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Design Situations and Limit States in the Design of Arctic Offshore Structures

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ABSTRACT

Design of arctic offshore structures, and especially the codification of the design approach as in ISO 19906, the International Standard for the design of arctic offshore structures, requires going beyond the empirical, pragmatic solutions that have been developed for offshore structures in mature, temperate regions. The limit states design philosophy, embodied in ISO 19906, provides an approach for addressing design situations arising from operational, extreme, abnormal, and accidental events so that the desired structural reliability is verified for the relevant limit states. The philosophy also needs to accommodate the effects of operating philosophy and measures (e.g. ice management, disconnection of floating structures).

The Limit States Design procedure accounts for risk and reliability through the use of combinations of actions with specified probabilities, resistance formulations, partial factors, and limit states which arise from each design situation. The limit states for each design situation, such as component failure, local damage, or complete loss of structural integrity, depend on the design situation. Design verification, to confirm the required reliability for each design situation, is key to the design of safe and competitive structures.

This paper discusses issues that are being considered in the current revisions of ISO 19906, and in ISO 19900 which is the overall philosophy and general requirements document.

KEY WORDS: Arctic offshore structures; Design situations; Hazards; ISO 19906; Limit states.

INTRODUCTION

The first edition of International Standard ISO 19906:2010 was published December 2010, as described in Spring et.al, 2011. The second edition of ISO 19900:2013 was published in 2013.

After some years of experience in use, and with advances in technical knowledge, the need for updating both ISO 19906 and ISO 19900 was recognised. There was also a need to improve consistency and interfaces with related standards, including with each other.

Work to revise ISO 19906 started in 2014. The updating is described in Muggeridge et.al., 2017, and is expected to be complete in 2018. The working draft has been in committee as IOGP-ISO/WD 19906, 2016.

Work to revise ISO 19900 started in 2016, and is expected to be complete in 2019. The working draft is in committee as IOGP-ISO/WD 19900, 2017, and is still being revised.

This paper discusses issues and makes proposals which may or may not be incorporated in the final revision work. It focuses on the Ultimate Limit States (ULS) and specifically on the extreme and abnormal design situations, with some discussion of hazards, risk, and reliability for offshore structures. A number of issues related to risk, reliability, limit states, and exposure levels were previously discussed in Thomas, 2015, to which this current paper is a sequel.

BACKGROUND

ISO 19906 provides requirements, recommendations, and guidance, for design of offshore structures in the physical environment of arctic and cold regions. It relies on the other ISO standards in the 19900 series for common structure types, general requirements, and non-arctic specific requirements. Figure 1 shows some typical arctic offshore structures.

Figure 1. Typical Arctic Offshore Structures (left and centre courtesy GazProm)

ISO 19900, first published in 2002, provides general and unifying principles for all types of offshore structures. These principles include the limit states design procedure using the partial factor approach, as well as considerations for hazards, design situations, exposure level, robustness, and limit states.

ISO 19906 is focused on supplementary provisions for offshore structures in arctic and cold regions. ISO 19906 relies on the “structure-type” standards such as ISO 19902 for fixed steel structures for general design requirements for specific types of structure, as explained in Muggeridge et.al., 2017.

The objective of ISO 19906 is to ensure that complete structures, including substructures, topsides structures, floating production vessel hulls, foundations and mooring systems in arctic and cold regions provide an appropriate level of reliability and performance with respect to personnel safety, environmental protection and asset value.

SOME BASIC CONCEPTS

Action and Load

The term “action” is used throughout ISO standards instead of the term “load”. ISO 19900:2013 defines action as “external load applied to the structure (direct action) or an imposed deformation or acceleration (indirect action)”.

Values of actions termed “representative values” are the actual (unfactored) values, such as actual weights and environmental loads calculated from actual parameters.

Hazard and Hazardous Event

A hazard is a potential source of harm: human injury, damage to the environment, damage to property, or a combination of these. If a hazard can be identified and monitored, such as for an iceberg or a hurricane, planned operational measures such as ice management, or shutdown and evacuation, can be initiated.

