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Level Ice Crushing Pressures for Estimating Mooring Loads

Jan Thijssen[1], Mark Fuglem[1], Freeman Ralph[1]

[1] C-CORE, St. John's, Canada

ABSTRACT

Ice loads are to be considered for any offshore development where ice is present to ensure sufficient structural capacity and global resistance. Design loads and allowable ice conditions can be specified using ice load models referenced in ISO 19906, in conjunction with a site assessment of ice and metocean conditions. Ice load models are developed specific to the ice failure modes expected given the local ice conditions. Analysis of full scale data is vital for confirming the relevant failure modes and validating the models, as ice failure is scale dependent and varies with ice conditions.

For fixed structures, the peak pressures dominate design, but for a moored floater the mooring offsets and resulting line tensions depend more on the magnitude of the sustained pressure during the event. For the moored floater scenario the failure mode of continuous ice crushing is shown to be significantly more severe than the failure modes resulting from interactions with a pack of small ice floes.

This paper presents an approach to establish appropriate ice crushing pressures for performing a mooring analysis, where the dominant failure mode is crushing (vertical-sided vessel at waterline). Full scale data from the northern Baltic Sea (STRICE dataset) is used to compose a parent distribution for sustained crushing pressure events. Example cases are provided, illustrating how ice pressure magnitudes can be obtained at specified return periods and exposure levels.

KEY WORDS: Ice failure, Crushing, Floater, Station keeping, Mooring.

INTRODUCTION

Whereas exploration and production activities have been diminishing in the North-American Arctic region in recent years, activities in sub-Arctic and moderate regions have been increasing. Several new oil discoveries have been announced on the Grand Banks of Newfoundland, and activities in the Barents Sea have also been ramping up. In these regions the majority of the sea ice is first-year ice, with possible old ice in trace amounts. In order to continue operations when sea ice is present, the loading scenarios need to consider ice actions for structure design, and to determine acceptable ice conditions during which operations can continue without the need for facility disconnection.

Moored vessels need to have a mooring analysis completed to demonstrate sufficient reserves in the mooring lines for extreme loading conditions. No industry wide accepted approaches are available for performing a mooring load analysis with ice actions. Guidance on performing mooring analyses for open water ice free conditions is covered in industry standards such as ISO 19901-7, APR RK 2SK and Class Society mooring codes. Some general guidance for determining ice actions on floaters is provided in ISO 19906 (2010) and Global Maritime (2016).

The guidance in ISO 19906 (2010) on determining ice actions is focused on fixed structure design, where the peak ice action at a specified target reliability is required. For moored vessels these peak ice actions may not be relevant when the mooring system is compliant. The peak actions of short duration will result in an acceleration of the vessel of equally short duration, which is unlikely to have a significant effect on the vessel offset. Rather, a time-averaged value is of interest for the design ice actions, at the target reliability specified by applicable codes and standards.

Various failure modes of the ice can be relevant for determining the mooring loads. Vessel disconnection or ice management can be planned to avoid the need to design for extreme ice conditions. A review is provided in this work of applicable ice failure modes based on mooring load data obtained from the Kulluk drilling vessel. The focus of this paper is ice failing in continuous brittle crushing, which is one of the failure modes that typically needs to be considered. The corresponding analysis is based on STRICE data, collected in the northern Baltic Sea. The approach from ISO 19906 (2010) is discussed for obtaining peak pressures, followed by an outline of the proposed approach to obtain sustained pressures.

COMPANION ACTIONS TO PRINCIPAL ICE ACTIONS

ISO 19906 (2010) indicates that the combined ice, wave, wind and current actions need to be considered. Joint probability of exceedance functions are typically preferred for finding the metocean conditions associated with the principal ice action. Even when the environmental data is available expert judgement is required due to the complex interactions between sea ice and metocean conditions. Typically the interactions are simplified to idealizations, and conservatism is incorporated to cover uncertainties. The pack ice load can be approximated as a constant preloading for the moored vessel scenario, similar to the wind and current forces. Associated wave actions can then be superimposed to find the combined loading response.

