EXTENDED BALTIC MODEL OF GLOBAL ICE FORCES

Tuomo Kärnä¹,², Yan Qu³ and Qianjin Yue³
¹Karna Research and Consulting, Helsinki, Finland
²Formerly VTT Technical Research Centre of Finland
³Dalian University of Technology, Dalian, China

ABSTRACT

This paper addresses a loading scenario where a sheet of level ice acts on a vertical structure and creates forces due to ice crushing. A simple expression has been derived by the authors to estimate the global ice pressure as a function of ice thickness and the aspect ratio. Full-scale data that has been recorded on a lighthouse structure in the Baltic Sea was used for the original version of this model. The present paper compares the new model with other data that has been obtained in the Beaufort Sea and in the Bohai Bay. Based on this comparison, a modified version of the model of the global ice force is developed herein.

KEY WORDS: Ice forces; Vertical structures; Global pressure, Size effect; Ice crushing.

INTRODUCTION AND OBJECTIVES

This paper addresses the problem of evaluating the magnitude of ice forces on vertical offshore structures. The highest forces due to level ice action arise in conditions where the ice fails by crushing. A common approach is to use a quasi-static ice force as a substitute for the time-varying ice force. Accordingly, the design ice forces for this loading scenario are defined by estimating the global ice force as

\[ F_G = p_G \cdot w \cdot h \]

where \( p_G \) is the global pressures, \( h \) is the ice thickness and \( w \) is the width of the loaded area of the structure. According to this definition, the parameter \( p_G \) represents the maximum peak value of a time-varying total ice force, occurring within a given time of exposure. The global pressure is defined as the average pressure over the nominal ice-structure contact area. The global pressure is also known as the effective pressure.

The global pressure depends on the size of the ice-structure contact area. This size effect can be expressed in several ways. A common approach has been to use the nominal contact area \( A = h \cdot w \) as the main parameter to explain the size effect in the form \( p_G = p_G(A) \). This approach has some disadvantages as discussed by Blanchet and DeFranco (2001). Therefore, various combinations of the three parameters \( h, w \) and \( w/h \) have also been used to predict the size effect in the from \( p_G = p_G(h, w) \) or \( p_G = p_G(h, w/h) \). L. set et al. (1999) as well as Shkhinek et al. (2003) made a synthesis of a large amount of results that has been obtained in earlier

Full-scale measurements have been conducted in the Gulf of Bothnia, which is the northernmost part of the Baltic Sea. The tests are described in Schwarz and Jochmann (2001). Kärnä et al. (2005, 2006a, 2006b, 2006c, 2006d) used this data to derive a formula that predicts the size effect. Due to this research, the size effect of the global pressure was expressed in the form

$$p_{EG} \propto h^n \cdot f\left(\frac{w}{h}\right)$$

where $n = -0.50$ for the test conditions concerned. Simple formulas were derived for the function $f(w/h)$ to define the effect of the aspect ratio on flat faced and circular structures.

The objective of the present paper is to first compare the results obtained in the Baltic Sea conditions with experimental results obtained in other sea areas. Second, the original model is modified to take account of other data obtained in thick ice sheets.

**REVIEW OF FULL-SCALE DATA**

The model derived from the Baltic Sea data can be verified by using full-scale data obtained in the Beaufort Sea and in the Bohai Bay. Therefore, this data is reviewed as follows.

**Pressures on a jacket leg in the Bohai Bay**

Wessels and Jochmann (1991) describe full-scale tests that were carried out on a jacket platform in 1989 and 1990. The test site was located in the Bohai Bay. Force measurements were done on a cylindrical leg using small load panels. The global force acting on the leg was then calculated from the compressive forces measured by these panels. The global forces were reported as 95% cdf values (Wessels and Jochmann 1991, Table 1). The markers in Fig. 1 show those data points that relate to level ice actions. An upper bound curve $p_{GUB} = 0.38 h^{-0.35}$ is also shown as determined by Kärnä and Qu (2005).