A hazardous event occurs when a hazard interacts with a structure, either alone or in combination with other conditions. If the effects are of sufficient magnitude, limit states can be exceeded such that failure occurs.

Ice actions can be plotted against return period (i.e. probability of exceedance) on an action hazard curve, such as shown in Figure 2 which is based on ISO 19900:2013, Figure A.1. Figure 2 shows various types of environmental actions including three ice action curves using data from IOGP, 2010 for 100m wide, vertical-sided GBS structures. The three curves are selected to illustrate that different types of ice can have very different curve shapes and slopes.

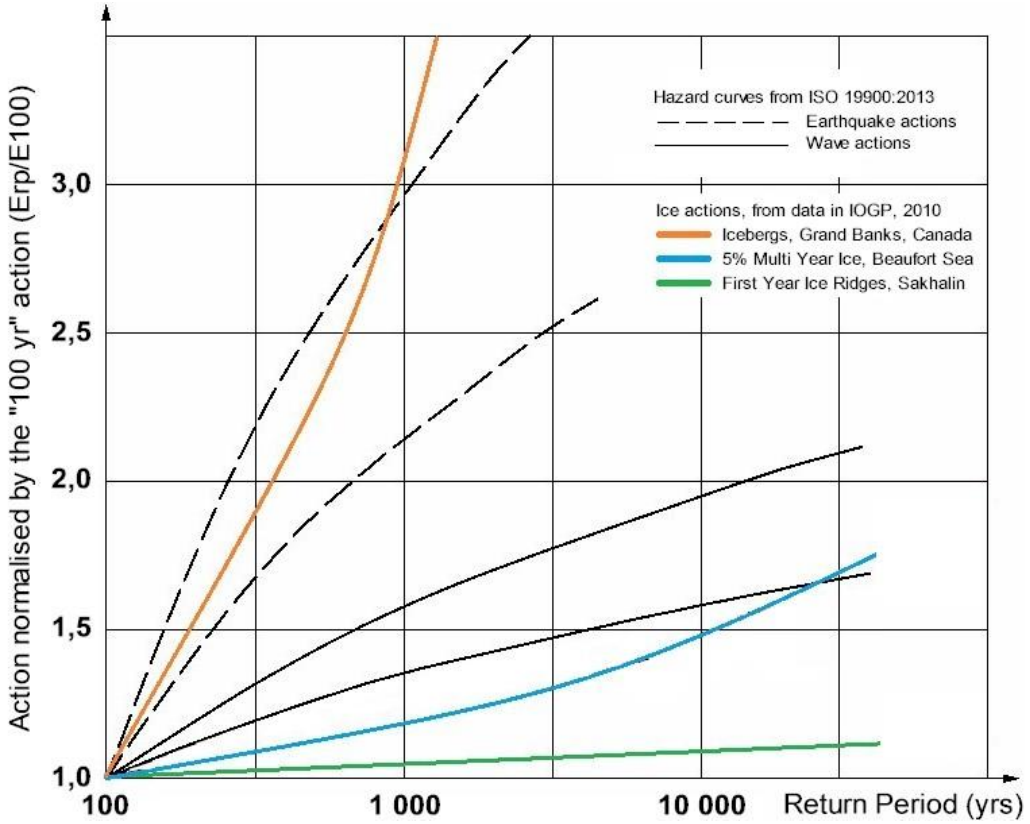

Figure 2. Typical normalised environmental action hazard curves for offshore structures

Extreme and Abnormal

The term "extreme" in ISO 19906 is reserved for events and actions with annual probability (of occurrence or exceedance) of 10^{-2} (100 year return period). This differs from some general use, where, "extreme" can be used as a generic adjective for severe environmental actions beyond an operating level, or as the maximum of a set of values within a defined time period.

Similarly, the term "abnormal" in ISO 19906 is reserved for events and actions used for abnormal design situations. The actual annual probability (of occurrence or exceedance) depends on the exposure level, see below, and is 10^{-4} for exposure level L1.