Several relevant complexities of pack ice affecting associated metocean conditions can be highlighted. The pack ice dampens the waves, with the level of damping depending on the distance to the ice edge. The presence of ice may be correlated to specific weather events (e.g. strong persistence northerly winds), resulting in correlated directionality and magnitude of associated currents, wind, waves and ice. Ice drift velocity, floe size and ice concentration depend on the associated metocean conditions. Figure 1 shows ice floes broken up by waves. Note the regular geometrical floe shape, which is reported to be the result of the location of the maximum strain exerted on the intact level ice sheet by the waves. Over time the floe shapes will likely become rounded due to collisions between floes.

Figure 1. Pack ice broken up in small floes by an incoming wave field (picture taken by Vernon Squire, from wikiwaves.org)

ICE FAILURE MODES KULLUK DATASET

ISO 19906 (2010) indicates in the normative section that full scale action and response data should be used for determining design ice actions for floating structures. Where no data is available at the location of interest, measurements from other regions may be extrapolated. It also indicates that the design ice actions should reflect relevant ice scenarios, limiting mechanisms and ice failure modes for the location of interest. A reference is provided in ISO 19906 to Wright (1999) regarding full-scale data applicable to ice actions on floaters, which will be further elaborated on here.

From operations of the Kulluk drillship in the 1980's in the Beaufort Sea (see Figure 2) several ice failure modes were specified from first-year ice interactions. The prevalent failure mode typically corresponded to the types of pack ice encountered. The vessel was equipped with a 30 degree waterline slope around its 70 m diameter round hull, inducing flexural failure when interacting with intact level ice. An extensive dataset was reported in Wright (1999, 2000) of the measured peak mooring forces, separated into subsets for the different failure modes.

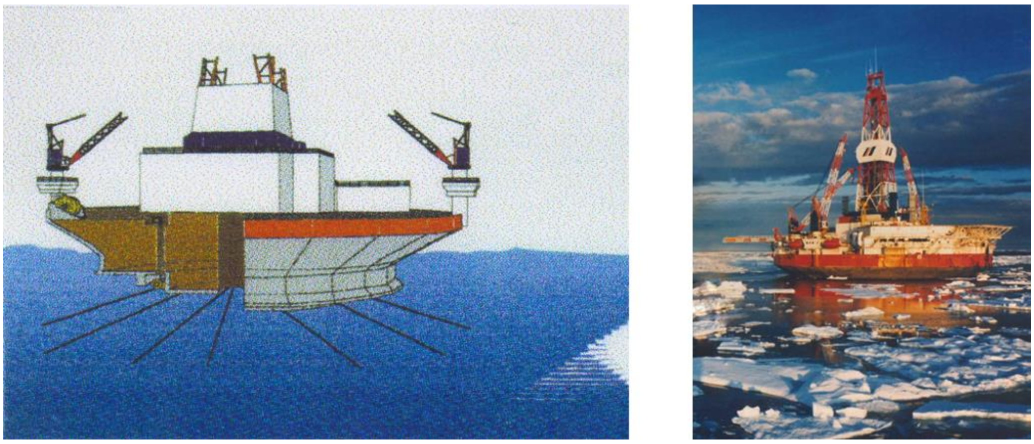

Figure 2. Kulluk drilling vessel (Wright, 2000)

Figure 3 illustrates the failure mode subsets. Managed floes typically cleared well around the vessel when in concentrations smaller than 9/10ths, with minimal loading on the mooring system. For concentrations of 9/10ths or higher the floes would not clear well around the vessel, forming a stationary rubble wedge in front at which the ice failure would occur. Level ice and large floes were found to fail in flexure, causing larger loads than managed ice. Comparisons of P95 peak mooring loads (Wright, 1999) are provided in Figure 4 for the different subsets.