This data set can be conveniently be used to discuss several practical problems of the present kind of data analysis. The first problem relates to the ice quality. It is known that the parent ice is seldom thicker than 0.35 m in this sea area. Therefore, most of the data points in the region $h > 0.35$ m should be considered as rafted ice. Rafted ice can be fully refrozen, in particular within small ice volumes that create forces on load panels. Therefore, the highest pressure values of such ice may have the same level of competence as the parent ice. In many cases, however, rafted ice is weaker than the parent ice. Under these circumstances, an upper bound curve can be used to study the size effect also in the region of $h > 0.35$ m. On the other hand, the use of these data points in a regression analysis almost certainly yields an uncertain trendline. The results of a regression analysis can be misleading also because the inclusion of data from events with low pressure values depends on subjective judgement.

Measured data points for $h < 0.10$ m were not shown in Fig. 1 because of a high probability of flexural failure in thin ice. Because of the possibility of flexural failure, some of the datapoints in Fig. 1 for $h = 0.10$ m may have been influenced by flexural failure. Kärnä and Qu (2005) provide further details of the problems related to data analysis as well as solutions to handle these problems.
Figure 1. Maximum crushing pressures measured on a 2.02 m wide leg of a jacket structure in the Bohai Bay (Wessels and Jochmann 1991).

Data on first-year ice events in the Beaufort Sea

Blanchet and DeFranco (1996) developed a formula for the global pressure using an extensive database on full-scale first-year ice load data. This database was used and updated by Blanchet (1998). All data points were standardised to correspond a width of $w = 162$ m. Using a special purpose software, each data point was accurately digitized from Fig. 7 of Blanchet (1998). Figure 2 shows how this data set predicts the global ice force as a function of ice thickness. An upper bound curve is shown as $p_{GUB} = 1.00 h^{-0.38}$.

Wright (1998) analysed several case histories that Molikpaq experienced in the winter 1985/86 in the Beaufort Sea. Based on the evaluated face loads and estimations of the corresponding ice thicknesses, ice pressures of the 60 m wide face of the structure were reported. Figure 3 shows the peak values of the global pressure in forty events where the thickness of first-year ice varied from 0.6 m to 2.0 m. The data points were re-plotted from Figure 4.13 of Wright (1998). An upper bound curve $p_{GUB} = 1.35 h^{-0.30}$ is also shown.

Timco and Johnston (2004) reported a reanalysis of the forces that were measured on the Molikpaq structure in the Beaufort Sea. Table 4 of their paper provides data on the global pressures. Data that was obtained while first-year level ice was acting on the structure at the
geographical location "Amauligak I-65" was used for the present analysis. The markers in Fig. 4 show the global pressure in 39 events where the ice failure mode was classified as crushing. The loaded width varied from 60 m to 105 m.

Previous analysis of the Molikpaq data shows that the panel pressures increased significantly when the ice velocity decreased from the range of \( v > 0.1 \text{ m/s} \) to a value around 0.06 m/s (Rogers et al. 1986; Fig. 6.1 of Hardy et al. 1996). Therefore, the data analysed by Timco and Johnston (2004) was classified herein into two groups in accordance with the ice velocity. The results of this classification are shown in Fig. 4. It can be seen that the global pressures amounted up to around 1.8 MP at ice velocities \( v < 0.9 \text{ m/s} \) whereas they remain in the range of \( p_G < 1.4 \text{ Mpa} \) at higher ice velocities. This phenomenon is apparently a result of a time-varying ice-structure interaction that was described above.

![Figure 4. Global pressures due to first-year ice.](image1)

![Figure 5. Global pressure due to multi-year ice; \( w = 60 \text{ m} \).](image2)

**Data on multi-year ice events in the Beaufort Sea**

All the data shown in Figs. 1 to 4 concern actions due to first-year ice. Global pressures due to multi-year actions have been analysed by Wright (1998) as well as Timco and Johnston (2004). Figure 5 shows data extracted from these two papers. This data indicates that the ice thickness has at most a very small influence on the global pressure when \( h > 2.5 \text{ m} \).