ISO 19900 explains the relationship between return period and annual probability, in particular that return periods of 100 years and 10,000 years correspond to annual probabilities of 10^{-2} and 10^{-4} respectively. Using “annual probability” terminology helps to avoid fruitless speculation about events 10,000 years in the future.

Limit states

ISO 19900 states that the performance of a structure, in whole or in part, shall be described with reference to a specified set of limit states beyond which the structure no longer satisfies the design requirements and is considered to have failed.

For the revision of ISO 19900, the limit states are divided into the following three categories:

- ultimate limit states (ULS);
- serviceability limit states (SLS);
- fatigue limit states (FLS).

Limit States for ULS design

Limits for ULS design include the following limit states:

a) ULS(a): failure of an individual structural component caused by design action effects exceeding design resistance (in some cases reduced by deterioration), including loss of structural stability (buckling, etc.);

b) ULS(b): loss of static equilibrium of the structure, or of a part of the structure, considered as a rigid body (e.g. overturning, sliding, sinking, or capsizing);

c) ULS(c): complete loss of integrity of the structure or vital parts of the structure when there is no further system ductility or reserve strength, including transformation of the structure into a mechanism (collapse or excessive deformation), loss of stationkeeping (free drifting);

The additional system resistance between failure of the first component with respect to ULS(a), and final collapse with respect to ULS(c), is determined by considerations of ductility, reserve strength, load shedding, energy dissipation, etc., i.e. robustness.

Exposure Level

Exposure level is a categorisation of potential consequences arising from a design situation. The required structural reliability depends on the exposure level.

ISO 19900 describes three exposure levels: L1, L2, and L3. The exposure level to be used in a design situation for design verification is determined by considerations of “life-safety” and of environmental and economic consequences.

L1 applies for a structure which is manned or has significant inventory (of hydrocarbons), and for which evacuation or shutdown is not planned in the event of the design situation under consideration. L2 and L3 can apply if increasing mitigation or elimination of risk to life safety and other consequences is demonstrated. Relevant measures can include hazard detection, monitoring and forecasting, success of ice management, staged shut-in of wells and shut-down of production and export facilities, and evacuation of personnel under prevailing conditions.

DESIGN SITUATIONS

It has been proposed that the concept of design situations be more clearly introduced into the revision of ISO 19906 as part of a more holistic approach to the overall design process, see Thomas, 2015. Now it is expected that the revised ISO 19900 will define different types of design situations, and the characterisation and specification of design situations.

This paper offers the author's view of information and proposals which may or may not be fully realised in the final publication of ISO 19900 third edition, due 2019.

Characterisation of a Design Situation

Design situations can be formulated for both serviceability limit states and ultimate limit states. Each design situation is characterised by relevant parameters and design criteria for which the design is verified, such as:

- Type of design situation;
- Hazardous event or dominating source of action (which provides the principal action);
- Exposure level(s) (includes aspects such as manning and inventory risk);
- Structural configuration (such as under construction, in-place, and damaged);
- Structural system (parts resisting event and actions);
- Operational measures (e.g. ice management, disconnection criteria, evacuation and shutdown criteria);
- Facility operational configuration (e.g. drilling, temporary works, tanker loading);
- Physical conditions and companion actions associated with the principal action;
- Combination of action types, with partial action factors;
- Partial material and/or resistance factors;
- Limit state (specific criteria for serviceability or ultimate limit state).

Choice of structural modelling and method of analysis can also depend on the design situation.

ULS Design Situations

A ULS design situation is specified for each hazardous event and for each dominating source of action. If a hazard curve has been developed, different hazardous events can be selected at different points on the hazard curve.

ULS design situations can be classified as follows:

- Operational
- Extreme
- Abnormal
- Accidental
- Short duration

ULS operational and extreme design situations are intended to ensure that, provided that limit states are not exceeded, there is no after-effect: no consequent reduction in structure reliability, no significant structural damage, no repairs needed for restarting or continuing operation. Limit states ULS(a) and ULS(b) apply. Partial factors, applied to representative values, provide a "safety" margin with respect to the actual limit state design values and structural damage.