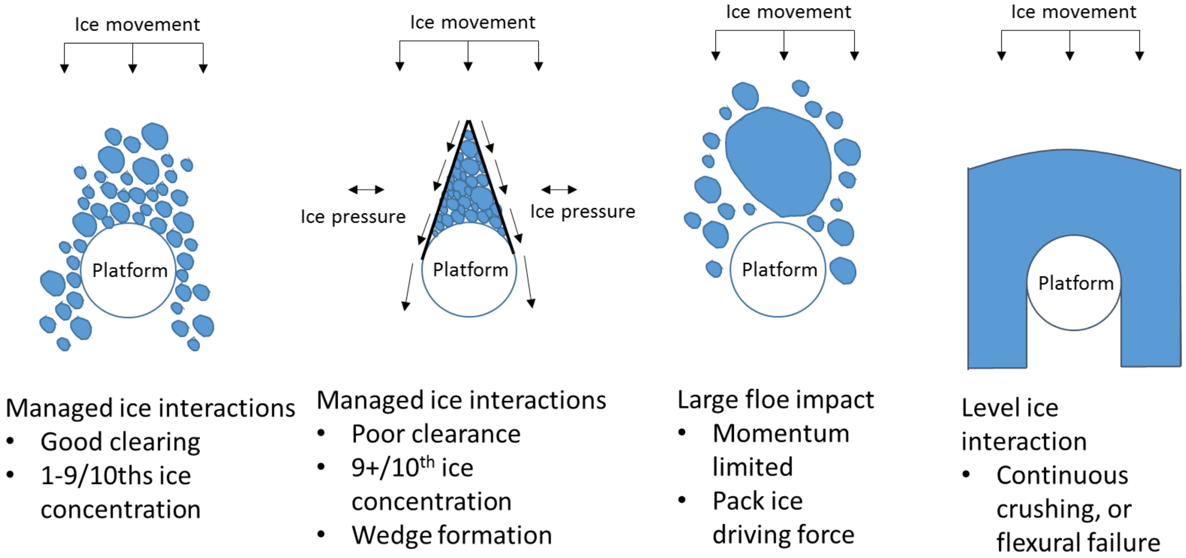

Figure 3. Pack ice failure modes types as reported in Wright (1999)

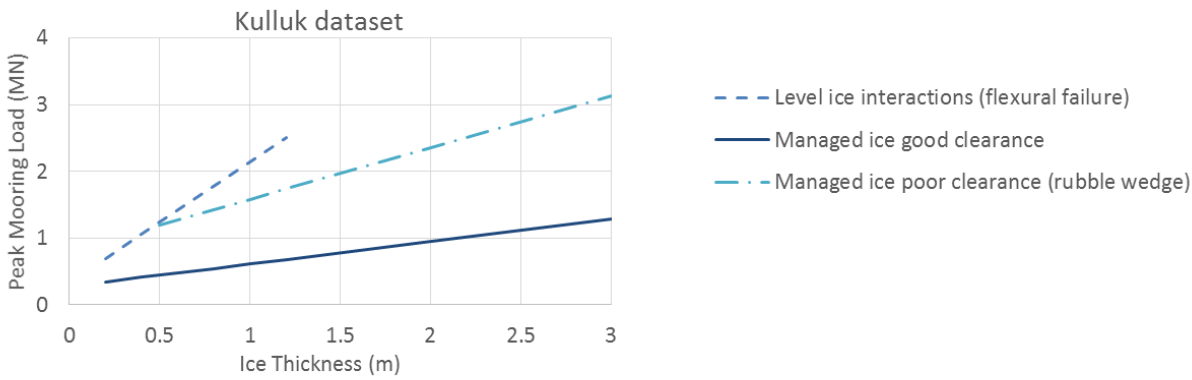

Figure 4. P95 fits of peak global mooring loads from Kulluk dataset (Wright, 1999)

In Thijssen et al. (2018) the managed ice load dataset from Wright (1999) was used for estimating daily maximum mooring loads on a hypothetical semi-submersible drilling vessel. As the semi-submersible had vertical-sided columns, the Kulluk data for level ice was not applicable for the large floe interaction scenario. Rather a sustained global ice pressure of 0.3 MPa was assumed for this scenario. This value of 0.3 MPa is significantly smaller than possible peak pressures as applicable to fixed structures.

