POAC'11
Montréal, Canada

Proceedings of the 21st International Conference on
Port and Ocean Engineering under Arctic Conditions
July 10-14, 2011
Montréal, Canada

POAC11- 029

PLATFORM SHAPE AND ICE INTERACTION: A REVIEW

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ABSTRACT
It is well known that the shape of a platform, especially at the ice line, affects ice failure modes and the resulting ice loads. The recently published ISO Standard for Arctic Structures provides methods for calculating loads on various shapes of platforms. This paper looks at three examples where additional insights and considerations are required to develop authentic design criteria.
The first example is interaction of thick ice with sloping platforms. Some modifications to the ISO algorithm for failure of thick ice on a sloping structure are presented and comparisons are made with a vertical structure. The second example is how to assess ice loads when protective ice barriers are used around a platform. The third example is how to develop design ice loads for sloping wide structures in shallow water.

INTRODUCTION
In addition to ice interaction, the shape and size of a platform will also be influenced by other factors such as platform purpose, water depth, wave climate, foundation conditions, seismicity and construction constraints.

The engineer's task is to select a platform shape which recognizes these other factors, provides an optimum shape for ice interaction and minimizes ice load uncertainties. The task is not simple. A shape which might be a good choice for one type of ice regime may not function well in a different one. A shape which might be good for deep water may not be good for shallow water. A shape which may minimize ice loads by reducing the water line width may suffer from dynamics due to cyclic ice loads acting on a more compliant structure. A wide structure in shallow water (or sitting on an underwater berm), will attract grounded ice rubble, and its shape at the ice line may become irrelevant if ice fails against the grounded ice rubble rather than the platform.

It is beyond the scope of this paper to provide a handbook for platform shape selection. Rather, the paper documents three examples where the current methods (e.g. in ISO 19906) need to be used with additional insights and full appreciation of ice interaction processes.

EXAMPLE 1: DESIGNING FOR THICK ICE
Vertical versus sloping structures
A concern facing engineers in designing platforms for the Arctic Ocean is the presence of thick multi year ice. An example of a severe design condition would be a large multi year hummock field with a design thickness of say 12 m (example only, but see Johnston at al, 2009). Assuming this was the design scenario; one of the first questions a designer would ask is whether it is best to use a vertical or sloping shape.

Using ISO 19906 (ISO, 2010), the global crushing pressure (p) on a vertical face is given by,

$$p = Cr\ t^{n}(D/t)^{m} \tag{1}$$

where p is in MPa; t is the ice thickness in m; D is the structure width in m; Cr = 2.8 for the Arctic (2.4 sub Arctic: 1.9 temperate); for ice thicker than 1 m; m = - 0.16; n = - 0.3.

Assuming a platform with an ice line diameter of 80 m, and 12 m thick ice, the ice load is calculated as 942 MN. (The associated crushing pressure is 0.98 MPa).

If the platform is designed with a sloping face, ISO can also be used to estimate the design load; but the calculation is more complex and requires a number of additional inputs. First though, it is of interest to calculate simply the ice breaking load (H_B). This is given as

$$H_B = 0.68\ \varepsilon\ \sigma_f\ (\rho_w\ t^5/E)^{0.25}\ (D + \pi^2\ l_c/4) \tag{2}$$

where σ_f is the ice flexural strength, ρ_w is the weight density of water, t is the ice thickness, E is the ice modulus of elasticity, l_c is the characteristic length of an ice plate, given by,

$$l_c = (E\ t^3/(12\ \rho_w\ (1-\nu^2))^{0.25} \tag{3}$$

and

$$\varepsilon = (\sin\alpha + \mu\cos\alpha)/(\cos\alpha - \mu\sin\alpha) \tag{4}$$

where α is the slope angle from the horizontal, ν is Poisson's ratio and μ is the friction coefficient between the ice and the slope.