ULS abnormal and accidental design situations are intended to ensure that, provided that limit states are not exceeded, there are no life-safety consequences or harm to the environment. There is however the likelihood of structural damage requiring repair or replacement of structure in order to restore adequate in-service reliability.

If structural damage occurs, e.g. after ULS(a) and before ULS(b) or ULS(c), a short duration, after damage design situation can be defined and fitness for continuing service can be assessed.

Extreme Design Situations.

Extreme design situations are defined for each extreme environmental event. The principal action arises from the extreme environmental event. Appropriate partial factors are applied for actions and resistances in order to verify that the design has adequate reliability.

The global behaviour of the structure is essentially elastic, even though local stress concentrations can exceed yield stresses and some nonlinear behaviour (e.g. pile-soil interaction) is expected. Some components may behave inelastically if their capacity to resist action effects is not reduced, e.g. plates in membrane action.

Abnormal Design Situations

Abnormal design situations are defined for each abnormal environmental event. The principal action arises from the abnormal environmental event. Structural reliability is achieved by the specified small probability of exceedance. All partial factors for actions, materials, and resistances are unity.

System and component ductility and reserve capacity may be taken into consideration in determining the ultimate resistance of the structure. Structural analysis may be non-linear and progressed to complete loss of structural integrity or collapse, with design resistance of individual components being exceeded and action effects being redistributed.

For abnormal environmental events when there are life safety implications, the structural integrity at the limit state needs to be assured to enable evacuation following event exposure.

LIMIT STATES DESIGN PROCEDURE

The limit states design procedure verifies that a structure has adequate reliability with respect to defined limit states in relevant design situations. Exceeding the limit state would result in failure. The steps can be outlined as follows:

- Hazardous events and other sources of actions are quantified;
- Design situations are defined for design verification to a limit state;
- Representative values of actions and resistance are derived from basic variables;
- Representative values of action types are derived from combining representative values of principal actions and companion actions;
- Partial factors are quantified, depending on the limit state and design situation;
- Design values for the design situation are calculated by factoring representative values;
- Design actions are applied in combinations of action types dependent on the design situation, and the structure is modelled and analysed to obtain the total design action effect, S_d, for the structure as a whole and for each component;
- Design resistance, R_d, is calculated from formulations using factored representative values of properties of materials and soils and of geometric parameters, or directly by factoring resistance formulations, for the structure as a whole and for each component;

- The design is verified for the relevant limit state by applying Equation (1).

$$S_{\mathrm{d}} \leq R_{\mathrm{d}} \tag{1}$$

The last four bullet points above are illustrated in Figure 3. It also shows the combinations of actions for two design situations. The curves are probability density functions for *S* and *R*.

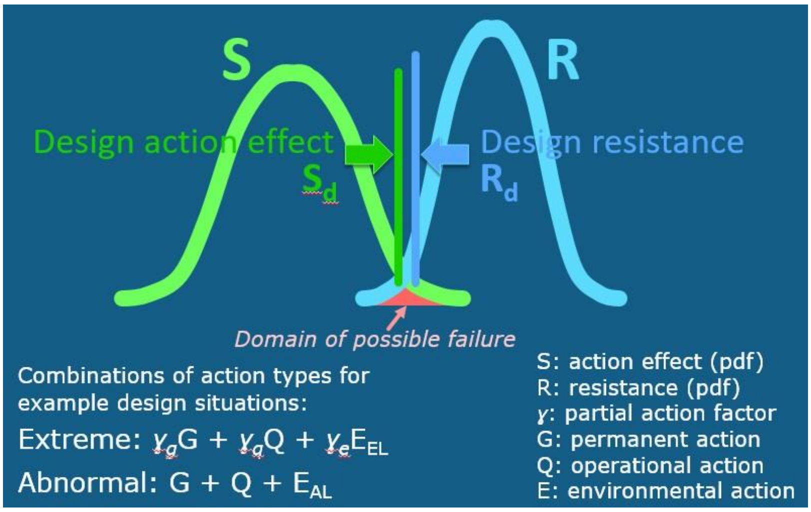

Figure 3. Probabilistic illustration of Equation (1)

RISK AND RELIABILITY

Risk Approach

It is common industry practice, to identify, assess, and manage all risks that can reasonably be foreseen, however unlikely. Risk events are identified, and can be assessed using a risk matrix to plot likelihood and consequence.