The ISO 19906 approach for finding peak pressures is reviewed in the following section, after which the proposed approach for finding sustained global pressures is presented, to provide a comparison of peak vs. sustained pressures. Quantitative comparisons are provided afterwards for an example structure 15 m wide, encountering 1 m thick level ice. It should be noted that dynamic effects (e.g. ice vaning) of ship shape vessels are not considered in this study.

PEAK GLOBAL LOADS FOLLOWING ISO 19906

Guidance is provided in ISO 19906 for determining peak global pressures at specified reliability levels, as appropriate for fixed structures. Section A.8.2.4.3.3 provides Equations 1 and 2 to determine the global design load F_G and the upper bound nominal crushing pressure p_G (Equation A.8-21) reprinted here as:

$$F_G = p_G w_s h \tag{1}$$

$$p_G = C_R \left(\frac{h}{h^*}\right)^n \left(\frac{w_s}{h}\right)^m \tag{2}$$

where C_R is an ice strength coefficient, h is ice thickness (m), h^* is a reference thickness of 1 m to keep units consistent, w_s is structure width (m), and n and m are empirical coefficients. Values $n = -0.5 + 0.2h$ (for $h < 1$ m) or $n = -0.3$ (for $h \geq 1$ m) and m = -0.16 are suggested.

For first-year ice in temperate regions ISO 19906 (2010) suggests $C_R = 1.8$ MPa, based on a limited number of full-scale measurements obtained in the northern Baltic Sea as part of the STRICE program (see Kärnä & Qu, 2006). The updated version of ISO 19906 (see Ralph, 2019) provides further guidance on adjusting C_R for exposure levels lower than those found in the northern Baltic, whereas typically peak loads decrease with decreasing exposure due to randomness in ice failure processes.

In Thijssen & Fuglem (2015) and Thijssen et al. (2016) an approach is presented to adjust C_R when the exposure level is different than the Northern Baltic, applying Equation 3.

$$C_R = -\alpha \ln(-\ln(F_P(p)) + \mu + \alpha \ln(N) \tag{3}$$

Here $\alpha = 0.1092$ (MPa) and $\mu = 0.7057$ (MPa) are Gumbel shape parameters (μ is mode, slightly smaller than the mean), $F_P(p)$ the cumulative distribution based on the required target reliability and N is the exposure term (number of loading events).

To find $C_R = 1.8$ MPa at a 10^{-2} annual probability of exceedance (APE) ($F_P(p) = 0.99$) as suggested in ISO 19906 (2010), a corresponding exposure of $N = 220$ can be found using Equation 3. When using $C_R = 1.8$ MPa the annual maximum ice thickness may be used to obtain F_G at a 10^{-2} APE.

APPROACH FOR SUSTAINED GLOBAL LOADS

The sustained pressure is more of interest for performing a mooring analysis, as the peak load of short duration is not likely to result in a significant change in offset. Data presented in Kärnä and Qu (2006) was used to find peak global pressures (i.e. $C_R = 1.8$ MPa in Equation 2), but this document also presented the corresponding event loads averaged across the actively loaded panels and in time. A total of 133 brittle crushing events were reported for 2000-2004, with an average duration of 7 minutes, on which the proposed approach is based on.

As the ice thicknesses were reported per event, and the panel width is known, the corresponding pressures can be obtained from the reported forces. The obtained pressure data is plotted in Figure 5 against ice thickness. A trend line is added to show dependence of pressure on ice thickness. The P50 values for sustained ice pressures range from 620 kPa at an ice thickness of 0.2 m, to 220 kPa at an ice thickness of 1.1 m. It should be noted that no details on the sensitivity to contact width is reported in Kärnä and Qu (2006). The probabilistic averaging approaches in Jordaan et al. (2005) and Kuiper (2009) report only width effects for the peak pressures. This may need to be further elaborated on when applying the proposed approach to wide structures.

