topic, while the remaining recommendations concern the use of uniaxial compressive strength. This is considered as a gap in ISO 19906.

The guidance provided in the ICESTRUCT GUIDELINE is based on the assessment of uniaxial compressive strength.

A. 8.2.8.2.2 Uniaxial compressive strength of first-year ice

ISO 19906 states that uniaxial compressive strength is maximum at strain rates of about 10^{-3} per second; the standard then provides strain rate dependent equations for compressive strength. It is here considered not very likely that the designer has sufficient information available for making statements about strain rate statistics during the required design life of the structure, and it is therefore considered more appropriate to simply provide equations in which the strain rate dependence has been removed. With a strain rate of 10^{-3} per second, ISO 19906 Eq. (A.8-76) (which is of particular relevance for sea ice against vertical structures) reduces to the simpler equation

$$\sigma_c = 8.1 \times \left(1 - \sqrt{\frac{\nu_t}{0.27}}\right). \qquad \text{(A.8-69)}$$

This is considered as basis for a potential ***amendment*** to ISO 19906.

However, a DNV-study of the analysis on which ISO 19906 Eq. (A.8-69) is based has revealed that alternative strength formulations could have been obtained, and it is not clear whether ISO 19906 Eq. (A.8-69) represents an average behaviour (i.e. the average strength at a given value of porosity, averaged over a statistical sample) or an '*upper bound*' behaviour. Based on analyses of recent measurements taken at Svalbard, the ICESTRUCT GUIDELINE, in section 3.4.2, provides an alternative equation for the uniaxial compressive strength of sea ice. This is considered as an alternative to ISO 19906.

A. 8.2.8.2.3 Uniaxial compressive strength of multi-year ice

Item not considered in the ICESTRUCT JIP.

A. 8.2.8.2.4 Ice borehole strength

Item not considered in the ICESTRUCT JIP.

A. 8.2.8.3 Flexural strength

For the purpose of predicting ice actions on sloping structures in Arctic conditions, where the actions are associated with flexural failure of the surrounding ice, it is usual to represent the mechanical behaviour of the ice by conventional beam and plate bending models. Thus, the bending moment capacity of the ice sheet is represented by a flexural strength. ISO 19906 Equation (A.8-80) has been implemented in the ICESTRUCT JIP as an equation for estimating the average flexural strength of first-year sheet ice. The equation is also given in the ICESTRUCT GUIDELINE, section 3.4.1, and a nominal value is also recommended therein. The latter is considered as basis for a potential ***amendment*** to ISO 19906.

ISO 19906 states that the flexural strength is defined as '*the extreme fibre stress in tension*'. That is not strictly true: the flexural strength is defined, for a beam of ice of rectangular cross section with height h and breadth b, as the quantity $\sigma_f = 6\ M_f\ /\ bh^2$, where M_f is the bending moment over the rectangular cross section *at flexural failure* of the beam. Hence, for ice, *flexural strength* is *interpreted* in terms of a bending moment capacity; it is a derived quantity obtained from an equation ($\sigma_f = 6\ M_f\ /\ bh^2$) based on simple homogenous beam bending theory. The flexural strength itself is *not* measured. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.8.4 Tensile strength

Item not considered in the ICESTRUCT JIP.

A. 8.2.8.5 Shear strength

Item not considered in the ICESTRUCT JIP.

A. 8.2.8.6 Fracture toughness

Item not considered in the ICESTRUCT JIP.

A. 8.2.8.7 Friction coefficient

The equations for global ice actions on a sloping structure require the coefficient of kinetic ice-structure friction μ as input variable, and this is generally considered to increase with decreasing relative sliding velocity and with decreasing temperature. Based on the work of Mäkinen et al. (1994) and Saeki et al. (1986), ISO 19906 recommends the sliding velocity dependent values given in Table (A.8-5) therein, unless other measured values are available. The ICESTRUCT GUIDELINE (sections 3.4.5.2 – 3.4.5.4) provide recommended nominal values for *preliminary design assessments*. This is considered as an alternative to ISO 19906, since the relative sliding velocity is ignored.

For detailed design, site-specific environmental data should necessarily involve a statistical description of the occurrence of slow drift velocity, in order to apply the tabulated ice-structure friction values in ISO 19906. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.8.8 Material parameters for ridge keels

The equations recommended in ISO 19906 for the ice ridge keel action are based on simple Mohr-Coulomb theory: they require a material *cohesion* and an internal *friction angle*, both associated with the assumed simultaneous failure along an assumed *planar* failure surface.

