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Ice properties in ISO 19906's second edition

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The second edition of ISO 19906 Arctic Offshore structures was issued in 2019. In this paper, we describe the changes that were made to sections dealing with ice properties and discuss the relationship between them and ice actions. The changes can be divided into five groups: 1) Physical properties (temperature, density and porosity), 2) modulus of elasticity, 3) ice friction, 4) mechanical properties in level ice (uniaxial and multi-axial compressive strength, flexural strength and borehole jack strength), and 5) the keel properties of first-year ridge (Mohr-Coulomb, macro-porosity). The standard is written in such a way so that simple approaches in design guidelines complement more elaborate models. Both currently face at least three challenges, namely, the lack of full-scale data, a complicated physical environment, and a lack of understanding of the deformation mechanisms taking place in the ice.

1. Introduction

The first international standard for ice actions on Arctic offshore structures was issued in 2010 and its second edition was published in 2019 (ISO 19906, 2019). Ice engineering and mechanics are important components of this standard. These are a relatively small niche in terms of expertise in science, technology, and engineering. Such that a stakeholder with an ocean engineering background, but without special ice competence, could find it challenging to use the standard if it is not adequately adapted for such users. Instead of developing simple engineering formulas to be used in design, there is a tendency in ice engineering to focus on complicated processes in the ice. The standard aims instead at a balance between presenting simple practical solutions and more elaborate theoretical and empirical solutions. The advantage of the simple formulas is that they can easily be used in probabilistic approach, and provide general guidance. Whereas the advantage of more advanced numerical and scaled models is that they include more physical phenomena and are often based upon well-established physical laws.

2. Purpose and scope of this paper

In this paper, we summarize the salient changes that were made to ice properties that occurred from ISO 19906's first edition (2011) to its second one (2019). We first describe general cases of ice action on structures, and briefly explain the importance of these properties. We then proceed with a summary of the changes in the properties themselves (temperature, density, porosity), followed those of level ice (strength properties) and rubble properties in the unconsolidated first-year ridge keels. We close off with a short discussion and a conclusion.

3. Ice actions in ISO 19906

ISO 19906 addresses ice actions on fixed and floating structures, global and local loads, and sloping and vertical waterlines. However, it has two basic cases: a) ice interaction with a vertical wall inducing crushing failure and b) ice interaction with a sloping wall or conical structure and corresponding flexural ice failure. The recommendations for these two cases illustrate diametrically opposite ways of dealing with ice actions and ice properties. In the first case, no ice properties are included, and in the second case, a number of physical processes and corresponding ice properties are identified.

The discussion in the following paragraphs pertains specifically to limit-stress ice-structure interactions, which occurs when there is sufficient energy or driving force to envelop the structure and generate ice actions across its total width. The limit energy interactions such as ice/icebergs impacts are not addressed herein.

For ice against vertical structures, the standard presents a simple empirical equation for the estimation of a deterministic design ice force (F_G) on fixed vertical structures exposed to drifting level ice where the driving forces are high enough to keep the ice drift velocity almost constant so that limit stress scenario occurs:

$$F_G = h_i \cdot w \cdot p_G = h_i \cdot w \cdot C_R \left[\left(\frac{h}{h^*} \right)^n \left(\frac{w}{h} \right)^m + f_{AR} \right] \qquad \textbf{[1]}$$

In that equation, p_G is the global average ice pressure [MPa], w is the projected width of the structure [m], h_i is the thickness of the ice sheet [m], h^* is a reference thickness of 1 m, m is an empirical coefficient equal to -0.16, n is an empirical coefficient equal to $-0.50 + h/5$ for $h < 1.0$ m, and equal to -0.30 for $h \geq 1.0$ m, C_R is the ice strength coefficient [MPa] (note that

C_R is not the same as the uniaxial compressive strength of ice!). Finally (new to the 2019 edition), f_{AR} is an empirical term taken from Määttänen and Kärnä (2011) and given by:

$$f_{AR} = e^{\frac{-w}{3h_i}} \sqrt{1 + 5\frac{h_i}{w}} \quad \textbf{[2]}$$

Equation 1 acknowledges a size effect as the global pressure decreases for increasing ice thickness and increasing structure width. However, it does not try to express any of the physical and mechanical processes that take place and govern this process, nor any ice properties.