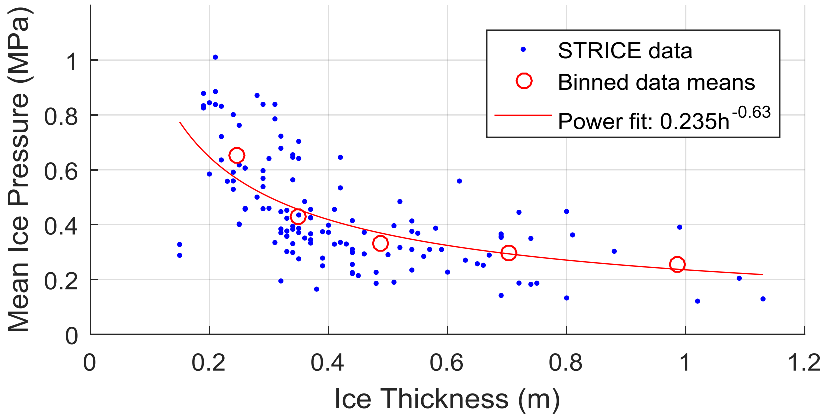

Figure 5. Mean pressure data STRICE (Kärnä & Qu, 2006)

To capture the variability of the loading events for performing extremal analyses in a single probabilistic formulation, the pressure data is normalized to a thickness of h = 0.5 m using the trend line from Figure 5. A parent distribution is obtained for these normalized sustained pressures, by fitting the ranked dataset with a Gamma distribution (see Figure 6). The Gamma distribution type was judged to be a better fit to the data than Weibull and Gumbel, which additionally tended to be less conservative on the extremes.

The resulting parent distribution for sustained pressure events (Figure 6) can be used to perform an extremal analysis. The exposure term (distance of continuous crushing) can be estimated for specific sites, with the corresponding number of loading events. The pressure values can be obtained from Figure 6, or extrapolated beyond the range of the dataset using the Gamma fit. This extreme pressure can then be corrected for a specific thickness using the power fit from Figure 5, as the data from Figure 6 is normalized to h = 0.5 m.

The approach proposed here for obtaining the normalized mean pressure is analogous to the procedure used to adjust the formulation to adjust C_R for exposure (Equation 3), and the results can be used in a similar fashion to obtain sustained global pressures at specified exposure level and target reliability.

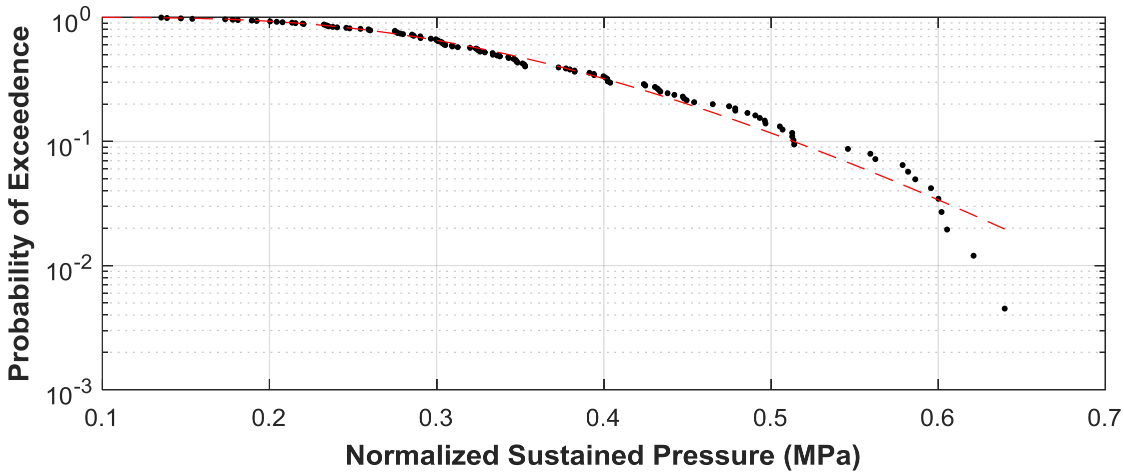

Figure 6. STRICE mean pressure data normalized to h = 0.5 m, with Gamma fit (shape parameter 9.087 and scale parameter 0.0392)

EXAMPLE APPLICATION

To illustrate potential applications of the presented data example scenarios were specified based on sea ice conditions on the Grand Banks offshore Newfoundland and the Northern Baltic Sea, both with very different magnitudes of exposure. Of interest for these example cases are the ULS ice pressures at 10^{-2} APE for a 15 m waterline width structure, with governing ice conditions of 1 m thick level ice.