Using accepted values for ice to steel friction, ice modulus, water density, an ice flexural strength of 350 kPa and a slope of 55 degrees, the breaking load is about 170 MN. This is a significant reduction from the crushing load of 942 MN. However, as indicated in Croasdale et al, (1994) and ISO (2010), once the ice has been broken, it still has to clear the structure and there are additional load terms. For thick ice which will not likely form significant rubble but ride up as a single layer, the two additional important terms are the ride up of the broken blocks up the slope (H_R) plus the force to turn the blocks at the top of the slope (H_T).

Using the expressions in ISO and the configuration shown in Figure 1, the various load components are shown in Table 1. Comparison of the values shows that there is still some advantage for the sloping structure but the gap is narrowed considerable.

Table 1: Comparison of ice loads in MN: vertical versus sloping; showing contributions.

Vertical Structure	Sloping Structure				
	Ride up height (m)	H_B	H_R	H_T	Total H Load
942	20	168	375	117	660
	25	176	470	117	763

It should also be noted that the vertical structure will be subject to higher frequency cyclic loads than the sloping structure. Experience suggests that there may be feedback between the cyclic deflections and the ice crushing process to induce higher crushing forces than for an absolutely rigid structure. The uncertainty surrounding this phenomenon is another possible reason for choosing a sloping structure.

On the other hand, ice blocks riding up a sloping structure need to clear without jamming. It can be appreciated from Figure 1 that overhanging decks would be problematic for thick ice. The design shown in Figure 1 is considered to be a good geometry to clear the thick ice, but the drilling and/or producing facilities would need to fit into a smaller footprint than a design with an overhanging deck. Another way to avoid jamming and improve clearing is to have the deck on a high narrow neck, but determining the optimum diameter and height of such a neck is subject to uncertainty and this solution may be more costly. Note that ride up may be limited by downward failure of the oncoming ice. An approximate calculation shows that a 15 – 20 m ride up can cause downwards failure of 12 m ice. But if the oncoming ice cannot fail downwards because it is in contact with the structure, then 25 m ride up is possible and is therefore considered.

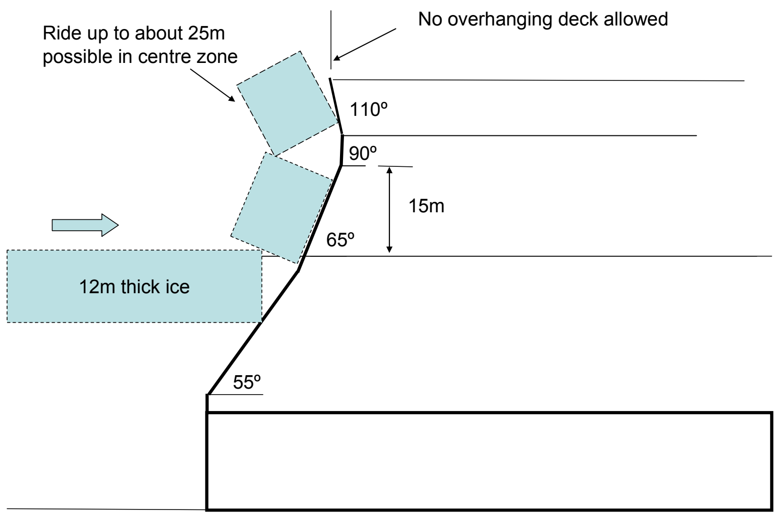

Figure 1. Thick ice acting on a sloping structure with expected ride up.

Improvements to the ice load method

The method of Croasdale et al (1994), which is also one method in ISO (2010), was originally developed in 1980 and refined for the design of the Confederation Bridge. The bridge piers are conical with a 52 degree slope, an ice line diameter of about 15 m and a shaft diameter of about 8 m. It was recognized at the time that certain conservatisms were embedded in the method. One was the assumption that the ice breaking across the width was simultaneous; another was that the ride up components acted as though on a 2D slope with the width at the top being the same as at the ice line. There are possibly other conservatisms because comparisons of measured and predicted loads show generally an over-prediction in the range of about 0 – 50 % (Tibbo, 2010).

The two conservatisms mentioned above may lead to even higher over-predictions for thick ice. It is therefore of interest to look at how some simple adjustments can be made to reduce them.