For ice failing against a sloping wall or conical cross-section, the approach identifies a number of different physical mechanisms, such as bending and breaking of the ice cover, sliding against structure wall, ice-ice friction, etc. For this type of scenarios, unlike the previous one, specific ice properties such as the flexural strength, ice-ice friction coefficient and ice-structure friction coefficient are factored in. The equations are quite long and will not be reproduced here. For more information, the reader is referred to section A.8.2.4.4 in the standard. Interestingly, one of the most critical parameters is also one of the most difficult to quantify: pile-up height.

Scale-model testing in basins is an important part of ice engineering. It requires identification of relevant full-scale (in-situ) ice properties, theoretical scaling (dimensionless ratios, etc.) and scaled-down ice properties in the basin. This is not trivial, and here we will only underline the difference between scaling of flexural and compressive ice failure. The flexural strength is an integrated property over the full ice thickness, and it is relatively easy to compare full-scale and basin scale values. Compressive failure is far more difficult because the same tests cannot (or only with great difficulties) be done in the field and in the basins.

4. Changes in ice properties in the second edition

In this section, we will summarize the changes that occurred in the new edition which relate with ice properties, both physical and mechanical. These are mostly dealt with in 8.2.4, 8.2.8, and 6.5.1, i.e. in the normative part of the standard, and in their corresponding clauses in the informative part. Some changes did occur in the normative part. For instance, in 'Global ice actions' (8.2.4), it is stated that ice-on-ice friction shall be considered. Also, for evaluation of local ice action (8.2.5), ice encroachment shall be considered. Otherwise, most of the changes are in the informative part.

Physical properties – temperature, density, and porosity

The ice temperature is by far the most important physical characterization of sea ice, and together with ice salinity and air fraction it largely governs the ice's physico-mechanical properties. Sea ice is a multiphase material consisting of ice, brine, and air. The ice and brine are often assumed to be in thermal equilibrium so that any change in temperature causes some melting or freezing and a corresponding change in the brine (and corresponding ice) fraction. By measuring the salinity, temperature, and density of an ice sample the air and brine fractions can be estimated with the equations given by Cox and Weeks (1983) for ice colder than -2˚C, and by Leppäranta and Manninen (1988) in warmer ice. Both these equations are derived through first-order principles, but one may also find many empirically-derived relationships between brine fraction, ice salinity, and temperature that may fit over a limited range.

The density is an important parameter, especially in scenarios where the ice buoyancy is vital, such as those involving a ship, floater interaction with ice and ridges and ice rubble interaction. In these cases, it is the difference between ice and water density that is important, and this magnifies any uncertainty in ice density determination. Ice is driven under the hull, creating buoyant forces and corresponding frictional resistance. In the case of an ice ridge, ice density, water density, and rubble porosity can be used to determine the effective buoyancy of its keel. If applying estimates for the ice density in ice action calculations, the uncertainty regarding density can have a significant impact on the results. As the rubble volume can change during a ridge-structure interaction event, the ice rubble density can also change. A particular care is needed for modelling of density in ice model basins, due to deviations between water density and ice rubble density from full-scale magnitudes. Validated numerical methods can be used to assess these sensitivities.

There are several ways of measuring ice density – the most commonly used in the field is direct mass/volume determination. The ice mass is relatively easy to measure, but the volume is challenging. The second edition acknowledges there are alternative methods, but points out they are more difficult to perform in the field. It also raises the importance of this parameter in assessing rubble porosity, particularly in model-scale studies (numerical methods can be used to assess these sensitivities). An alternative approach, not mentioned in the standard, is the hydrostatic method, where the ice mass is measured in air and submerged in a fluid. This method avoids the uncertainty of a direct estimation of volume and achieves a much better accuracy and precision (Pustogvar and Kulyakhtin, 2016). The method takes more time, but should be considered in future editions of the standard.

Modulus of elasticity

The elastic modulus of ice can be either the *'true'* (Young's, E) or *'effective'* (quasi-static, E_f) elastic moduli. Young's modulus of ice is representative of deformation mechanisms of a purely elastic, time-independent nature, and is obtained from dynamic measurements (e.g. acoustic), involving very high deformation rates. However, ice naturally exists at a temperature that is very close to its melting point, which is why the concept of an effective modulus becomes relevant. It implies the deformation is not only elastic, but also comprises time-dependent recoverable strain, and non-elastic non-recoverable deformation (creep). The effective modulus is significantly lower at lower strain rates, in most scenarios of engineering relevance (Sinha, 1978, 1982). The 2019 edition of ISO 19906 explicitly acknowledges this challenge by recommending usage of an 'effective' modulus and 'effective' Poisson ratio. The 2019 edition offers this equation for guidance, where ν_b is the brine volume fraction and E is given as [GPa]:

$$E_f = 5.31 - 0.436{\nu_b}^{0.5} \quad \textbf{[3]}$$

The standard also recommends a value of 0.42 for the effective Poisson ratio, and 0.33 for the true Poisson ratio.