The annual exposure to ice crushing in the Northern Baltic is estimated in Thijssen & Fuglem (2015) as 135 km annually, hence for $N = 220$ the crushing distance per event can be estimated as approximately 0.6 km. For the Grand Banks of Newfoundland the exposure to sea ice is significantly lower. On average in the past 20 years sea ice was reported in the CIS ice charts at the White Rose field for only 5 days every 3 years. Additionally, it is rare for this sea ice to consist of continuous level ice or large floes, as required for the failure mode to be continuous crushing. Based on the above and judgement, 0.5 km continuous crushing is conservatively estimated on an annual basis for the Grand Banks, for this example scenario.

Based on the average event velocity and event durations the corresponding crushing distance can be estimated as 73 m. This value is used for the example scenario to estimate the annual number of loading events, e.g. for 135 km of annual crushing a total of 1,850 loading events result, given loading events occur in continuous succession.

Following the above inputs, the approaches outlined in this paper were followed to obtain both the peak and mean pressures at 10^{-2} APE, with the results shown in Table 1. The C_R values as obtained from Equation 3 are shown as well for the two locations. The results show that exposure can be accounted for specifically, and mean sustained pressures are significantly less than the peak pressures.

Table 1. Example case results of global pressures on 15 m wide structure

Sea ice scenario	APE	Level ice thickness (m)	Annual ice crushing (km)	Mean pressure (MPa)	Peak Pressure (MPa)	C_R (MPa)
Grand Banks	10^{-2}	1.0	0.5	0.53	0.77	1.18
Baltic Sea			135	0.73	1.16	1.80

Although the mean pressures are lower than the peak pressures, they are significantly greater than the mooring forces measured on the Kulluk as illustrated in Figure 4. For example the P95 sustained global crushing pressure for 1 m thick level ice can be obtained as 0.37 MPa. Then if the entire 70 m waterline width of the Kulluk would be loaded at 0.37 MPa, the corresponding mooring forces would be an order of magnitude greater (26 MN) than the reported level ice forces in flexural failure (approx. 2 MN from Figure 4).

CONCLUSIONS

A simplified approach is proposed in this paper for determining the crushing pressure as input to a mooring analysis of a moored vessel. The paper provides an initial probabilistic assessment of mean pressures reported from the STRICE dataset, and shows how an extreme values can be obtained for e.g. ULS conditions. Forces from continuous crushing of large floes or level ice sheets were found significantly greater than those associated with broken ice.

The approach is applicable to floaters with a vertical shape at the waterline that induces continuous crushing failure of the ice. No considerations are provided on determining loads for dynamic vessel events, such as ice vaning. The analysis follows the recommendations from ISO 19906 (2010) for determining ice actions on floaters to base the analysis on full-scale data and include exposure considerations.

Exposure values are estimated for the examples for illustration of potential applications of the dataset. Analysis of site specific sea ice data is required to determine appropriate exposure values for the relevant failure modes of the ice. Conservative simplifications may be required where data is lacking or severe uncertainty exists.

Further investigations are recommended on reviewing the time series of additional full-scale data sources, such as Moliqpak pressure data (from Beaufort and Sakhalin), the recent Viking station keeping trials, Kulluk operations in the Beaufort Sea, and the STRICE dataset. By analyzing the time series the specific dynamics of the vessel can be better accounted for (e.g. relate averaging period to natural period response), and the size effect better specified (thickness and width effects). A time domain response model can be set up to find the appropriate averaging period for the ice loads, to better account for the load variability and correlation in time.

As this paper is limited to continuous brittle crushing ice failure, a similar analysis can be done for the ductile load data from STRICE associated with slow interactions. The ductile to brittle transition may explain the findings in Liferov et al. (2018), where observations of a cyclic mooring response were reported. In these station keeping trials the mooring tension was reported to build up with minimal relative motion between the ice and the vessel, followed by a load release as the ice started to fail and the vessel gained forward momentum in surge.

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