Effective Internal friction angle

ISO 19906 refers to a fairly large range of values (from 10 to 80 degrees) for the keel internal friction angle, though a more narrow range from 20 to 40 degrees is suggested as '*generally accepted*'. This is consistent with other reported values given in the range from 25 to 45 degrees (Liferov and Bonnemaire, 2005). For the purpose of aiding designers, the ICESTRUCT GUIDELINE recommends a single nominal value (section 3.5.2.2). This is considered as basis for a potential ***amendment*** to ISO 19906.

Effective keel cohesion

ISO 19906 refers to a large range of values (from 0 to 100 kPa) for the ice ridge keel cohesion. No reference is given to Heinonen (2004) who suggested that the effective keel cohesion could be expressed as a function of the effective internal friction angle. For the purpose of aiding designers, the ICESTRUCT GUIDELINE recommends a single nominal spatially averaged value (section 3.5.1.4) consistent with the recommended internal friction angle and with the results of Heinonen (2004). These comments are considered as basis for a potential ***amendment*** to ISO 19906.

Effective keel porosity

In clause A.8.2.8.8, ISO 19906 refers to a range of keel porosity from 0.1 to 0.5; but in A.8.2.4.5.1, ISO 19906 refers to a range of keel porosity from 0.1 to 0.4. For the purpose of aiding designers, the ICESTRUCT GUIDELINE (section 3.3.3.2) recommends a single nominal spatially averaged value consistent with the conclusions of Høyland (2007) and Leppäranta and Hakala (1992). These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.8.9 Elastic modulus

In addition to requiring an estimate of the flexural strength, the conventional beam and plate bending models adopted for predicting ice actions on sloping structures also require an estimate of the elastic modulus (or Young's modulus) as an input variable. Its role is to represent the flexural stiffness of the ice in a quasi-static load-response sense. The elastic modulus measured via ultrasonic measurement techniques represents the true elastic modulus (Young's modulus), whereas the modulus measured via quasi-static load-response techniques represents *an effective 'modulus'*, taking into account not only the time independent elastic strain but also the time dependent but reversible strain (or reversible creep). The elastic modulus required for ice action predictions based on simple quasi-static load-response models is the *effective modulus of ice*, which is expected to be *smaller* than the true elastic modulus (i.e. Young's modulus) due to the reduced 'stiffness' associated with the creep. The modulus is typically given as a function of relative brine volume or of porosity, based on measured data, as indicated in ISO 19906 Eq. (A.8-84). It is, however, not clear from ISO 19906 whether the modulus given therein is an effective modulus (thus appropriate for quasi-static analysis) or a 'true' modulus, which in any case is larger than the required effective modulus (and thus not necessarily appropriate for quasi-static analysis). The lack of any discussion on this issue in ISO 19906 is considered here as a gap therein. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

The background of ISO 19906 Eq. (A.8-84) is unclear. The ICESTRUCT GUIDELINE, in section 3.4.3.1, provides an alternative equation which is based on the *in situ* measurements made by Anderson (1958). This is considered as an alternative to the recommendation in ISO 19906.

The ICESTRUCT GUIDELINE, in section 3.4.3.2, provides a suggestion for a nominal value. This is considered as basis for a potential ***amendment*** to ISO 19906.

*Additional note on **Poisson's ratio**:*

In ISO 19906, ***Poisson's ratio*** appears in Croasdale's action equations, and its numerical value is simply given in the list of symbols as 0.3, used as a nominal value. No additional discussion is provided. This is considered as a gap in ISO 19906.

In the ICESTRUCT GUIDELINE the nominal value of Poisson's ratio is given as larger than 0.3, in order to take into account creep effects and deformation at low strain rates. Values close to 0.3 are typically associated with results from ultrasound measurements, which involve large strain rates, and larger values than 0.3 have been reported for low strain rates, although the topic appears incompletely investigated in the literature. As Poisson's ratio ν appears in $(1 - \nu^2)$ in the denominator of one of the terms in Croasdale's ice action equations, it is considered more appropriate to use a larger value of Poisson's ratio than 0.3. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A. 8.2.8.10 Density

The commentary provided in ISO 19906 on sea ice density is entirely based on the study by Timco and Frederking (1996), who suggest that first year sea ice density remains fairly constant around 900 kg/m^3 during the winter, except towards the end during melting when the density appears to decrease. In addition, Timco and Frederking (1996) list a set of measured values from different sources (note: the values referred to here are those 11 values given by Timco and Frederking as '*density below waterline*' and free from brine drainage). Their largest reported value is[1] 0.94×10^3 kg/m^3, but that value only appears in one of the 11 relevant references; the largest value reported from the other 10 references is 0.93×10^3 kg/m^3. Their lowest reported value from the 11 references (for density below the waterline and for ice samples free from brine drainage) is 0.89×10^3 kg/m^3 (from Sinha, 1984), but the original reference appears to indicate 0.88×10^3 kg/m^3 (Sinha, 1984).