In the oil and gas industry, the concept of acceptable level of risk, or tolerable risk, is qualified by the over-riding imperative that no level of risk can be accepted, or tolerated, without a risk management plan. The challenge is what type of risk mitigation or risk management to apply.

The underlying approach of ISO 19906 is that there is a break point at which risks transition from requiring avoidance by design, to being managed by other means such as operational contingency planning. This is illustrated in typical risk matrix form in Figure 4.

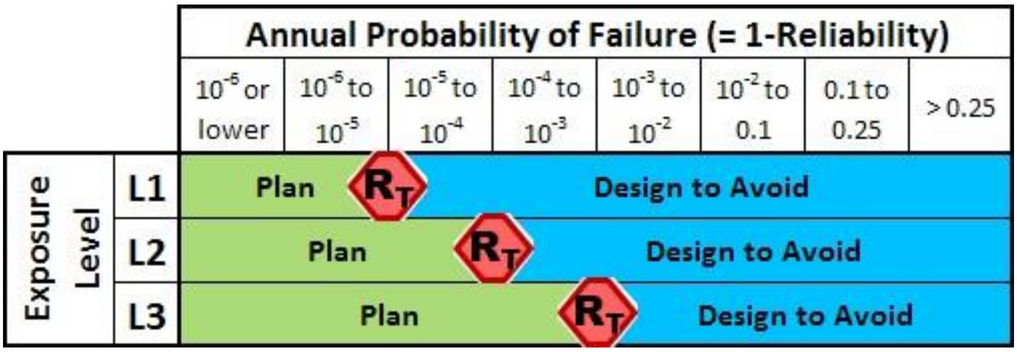

Figure 4. Risk Matrix showing Reliability Targets (R_T) for different Exposure Levels

Reliability Target

The break point between "design to avoid" and other planning, see Figure 4, is expressed as a "reliability target" (R_T) for the structural design verification. R_T is expressed in terms of an annual probability of failure. Failure, in the context of structures, is the risk event associated with exceeding a limit state. Targets can depend upon a variety of factors, see HSE, 2002.

ISO 19906 quantifies ULS reliability targets for each exposure level as $1\text{-}10^{-5}$ for L1, $1\text{-}10^{-4}$ for L2, and $1\text{-}10^{-3}$ for L3, as illustrated in Figure 4. The approach, and the calibration of the ISO 19906 partial action factors to these reliability targets, is explained in Thomas et.al., 2011.

The underlying philosophy of the design approach of both ISO 19900 and ISO 19906 is to ensure that the structure has the appropriate level of structural integrity. This is achieved by demonstrating, by means of structural design and, where applicable, operational measures, that the specified reliability target is satisfied. This is deemed to be achieved by using the limit states design procedure with appropriate partial factors and probabilities.

EXTREME-LEVEL AND ABNORMAL-LEVEL EVENTS AND ACTIONS

Likelihood and Quantification

ISO 19906 requires that representative values for ice actions (and for other environmental actions) are determined both at extreme-level (EL) and at abnormal-level (AL) for all relevant types of event. An ice event is defined as occurrence of ice-structure interaction for which ice actions are calculated. These are hazardous events with specified probabilities which need to be combined with analysis of resistance probabilities, ref. Figure 4, in order to quantify the probability of the risk event (failure). Then it can be plotted on a risk matrix, similar to Figure 4.

EL and AL ice actions represent events in different design situations, and are independently aimed at verifying that, after applying partial action factors and resistance formulations including reserve strength, the structure reliability target is achieved for each design situation.