Figure 2 shows the possible approach. It is suggested that the ice breaking term be considered as the breaking of three separate non-simultaneous zones.

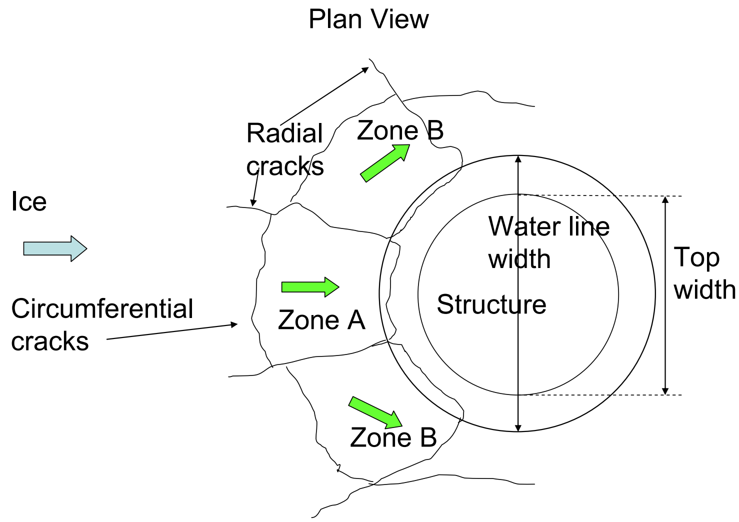

Figure 2. Multi zone model for ice on a sloping structure.

A non-simultaneous factor is introduced in the method, which has a minimum value of 0.33 and a suggested value based on judgment of 0.5. For ride up, it is suggested that the two side zones (B) only ride up half the height of the centre zone (A). So the average height is 0.67 of the maximum ride up of the centre zone. In addition it is assumed that the H_T term (the force to turn the blocks to the vertical when they meet the shaft) is also only calculated for the centre zone. The blocks riding up from the side wedges are assumed to be cleared sideways without being turned to the vertical. With these simplifications, H_T is calculated based on one third of the width.

Table 2 shows the results of these modifications compared to the current ISO formulation. As can be seen, the total global load for 12 m thick ice is now reduced to 336 from 660 MN and there is a potential significant advantage for the sloping structure over the a vertical face load of 942MN.

Table 2: Comparison of loads using a multi zone model for breaking and ride up.

Vertical Structure	Sloping structure					
	Ride up height (m)	H_B	H_R	H_T	Total H Load	ISO method
942	20	46	251	39	336	660
	25	48	314	39	401	763

Validity of methods and other issues

There is very little experience of thick ice interacting with offshore structures, either in crushing or in bending. Full scale data on crushing is extrapolated based on plausible pressure/area trends developed for much thinner ice than 12 m, and 7 m seems to have been the thickest ice in the data sets. There is also debate on the interpretation of existing full scale crushing data (note the papers at this conference). It is also noted that the crushing data on multi year ice from the Beaufort is higher than that obtained at Hans Island, even allowing temperature corrections. In general, it would appear that the crushing loads based on the current ISO Arctic formula may be conservative. But more data on thick ice interacting with vertical structures is needed to be sure, and to improve confidence.

For sloping structures, again there is a lot of data for ice below 2 m thick (e.g. Confederation Bridge), but no data for thick ice (except perhaps from large icebreaker experience). For sloping structures, data, experience and theory show that the breaking load is much lower than the equivalent crushing load (and this is without a size effect on flexural strength which may be present but is uncertain). However, it is the clearing process that is critical in keeping loads below the crushing load. With thick ice, broken blocks pushed upwards may jam into overhanging decks and so these must be avoided or positioned much higher than many designs often propose. Although this author does not favour model testing as a way to determine ice loads, they may help, if devised properly, to improve shapes to better cope with ride up and clearing of thick ice.