Ice friction

The 2010 edition of the standard gave values for the friction of ice on concrete and of ice on steel, at three different sliding speeds. The new standard also includes a discussion of the friction of ice on ice, since this value is included in many models of ice-ice interactions, including discrete element models (see e.g. Ranta et al., 2018). The dependence on sliding speed was made explicit: "*Ice-ice friction decreases with increasing sliding speed, from a maximum of $\mu = 1$ at $v_s = 10^{-6}$ m/s to $\mu = 0,02$ at $v_s = 1$ m/s, with $\mu = 0.1$ at $v_s = 10^{-2}$ m/s*" (ISO 19906, 2019, p. 260). This description is the standard's attempt to concisely summarise the experiments discussed in Maeno et al. (2003). In many situations, either the sliding speed is not known or the sliding speed varies within the model, in which case a single friction coefficient is needed. For these situations, the standard recommends using $\mu = 0.1$. In models where it is possible to include more complexity, the standard notes that temperature and memory effects (i.e. previous sliding history) may be relevant, and directs users to Schulson and Fortt (2012) for further information. Understanding how these second-order friction effects (e.g. dependence on memory, temperature, sliding speed) affect models of ice dynamics is an ongoing research topic (see e.g. Lishman and Polojärvi, 2015).

Two further changes have been made to the discussion of friction in the standard. First, a statement that "*the static friction coefficient can be up to five times greater than the kinetic friction coefficient at 0.1 m/s*" has been amended to read "*the static friction coefficient has been measured to be up to five times greater than the kinetic friction coefficient at 0.1 m/s, and higher ratios are possible*" (ISO 19906, 2019, p. 269). This reflects recent research showing that static friction can continue to increase until it approaches the shear strength of level ice (see e.g. Scourfield et al., 2015). When updating this change, it was felt that the original statement suggested an upper limit on the static friction of ice, and that this statement is contradicted by experiments and by intuition. Taken as originally written, the statement could have led users to underestimate potential ice forces due to friction. Second, a suggestion was added for users of the data on ice-concrete and ice-steel friction, that if sliding speed is not known, a value of 0.01 m/s should be used for this parameter. This sliding speed leads to the highest listed values of ice friction, which in turn should lead to conservative design in situations where sliding speeds are not known.

The changes made, then, can be summarised as: 1) Inclusion of data on ice-ice friction; 2) removal of a potentially misleading reference to an upper limit on static friction; and 3) inclusion of a suggested single value for friction of ice on steel and ice on concrete. The rest of the discussion of friction, and the recommendations to users, have otherwise been left unchanged.

Level ice

The standard focusses mostly on properties that can be measured in-situ, i.e. in the field. The most commonly used approach is the small-scale uniaxial compressive strength (σ_c) test, the flexural strength (σ_f) test and the borehole jack (BHJ) strength test. These three different tests are a compromise between 1) testing something with a clear theoretical basis, which can be used effectively in mechanical modelling (σ_c), and 2) testing something that simulates the state of the ice in a real interaction scenario (BHJ or σ_f).

The uniaxial compressive strength of ice is the most commonly measured mechanical property in the field, because it is manageable and it is readily applicable to scenarios involving a narrow structure, taking into account a relation to ice actions for limits stress crushing (Korzhavin, 1962). When the structure gets wider, other effects related with the aspect ratio come into play and the relationship between ice action and σ_c is lost. A sufficient number of tests are performed, so as to be able to obtain trends of the uniaxial compressive strength versus ice porosity. The new edition of the standard includes the equations of Moslet (2007), which are based on porosities up to 0.38. In contrast, the equations of Timco and Frederking (1990) had data with porosities up to 0.19. The equations derived from Moslet (2007), for horizontally- and vertically-loaded sea ice uniaxial strength [MPa] respectively, are:

$$\sigma_c = 8\left(1 - \sqrt{\frac{\nu_t}{0.7}}\right)^2 \qquad \textbf{[4]}$$

$$\sigma_c = 24\left(1 - \sqrt{\frac{\nu_t}{0.7}}\right)^2 \qquad \textbf{[5]}$$

In these equations, ν_t is the total porosity. **Figure 1** is a corresponding plot. As this figure shows, the variability is large and the equation express some kind of upper limit. It would perhaps be more useful to define an average function and study the spread.