Hence, a *nominal* range of first year sea ice density may then be given as [880, 940] kg/m^3, about a *nominal* value of 900 kg/m^3 (here ignoring the issue of precision). This is also given in the ICESTRUCT GUIDELINE, section 3.2.4.8, as the recommended nominal value. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

Recent measurements of bulk density of first year sea ice (see Figure 2 below) indicate that it is indeed possible (and relatively easy) to obtain a probabilistic description from measured data, if required. However, site-specific measurements should always be made. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

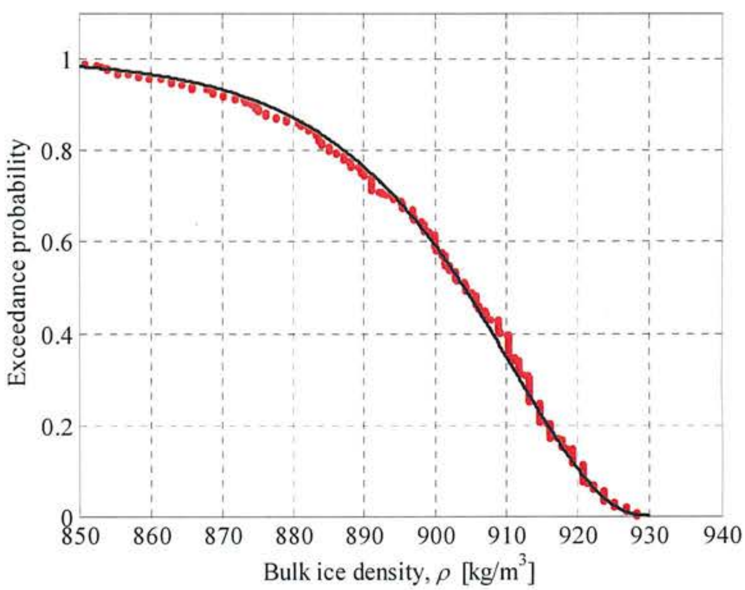


Figure 2: Exceedance probability for bulk density of first year sea ice (based on measurements near Svalbard). Continuous curve: beta distribution.

[1] Note: the use of the decimal form with two significant figures, e.g. 0.94×10^3 kg/m^3, is deliberate, because the uncertainty in the measurements does not warrant a greater precision. The use of two significant figures here implies that the results are only precise to the nearest 10 kg/m^3 (i.e. 0.01×10^3 kg/m^3).

A.8.3 Metocean related actions

Item not considered in the ICESTRUCT JIP.

A.8.4 Seismic actions

Item not considered in the ICESTRUCT JIP.

A.9 Foundation design

Item not considered in the ICESTRUCT JIP.

A.10 Man-made islands

Item not considered in the ICESTRUCT JIP.

A.11 Fixed steel structures

Item not considered in detail in the ICESTRUCT JIP.

A.12 Fixed concrete structures

Item not considered in detail in the ICESTRUCT JIP.

A.13 Floating structures

A.13.1 General

As clearly stated in ISO 19906 clause 13.1 (i.e. in the normative section), compliance with the normative requirements of ISO 19901-7 and ISO 19904-1 must be satisfied, as discussed below.

A.13.2 General design methodology

It should be noted that design based on exposure level considerations (as, for example, adopted in ISO 19902 and ISO 19906) is ***not applicable to mobile offshore units.*** This is stated in ISO 19901-7, under '*Stationkeeping systems for floating offshore structures and mobile offshore units*', clause 6.1.1 (*Design requirements: exposure levels; general*):

> '*In order to define appropriate design situations and design criteria for a particular structure, the concept of exposure levels was introduced. [...]. These concepts and definitions apply to the design of the class of floating structures covered under a) but not to those of b) (mobile offshore units) as given in the Scope of this part of ISO 19901*'.