In developing optimum designs for the Arctic Ocean, other factors beyond those discussed above also have to be recognized. Ridges will be thicker than 12 m but once broken may clear better on a sloping structure. A vertical structure may have to be designed for the crushing of the ridge using full thickness averaged across the diameter. Ice Islands are another issue and could be 30 m or more thick. It is likely that either protective underwater berms will be needed, or the platforms abandoned rather than be designed for these rare features (unless Limit Force methods can offer relief). Regardless, the Limit Force methods need to be incorporated into the overall approach for thick ice features, and may lead to lower loads (See Croasdale, 2009 and ISO 2010).

EXAMPLE 2: LOADS ON STRUCTURES SEPARATED BY NARROW GAPS

In recent years, the use of ice barriers to protect platforms in shallow water has been developed. A typical deployment with two barriers on each side of a central platform is shown in Figure 3. In the example shown, the central platform is obviously completely protected from East – West ice movements (assumed across the page). North- South ice movements act on the ends of the platform, but these are of reduced dimension, so the design ice loads for the central platform can be lower than for an unprotected platform.

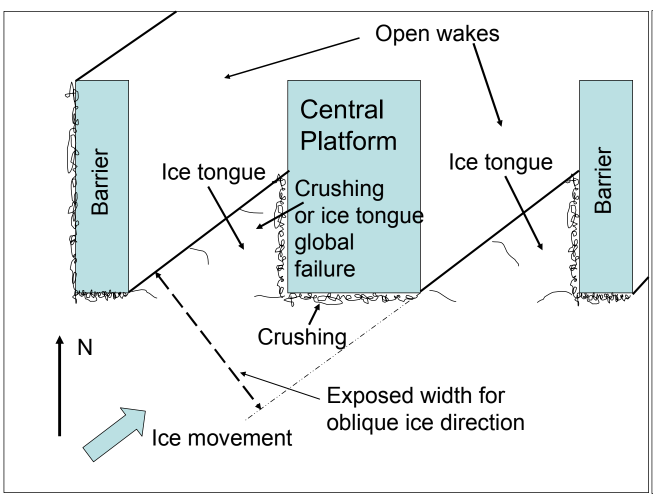

Figure 3. Oblique movement with ice barriers

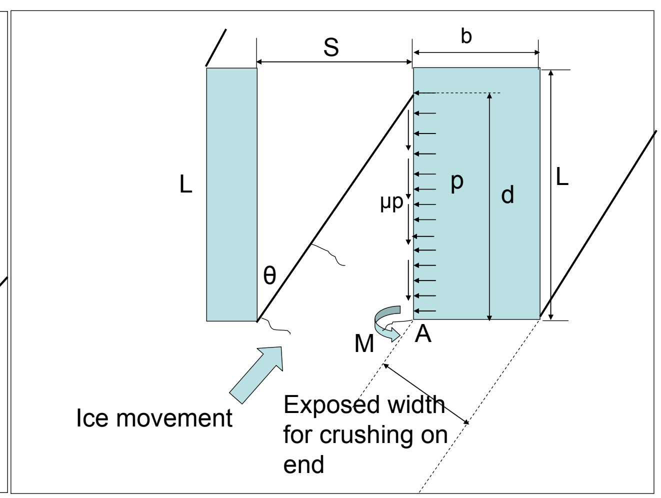

Figure 4. Geometric Parameters

One concern is that oblique loads will act on a greater exposed width than the ends of the platform. On the other had, the ice tongue shown in Figure 3 which acts on the side of the platform has a free edge, and is likely to be cracked because of prior interaction with the upstream ice barrier. It may also fail globally rather than in crushing against the side of the platform (by in-plane bending). The pressure (p) along the side of the platform (assuming vertical sides) will then be the lower of either crushing (possibly reduced from ISO values because of the free edge and cracking) or the pressure to fail the ice tongue in in-plane bending. ISO does not cover in-plane bending. The limit to p from in-plane bending can be derived by taking moments about the corner A in Figure 4.

$$M_A = 0.5\ p\ d^2\ t \qquad (5)$$

where M_A is the bending moment at A, p is the ice pressure, d is the length of ice contact and t is the ice thickness.