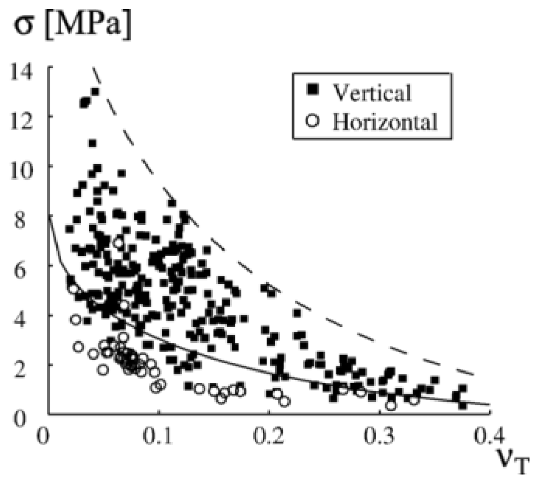

Figure 1. Uniaxial compressive strength plotted as a function of total porosity (from Moslet, 2007, Fig. 3).

The flexural strength is usually defined by linear elastic beam theory with homogeneous material properties. Because it is an integrated property (averaged over the whole ice thickness), it should not be compared directly with the tensile strength, even though the values are similar and linked. The beam size requirements are such that the water foundation effect is accounted for. A possible size-effect was also examined, but could not be documented from the published literature, e.g. Parsons et al. (1992) were not able to clearly demonstrate its existence.

The text about multi-axial behaviour was rewritten so as to explain that there is no such thing as multi-axial strength, and that a three-dimensional failure envelope is necessary to analyse and use data from multi-axial tests. **Figure 2** shows an example of a failure envelope, obtained from the yield stress for various confining conditions. These parameters typically have a large variability, such that a large number of tests in the field are required.

Both tensile and shear strength can be used to establish failure envelopes. Direct testing of tensile strength has mostly been done in the laboratory, although an increasing number of these tests done in the field are also reported. The text is unchanged from the 2010 edition. As for shear strength, few results have since been published. One challenge with these tests is to be able to carry them out with zero normal stress on the sample.

The borehole jack is used in-situ and the ice is multi-axial state of stress. This test is more representative of an ice crushing scenario than is a uniaxial test. However, it is difficult to use these data for mechanical modelling because the stresses spread and dissipate in the ice sheet. Several failure modes are typically observed, and the definition of the borehole strength, $\underline{p_u}$, depends on the failure mode (Sinha et al., 2012, Justad and Høyland, 2013, Johnston, 2014). When expressed over the full thickness of the ice, the depth-averaged borehole strength ranges from 3 MPa to 30 MPa for FY sea ice, and up to 34 MPa for MY sea ice over the range of ice temperatures tested. Strengths of 49 MPa have been measured in cold MY ice (Johnston, 2014, Johnston, 2016).

Ice fractures frequently when interacting with structures, but so far neither of the ice action models in the standard requires fracture properties. The discussion around fracture properties was limited to fracture toughness. The text was modified to express the scientific disagreement on whether or not a one-parameter model (fracture toughness) can be useful.

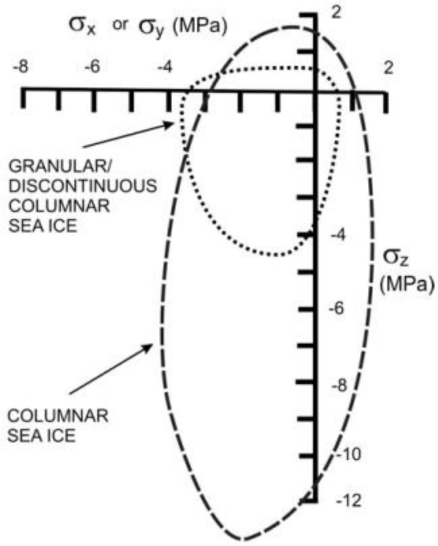

Figure 2: Example of a failure envelope for two ice types (from Timco and Weeks, 2010, Fig. 13). Stresses (σ) along x, y and z are taken into consideration. Positive and negative stresses are tensile and compressive, respectively.