Figure 5, based on the risk matrix of Figure 4, shows the EL and AL actions (denoted by E and A in the figure) for each exposure level, in a matrix space defined by likelihood of ice event.

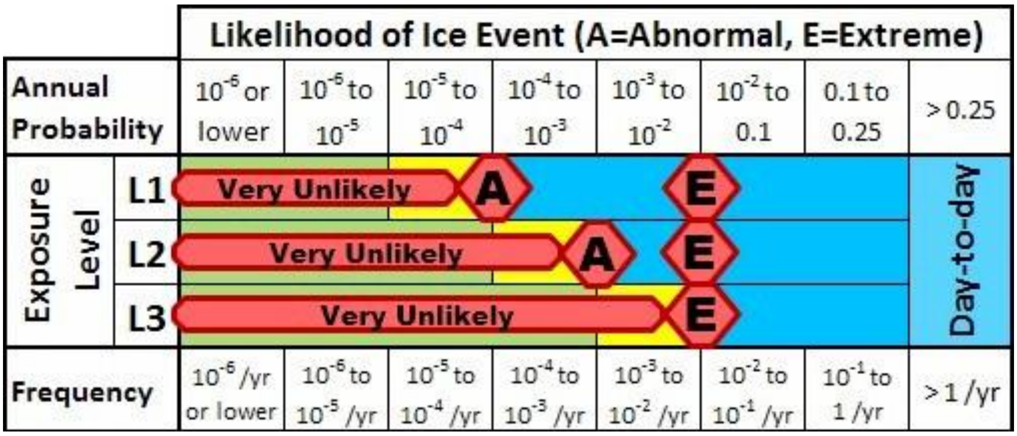

Figure 5. Likelihood Matrix showing EL and AL Ice Events

It is important to not confuse the concept of risk event, which relates to exceeding the relevant limit state in a defined design situation, with the concept of hazardous event, for which actions are calculated for design verification. For the former, various target failure probabilities have been quantified, see HSE, 2002, depending on life safety for the individual, the type of event and, in some approaches, likelihood of other risk events. For the latter, design event occurrence probability is specified, except for earthquakes, as 10^{-2}, 10^{-3}, or 10^{-4}, as indicated in Figure 5.

Action Hazard Curves

The values of actions for the prescribed event probabilities can be read from an action hazard curve for the hazardous event, such as those shown in Figure 2. Figure 6 is an alternative representation of action hazard curves, with axes swapped and not normalised, showing indicative curves for actions for different ice types.

It is also possible for different ice types to be dominant at the different levels. The EL ice action in Figure 6 arises from MY ice ridges, while the critical AL ice action could arise from icebergs.