**MODIFICATION OF THE BALTIC MODEL**

Three major conclusions can be made from the data that is shown in Figs. 1 to 5:

- Global forces on compliant structures can increase at a range of low ice velocities. This was not the case in the very stiff lighthouse that provided data for the model described in Kärnä et al. (2006d). Therefore, it is inferred that the influence of the compliance should be considered in a formula for the global ice pressure.
- The ice forces arising in Arctic sea areas appear to be higher than in the sub Arctic ice regimes.
- The thickness effect \( p_{EG} \sim h^{0.34} \) predicted in Kärnä et al. (2006d) is in good agreement with the first-year data that covers the thickness range from 0.2 m to about 1.5 m (Figs. 1 to 3). However, the thickness effect appears to be much smaller for multi-year ice in the range \( h \geq 2.5 \text{ m} \).
The basic structure of Eq. (2) copes with the first two of these conclusions. However, the third conclusion made above shows that Eq. (2) is not valid for very thick ice. Therefore, an effort was made to modify the basic form of Eq. (2) such as to make it compatible also with data on thick ice.

As a first trial, Kärnä et al. (2005) studied the influence of the ice rubble that accumulates above and underneath an ice sheet that is acting on the structure. Soil-mechanical equations were used to evaluate the additional forces created by this phenomenon. The first simulations indicated that this kind of rubble accumulations has practically no effect on the global pressure if \( h < 1 \) m. In the range of \( h > 2 \) m the additional effects were found to have and effect that might explain the change in the thickness effect while the thickness increases. However, this model had to be dismissed because the force magnifying effect arises from this model only in conditions where the height of the rubble pile is assumed to be higher than what is physically possible.

It was appreciated that the physical reasons for the very complicated thickness effect described above is not understood at present. Hence, a straightforward curve-fitting approach was adopted. It was found that the size effect model described in Kärnä et al. (2005d) can be modified as

\[
p_{EG} = \gamma_D \gamma_S A_{IR} h^n \left( \frac{w}{h} \right)^{-0.16}, \text{ with} \]

\[
n = \begin{cases} 
-0.50 + \frac{h}{8}, & \text{for } n < -0.36 \\
-0.36 + \frac{h}{80}, & \text{for } n \geq -0.36 
\end{cases}
\]

where

- \( p_{EG} \) is an equivalent global pressure for a quasi-static design,
- \( \gamma_D \) a dynamic magnification coefficient to consider inertial effects,
- \( \gamma_S \) a coefficient to consider the magnification of the external force due to alternating ductile-brittle crushing that can occur for a compliant structure,
- \( A_{IR} \) an ice regime parameter, which considers the variations of the forces encountered in different ice regimes. The influence of the time of exposure is also considered by this parameter.

The ice regime parameter \( A_{IR} \) is here non-dimensional, the ice thickness \( h \) as well as the width \( w \) are expressed in [m] and the global pressure is obtained in [Mpa].

Figure 6(a) shows a comparison between the “Baltic model” derived in Kärnä et al. (2006d) and the expression (3) in the prediction of the annual maxima of the global pressure on the lighthouse Norström grund. The calculation was made using the parameter values of \( \gamma_D = 1.0, \gamma_S = 1.0 \) and \( A_{IR} = 1.25 \).

Based on Eq. (3), Fig. 8(b) shows predicted maximum annual values of the global pressure for first-year ice (FY) and for multi-year ice (MY). The two amplifying coefficients were taken as \( \gamma_D = 1.0 \) and \( \gamma_S = 1.4 \). The ice regime parameter was assumed as \( A_{IR} = 1.75 \) for first-year ice and \( A_{IR} = 2.1 \) for multi-year ice. The 20% higher \( A_{IR} \) value for the multi-year ice is justified due to

the results provided by Wright (1998). Figure 8(b) also shows data points determined by Wright (1998) as well as Timco and Johnston (2004). This data is based on short-term measurements. Therefore, the comparison is made in Fig. 8(b) on the basis of annual maxima. Finally, the dotted line in Fig. 8(b) depicts the “Gulf” curve $p_G = 1.5 h^{-0.174}$, which is commonly used in the design (Masterson and Spencer, 2001).

![Figure 6. Predictions of the annual maxima of the global pressures for the lighthouse Norströmgrund (a) and for the Molikpaq structure (b).](image)

**DISCUSSION**

The new model defined by Eq. (3) predicts the global pressure due to the actions of level ice sheets against vertical structures. The size effect is formulated using a non-dimensional equation where the ice thickness and the aspect ratio are used as two independent factors. For a fixed aspect ratio of $w/h = 1$ the model would predict the size effect as $p \sim h^{-0.5}$. This is what the data obtained on force panels showed on the lighthouse Norströmgrund. However, in the range of $w/h > 2$ where the final model is valid, the thickness effect for a fixed width of the structure can be expressed as $p_EG \sim h^n$ where $n \approx -0.3$ for thin first-year ice and $n \approx -0.1$ for thicker multi-year ice.