The issue is not addressed in detail in the ICESTRUCT GUIDELINE; it is highlighted here for the purpose of addressing a critical gap in ISO 19906. It may also be noted that ISO 19906 is in fact not applicable to mobile offshore units (see ISO 19906 clause 1), but this is not reflected in the presentation of the exposure level design approach. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

Also, for floating structures in ice, the focus should be on characteristic *ice action effects*, not on characteristic ice actions (as is the case in ISO 19906). Characteristic ice action effects may be obtained from a full probabilistic analysis, using an appropriate non-linear computational response model. As an *alternative* to a full probabilistic analysis, the *environmental design contour* approach may be used. This is frequently used in offshore structure design for open sea environments, and the approach is compatible with relevant recommendations in the ISO 19900-series of standards (see, e.g., ISO 19901-7, clause 6.4.1):

> '*In particular, an environmental design situation consists of a set of actions induced by waves, wind, current and ice (if any) on the floating structure, on the risers and on the mooring system, as applicable, and is characterized by a given return period for one or more environmental variables or for a contour of environmental variables.*'

Each point on the environmental design contour represents a pair of key environmental input parameters (e.g. ridge keel draught and consolidated layer thickness) associated with a prescribed exceedance probability for the response, or action effect, of interest. The response, or action effect, of the structure must be checked at points along the contour. At some point along this contour the response, or action effect, will be a maximum of all action effects along the contour. This point is the *design point*; it represents the *design values of the input parameters* describing the contour. The action effect resulting from these particular input parameters, represented by the design point, is then multiplied by a prescribed factor. The result is an estimate of the required characteristic action effect, associated with a prescribed return period (e.g. 100 years, for ULS design). These comments are considered as basis for a potential ***amendment*** to ISO 19906, as they would make ISO 19906 compatible with ISO 19901-7.

The environmental design contour approach is adopted in the ICESTRUCT GUIDELINE, and it is recommended that this is also adopted in Arctic design practice in general, in line with standard offshore design practice for open sea structures. This comment is considered as basis for a potential ***amendment*** to ISO 19906.

It should be noted that the specific formulations of the environmental design contours and the formulations of the design criteria (involving also factors that transform the maximum action effect into the required characteristic action effect) are interrelated and should not be separated from each other (ISO 19901-7, clause 6.4.1):

> *'Criteria to be met by the design can be directly related to the specific formulation of the design situations. In this case, design situations, calculation process and design criteria are interrelated and should not be separated from one another.'*

This means that design contours and associated multiplication factors appear together either in a design standard, in a recommended practice, or in a design basis:

(1) The former (e.g. a standard or recommended practice) usually includes formulations that are considered generic and that have been calibrated to yield reliability levels close to the target reliability levels, for many different types of structures in different environments.

(2) The latter (the design basis) may include ***site-specific*** formulations, developed by metocean specialists for the designers, and here the contour formulations *and* any associated factors have been formulated and given *together* such that the target reliability levels are achieved. This allows the designer to perform the necessary design checks without performing probabilistic analyses.

The issues associated with the general design methodology are not addressed in detail in the ICESTRUCT GUIDELINE; they are highlighted here for the purpose of addressing a critical gap in ISO 19906. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A.13.3 Environment

In conformance with the environmental descriptions used for offshore structures in open sea, it is recommended, as a result of the ICESTRUCT JIP, that joint contingency tables of key ice parameters are generated based on measured environmental data. The information in these tables is then used to generate *environmental design contours* (see comments under A.13.2 above). The concept of joint contingency tables (or scatter diagrams) should be familiar to designers working on offshore structure design for open sea environments. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

It is sometimes argued that ice data is insufficient for generating contingency tables. The remedy here is to expand the database of measurements. It is still possible to perform statistical inference techniques, taking into account probabilistic model uncertainty due to limited samples. The results of such techniques, when applied correctly, are conservative estimates of characteristic values of the quantities being considered. These estimates are conservative in the sense that their magnitudes will reduce as model uncertainty is reduced (see also comments under A.8.2.2.7). These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A.13.4 Actions

ISO 19906 maintains the focus on the determination of design ice actions even for floating structures in ice, rather than focusing on *ice action effects* directly. The view taken in the present document is that it is considered potentially unsafe to focus on design ice actions on floating structures in ice. It also appears to be in direct violation of the normative requirements of ISO 19904-1, clauses 5.5.1 and 6.4.2:

> '*Action effects such as motions, accelerations, forces and stresses shall be evaluated for all defined design situations, and shall be compared with the system and component strengths to ensure the existence of reserve against loss of stability, structural failure or other undesirable occurrences.*' (ISO 19904-1, clause 5.5.1.)