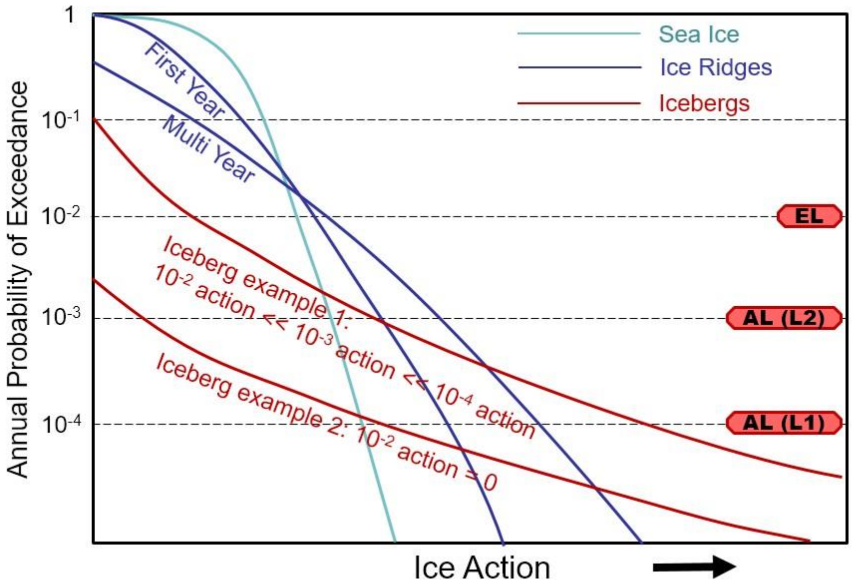

Figure 6. Action-Hazard curves for various types of hazardous ice events

Impact of Non-linear Action Hazard Curves

Few action hazard curves are linear (on a log-probability chart). The "slope" varies with ice type and geographic location. Action hazard curves for icebergs are particularly steep and curved, see Figure 2. Figure 6 illustrates that the ratio of the EL (10^{-2}) value to the AL for L1 (10^{-4}) value of the action hazard arising from a specific hazard is not consistent. The magnitudes of the ice actions also varies with ice type, location, and structural configuration.

Most curves in Figure 6 have both an EL value and an AL (L1) value of characteristic ice action. With reference to IOGP, 2010 typical ratios can be 1.20 for first-year ice ridges and 1.35 for multi-year ice ridges.

For icebergs where the action hazard curve has the form shown for "iceberg example 1", a typical ratio could be 4, as shown for the Labrador Sea. In this example the 10^{-2} p.a. (100-year) value when factored by the partial factor of 1.35 is much less that the value of the 10^{-4} p.a. action. Widianto et al., 2013 showed that the calculated 10^{-4} p.a. iceberg action can be up to 9 times the 10^{-2} p.a. (100 year) iceberg action at the Hebron location, offshore Newfoundland.

It is a myth that the intention of the factored EL ice action is to result in a value of design action with 10^{-4} p.a. probability of exceedance, thus emulating or substituting for the value of the AL ice action. This is one reason for defining separate design situations for extreme and abnormal.

Impact of Action Hazard Curves for Less Likely Events

For icebergs where the action hazard curve has the form shown for "iceberg example 2" in Figure 6, the iceberg encounter probability can be less than 10^{-2} p.a. This could be typical for some areas off the East coast of Canada, off Greenland (Baffin Bay) and for the Barents Sea.

Therefore the 10^{-2} per annum (100-year return period) representative/characteristic ice action value does not exist for "iceberg example 2", it is zero for this design situation, Design verification for this hazard will use only the hazardous event which causes the AL ice action.

There can be significant uncertainties in estimating abnormal ice actions. Discussion of types of uncertainty and approaches for taking this into account can be found in IOGP, 2010.

Operational Measures to Modify Action Hazard Curves

Ice action hazard curves can be modified by operational measures, both for fixed (gravity-based) and for floating structures. If operational procedures such as ice management and/or (for a stationary floating structure) disconnection are a part of the design philosophy to verify structural reliability, all relevant elements of the operational procedures need to be determined, documented, and applied throughout the service life.

For example, the iceberg encounter frequency associated with Grand Banks platforms offshore Newfoundland – Hibernia, Terra Nova, White Rose and soon Hebron – is about 0.02 per annum in the absence of iceberg management and can be about an order of magnitude less with adequate ice management. The corresponding EL ice actions from icebergs are minimal.

If a stationary floating structure is designed to disconnect and move off station, the hazard curve for environmental actions can be limited by the pre-defined conditions and probability of success for disconnection. This can modify or limit the value of the AL ice action and, depending on the criteria for disconnection, the value of the EL ice action. Further discussion can be found in Makrygiannis et al. (2011).

PLANNING FOR VERY UNLIKELY HAZARDOUS EVENTS

General

Very unlikely hazardous events have also been termed "beyond abnormal", see Thomas, 2015, because the upper probability limit of "very unlikely" varies with exposure level, see Figure 5.

The limit states design procedure does not require a design situation to be defined for very unlikely hazardous events. Therefore a very unlikely hazardous event, for which the structure is not designed, could cause collapse. This would be a risk event for which the risk can be assessed and put on a risk matrix, as previously discussed.

Assessing and Planning for Very Unlikely Events.

With reference to Figure 5, the areas in yellow indicate very unlikely hazardous events which occur with an annual probability up to an order of magnitude less than that of the abnormal event. Potentially they can cause a risk event with a probability greater than the reliability target.