First-year ice ridge keels (rubble properties)

In ISO 19906 (2019), the text on ice ridges, or ice rubble properties, has been extended and rewritten, focussing on friction angles, cohesion and macro-porosity through explaining some of large variability reported is due to systematic seasonal (temporal) and spatial variations. We have changed the title to reflect that it only deals with the properties of *the unconsolidated part of first-year ridges*. The section starts with describing the two approaches to describe the material; so-called *continuous* and *discrete*. Both have their advantages, but since the formulas describing the load (A.2.8.4.5.1, Eq. A.8.50) are based on the continuous approach and require the two material properties – cohesion and friction angle – as well as the macro-porosity, the text deals only with these three parameters.

The two-parameter Mohr-Coulomb model does not include volumetric compressibility, but in reality, the friction angle depends on the volumetric compression. In experiments, one will find different friction angles for the same material if the boundary conditions give different volumetric compression (Kulyakhtin and Høyland, 2015). The range of suggested values are modified to 24-45 degrees. The cohesion decreases with depth, and is probably at maximum just below the consolidated layer. This is partly due to stronger freeze-bonds because of higher confining stress, perhaps also due to lower macro-porosity higher up in the keel. Finally, the reported values of cohesion from both laboratory and field tests seem to increase with increasing block thickness. It is not clear why, but the standard suggests that it might be the box size / block size ratio that actually gives the variability in reported cohesions.

Macro-porosity values range from about 10% to 50% and the new text suggests that is mostly due to systematic variations. These are reported somewhat differently from the Baltic Sea (low salinity water) and other more saline waters. In saline ridges, it seems to increase from a minimum value just below the consolidated layer, while Baltic ridges are reported to have a mid-keel minimum. We do not know why. The melting also seems to be different as saline ridges are reported to have macro-porosities down to 10% in early summer, whereas no such values were measured in the Baltic. In summary, it looks like the differences between low-saline Baltic and saline ridges occur in the melt season. This corresponds to the fact that the growth rate for freshwater ice and saline ice is approximately equal, but the melting rate is quite differently.

5. Discussion

As mentioned in the introductory section, the standard is written in a way that simple approaches in design guidelines complement more elaborate models. Both currently face at least three challenges:

- A lack of full-scale data, particularly a combination of ice loads, structural response, ice properties, and failure modes.
- A complicated physical environment – the ice field is neither stationary, nor ergodic, and the ice properties are many and uncertain (compared, for instance, to waves where water density and viscosity are well known). This is related with the first challenge.
- A lack of understanding of how small-scale mechanical properties and failure mechanisms (cracking, pressure melting, solid-state recrystallization, etc.) scale-up and govern ice actions. Such an understanding of floating ice faces difficulties not encountered in other fields of structural and mechanical engineering, such as time-independent parameters (Young's modulus) which have de facto values (in these other fields). The reason is that ice is a high-temperature material, i.e. it naturally exists at very high homologous temperatures, such that, even at high engineering strain rates, time-dependent deformation processes occur alongside the pure elastic response (Sinha, 1978, 1984). To compensate, 'effective' values have to be resorted to, which at times may either be educated guesses or are used as a curve-fitting parameter.

Nonetheless, significant progress has been achieved in this second edition. The new guidance provided in section A.8.2.8.2 on ice strength under multi-axial stress state is an example of such an improvement. A failure envelope is much better suited to describe ice strength under multi-axial loading conditions and to analyse and use data from multi-axial testing. Moreover, the new standard suggests a systematic seasonal variability in properties, and this can be useful when modelling the load for different times of the year. In a probabilistic modelling, this will reduce the uncertainty and help to estimate better ridge load distributions.

There are gaps in information also. For instance, several properties that are discussed in the standard (e.g. the strength of granular ice) are not incorporated into ice load calculations using the analytical methods provided by the standard. This could mean that, if numerical approaches are used, the properties that are provided may be insufficient to model the constitutive response of ice. Moreover, the role of damage mechanics in ice failure and fracture is not discussed. Uniaxial testing requirements have been established, but what about those for biaxial and triaxial testing?

6. Conclusions

The second edition of ISO 19906 Arctic Offshore Structures was issued in 2019 and we have described the changes in the sections dealing with ice properties and discussed the relationship between these properties and ice actions – the ice properties combined with structural characteristics govern the ice actions. The ice environment is more complex to characterize than the corresponding ocean environment, i.e. wave, current and wind regimes. Fundamentally, ice is characterized by a much larger spatial and temporal variability, and ice properties are more challenging to measure, estimate or monitor, compared to human-made engineering materials. Any progress in the development of ISO 19906 for assessing ice actions will rely on a combination of:

- More full-scale data on ice-structure interactions.
- Better quantification and understanding of fundamental ice properties, both physico- and thermo-mechanical, as well as adequate statistical representations.

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