Three parameters are used to consider other factors that are relevant in the load prediction. The parameter $A_{IR}$ is used in Eq. (3) because the ice regime (sea area) has a significant effect on the global pressures. This was found earlier by Masterson et al. (2000). Factors that apparently influence this parameter include the ambient temperature, large scale deformations of the pack ice as well as heterogeneity of the natural ice sheets. Masterson et al. (2000) used the sum of freezing degree days as an explanatory factor to predict the differences that are met in different sea areas.

The parameter $A_{IR}$ is also used to consider the fact that the maximum ice force increases with the time of exposure. Kärnä and Qu (2006c) describe a method of extreme value analysis that can be used to consider the influence of the time of exposure.

It is generally known that the external ice forces can increase significantly in a range of low velocities. The data obtained at the lighthouse Norströmgrund indicates, however that such an increase can not easily occur if the structure is very stiff at the waterline (Kärnä et al. 2005). Therefore, a coefficient $\gamma_S$ is adopted in Eq. (3) to consider the magnification of the external force as a function of the compliance of the structure.
The time varying external force is magnified within the structure due to inertial effects. A dynamic magnification factor $\gamma_D$ is used to consider this. By adopting this factor in Eq. (3) we can justify an approach where a quasi-static load defined by Eqs. (1) and (3) is used as a substitute for the time-varying ice force. Kärnä et al. (2006b) show how this parameter depends on the aspect ratio, fundamental frequency and the damping ratio of the structure-soil system.

The results shown in Fig. (6) indicate that Eq. (3) can most likely be used in a wide range of conditions by using appropriate values of the parameters involved. However, further research should be conducted to clarify how the parameters $\gamma_S$ and $A_{IR}$ should be selected in different conditions. Preliminary values for these parameters can be obtained from Kamesaki et al. (1996) and Kärnä et al. (2005, 2006d) as well as from this paper.

CONCLUSIONS

Based on an extensive data analysis, a new expression was derived to describe the size effect in ice crushing. The aspect ratio and the ice thickness are the main parameters of this equation. An ice regime parameter is used to account for the differences met in the ice forces in different sea areas. In addition, a magnifying parameter is used to consider that the external pressure on a compliant structure may increase at a low ice velocity. A second magnifying factor is needed to consider the dynamic magnification due to inertial forces. Details of this development are further clarified in the main report of this research as well as in four accompanying journal- and conference papers. The experiences obtained in this development show that the ice forces to be expected in the mild conditions such as in the Baltic Sea and in the Bohai Bay are significantly lower than in the Beaufort Sea. It is a challenge for further research to understand the reasons for this difference.

ACKNOWLEDGEMENTS

This work was funded mainly by the European Commission under the Contract No TREN/04/FP6EN/S07.31041/503721. The working group ISO TC67 SC7 WG8 has also provided significant support along with the companies Petro-Canada and Statoil. Ice experts working for the working group WG8 gave very valuable comments and advice. In particular, the support provided by Denis Blanchet, Walt Spring, Peter Jochmann, Joachim Schwarz, Andrew Palmer, Dan Masterson, Dmitri Matskevitch, Lennart Fransson, Bob Frederking Garry Timco, Karl Shkhinek, Sveinung Loeset, Dilijan Mirzoev Dmitri Onishchenko, Koh Izumiyama, Takahiro Takeuchi and Naoki Nakazawa is appreciated.

REFERENCES


Kärnä, T., Qu, Y. and Yue, Q.J. (2006b). An equivalent lateral force for continuous crushing. *Proc. 25th Int. Conf. on Offshore Mechanics and Arctic Eng*. June 4-9, Hamburg, Germany (accepted).


Kärnä, T., Qu, Y. and Yue, Q.J. (2006d). Baltic model of global ice forces on vertical structures. This volume IAHR’06 proceedings.