> '*For ULS conditions, representative metocean actions shall be established with the intention of resulting in the most onerous metocean action effects with the return period of 100 years. Different structural components can be affected to a different extent by the same design situations. Consequently, a range of design situations shall be used to ensure that the most onerous conditions for all types of structural components are identified.*' (ISO 19904-1, clause 6.4.2.)

The key issue is this: it is *the action effect* which must be checked against system and component strength (see also the Barents 2020 report, 2012). The ice failure process, when considered as a random process, can be strongly non-stationary, and the ice actions on a floating structure in ice are generally implicitly and non-linearly dependent on the configuration of the structure, which again depends on the ice actions, and so it is generally *not possible* to simply *apply* an 'external' 100-year global ice action and expect to obtain the 100-year ice action effect. This is also mentioned above on page 15, under the section on '*Design Philosophy*', under the heading '*The Limit State Criteria and Characteristic Action Effects*'. This issue is not addressed in detail in the ICESTRUCT GUIDELINE, but highlighted here for the purpose of addressing a critical gap in ISO 19906. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

The required remedy is to reformulate the design criterion such that the design check involves a comparison of a factored resistance against an action effect arising from a combination of *factored ice action effects* and other factored actions and/or action effects. Here, the ice action effect which is to be factored is a *prescribed characteristic action effect*. Provided a suitable numerical ice-interaction global response model is available, it is possible to define an ice environment and to compute the response (i.e. ice action effects) of the structure in that ice environment. In other words, the ice action effect associated with a prescribed ice environment is obtained directly. Characteristic action effects may then be obtained from probabilistic analyses. Here, the global ice action is *not* quantified explicitly and independently, as they may be in the case of fixed structures. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

See also the comments above under A.7.2.2.

A.13.5 Hull integrity

It is stated in the normative clause 13.5.3 ('*Structural analysis and design*') that:

> '*Global ice actions shall be specified in accordance with 8.2.4. The global ice action shall be applied to determine whether the structure meets the ULS and ALS criteria for the floating structure as a whole and for the area in the vicinity of the impact point*'.

The view taken in the present document is that this requirement is considered unsatisfactory and potentially unsafe. It also appears to be in direct violation of ISO 19904-1 (clauses 5.5.1 and 6.4.2). See also the comments above under clause A.13.4. These comments are considered as basis for a potential ***amendment*** to ISO 19906.

A.13.6 Hull stability

Item not considered in the ICESTRUCT JIP.

A.13.7 Stationkeeping

The item is not addressed specifically in the ICESTRUCT GUIDELINE, however, it may be noted that ISO 19901-7 specify normative requirements on the design of stationkeeping systems. See also the comments under A.13.1 above.

A.13.8 Mechanical systems

Item not considered in the ICESTRUCT JIP.

A.13.9 Operations

Item not considered in the ICESTRUCT JIP.

A.14 Subsea production systems

Item not considered in the ICESTRUCT JIP.

A.15 Topsides

Item not considered in the ICESTRUCT JIP.

A.16 Other ice engineering topics

A.16.1 Ice roads and supplies over ice

Item not considered in the ICESTRUCT JIP.

A.16.2 Artificial ice islands

Item not considered in the ICESTRUCT JIP.

A.16.3 Protection barriers

Item not considered in the ICESTRUCT JIP.

A.16.4 Measurements of ice pressure and actions

This item was considered in the ICESTRUCT JIP, but is not addressed in the ICESTRUCT GUIDELINE.

A.16.5 Ice tank modelling

This item was considered in the ICESTRUCT JIP, but is not addressed in the ICESTRUCT GUIDELINE.

A.16.6 Offloading in ice

Item not considered in the ICESTRUCT JIP.

A.17 Ice management

This item was not considered in the ICESTRUCT JIP, however, reference should be made to the Barents 2020 report, in which the following statements are made (Barents 2020 report, 2012, page 70):

> '*If physical ice management is required in order to justify reduction of the design action, it shall be documented that the physical ice management is able to handle the conditions that may lead to EL and AL ice actions*'.

A.18 Escape, evacuation and rescue

Item not considered in the ICESTRUCT JIP.

ADDITIONAL INFORMATION AND GUIDANCE ON ISO 19906, ANNEX B

(informative)

Regional information

Annex B of ISO 19906 contains a great deal of information about regional ice conditions. The ICESTRUCT GUIDELINE summarizes, in section 5, the given information on cumulative freezing degree-days and sea ice conditions for different geographical locations. Although the data given in ISO 19906 Annex B should not be used for detailed design, *some* of the information given therein may be used for *preliminary* design assessments (see the ICESTRUCT GUIDELINE, sections 5 and 3.2.1 therein).

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