The significance with respect to the risk profile of the structure could be an issue that the owner chooses to assess, due to the potential for economic loss and other consequences. The owner in discussion with other stakeholders could develop risk management policy and planning, to determine contingency plans, equipment, processes, and resources to manage the response to the approaching hazard and to mitigate any consequences of a very unlikely hazardous event. However, care should be taken in how reliability targets are interpreted with respect to actual failure probabilities, see HSE. 2002, when assessing the relative risk.

Hazards potentially causing such risk events can include ice islands and large icebergs at some locations. For the Skrugard location, the annual iceberg encounter frequency was assessed as 2.6 x 10^{-5} (Eik et.al., 2013). Therefore, to ISO 19906, the structure design does not need to be verified for resisting icebergs. If an iceberg impact would then cause collapse, the probability of occurrence of the risk event could be similar to that of the hazardous event.

ADVANTAGES OF APPLYING DIFFERENT EXPOSURE LEVELS

A structure, sub-structure, or structural component may have an exposure level that is particular to a specific design situation, if risks and their consequences are managed and mitigated.

A reduction from L1 to L2 for anything larger than the EL event could result in significantly lower AL ice actions. An iceberg action hazard curve presented in Widianto et al., 2013, is annotated in Figure 7 to show that the magnitude of the AL iceberg action at the Hebron location, offshore Newfoundland, would be reduced by 60%.

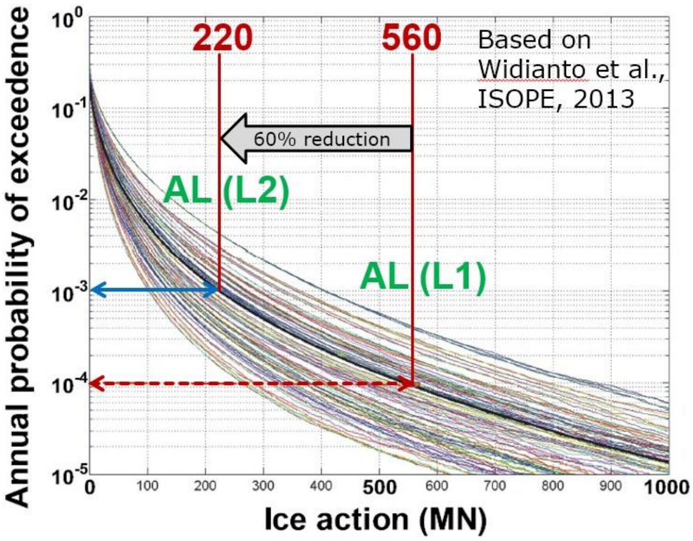

Figure 7. Effect of Exposure Level on AL iceberg action

But there could be significant costs for operational measures and emergency response capability for life safety and environmental protection in accordance with the governing standard (ISO 19900).

Benefits could include cost savings for construction of new structures or enabling an existing structure to continue operating, despite possible deterioration. After establishing the scope and cost of measures and savings, this could essentially be an economic decision by the owner.

CONCLUSIONS

ISO 19906 represents a significant step forward from the traditional approach to the design of offshore structures which has been largely derived from steel jackets and lattice tower structures. Design for all types of structures for arctic and cold regions requires design verification for abnormal design situations, modification of action hazard curves if using operational measures, and consideration of reliability targets,.

Designers need to identify all foreseeable hazards and consider all relevant hazardous events and design situations in the design of arctic offshore structures. The shapes and magnitudes of action hazard curves can vary significantly for different types of ice, for different locations, and for different operational measures.

Defining design situations specifically for extreme and abnormal ice events and actions, with associated ultimate limit states design criteria, will bring more clarity to the design process.

Reliability targets define a break point between risk avoidance by verification of the structural design, and risk management by other means. ISO 19906 encodes the design approach into a limit states design procedure in order to ensure an appropriate level of reliability and acceptable performance in the defined design situations.

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