From elastic bending theory, the flexural stress (σ_f) can be related to bending moment and the cross section of the beam as follows,

$$\sigma_f = 6\ M_A /(t\ S^2) \qquad (6)$$

where S is the gap between barrier and platform. Combining (5) and (6)

$$p = 0.33\ \sigma_f\ (S/d)^2 \qquad (7)$$

and,

$$d = S/\tan\theta \quad \text{(But can't exceed the length of the platform, L)}$$

where θ is the angle of ice direction from the long axis. So, by substitution,

$$p = 0.33\ \sigma_f\ (\tan\theta)^2 \qquad (8)$$

Except that for angles of θ that would lead to d being greater than L, p will be independent of θ and given by.

$$p = 0.33\ \sigma_f\ (S/L)^2 \qquad (9)$$

There is also a frictional shear associated with p. The ice load on the side of the structure resolved in the direction of motion (Fs) is therefore:

$$Fs = p\ d\ t \sin\theta + \mu\ p\ d\ t \cos\theta \qquad (10)$$

Note that p is the lower of either that derived for the ice tongue failing in in-plane bending or the value based on crushing. (Crushing will control for small values of d (high values of θ)) because the moment arm to fail the ice tongue in bending is much reduced.

The ice load due to crushing on the end of the structure in the direction of motion (F_E) is estimated using the projected width normal to the ice motion (see Figure 4).

$$F_E = \sigma_c\, b \cos\theta \qquad (11)$$

where σ_c is the ice crushing pressure as derived using ISO (Eq. 1 in this paper) and b is the end width of the platform (see Figure 4).

The total global load is given by $F_s + F_E$. Figure 5 shows the results of using the above theory for the following inputs; platform length, 100 m; platform width, 50 m; barrier length, 100 m; separation distance, 100 m; ice thickness, 1m; ice flexural strength, 350 kPa; side friction coefficient, 0.1. Note that a strength reduction (of 0.7) for crushing on the platform side because of the free edge is applied; this is adjustable based on judgment.

The results in Figure 5 show that using the approach with the global failure of the ice tongue gives a maximum ice load of about 53 MN for 100 m barriers placed 100 m from the platform long side. This compares with a load of about 100 MN for the same structure with no barriers. Prior to this new theory, the predicted load with barriers would have been about 80 MN.

The approach can be applied to investigate how the loads vary with barrier separation. The same principles of analysis can also be applied to more complex arrangements, for example using more barriers, various barrier lengths and platforms with spaced substructures supporting a common deck.

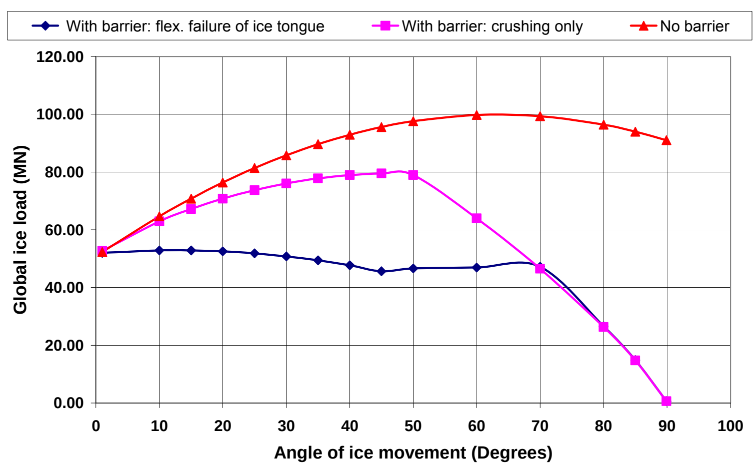

Figure 5. Loads on a platform with and without barriers as function of ice direction and methods

EXAMPLE 3: WIDE SLOPING STRUCTURES IN SHALLOW WATER

Care is required when using algorithms for wide sloping structures in shallow water. Figure 6 shows a sloping ice barrier in the North Caspian Sea. It can be seen that ice movement against it has created a large grounded rubble pile. Such grounded rubble, once established (and not removed for operations), will completely protect a structure from ice loads because the sliding resistance of the grounded rubble is greater than the ice load applied at its perimeter. However, for design, the ice loads prior to the establishment of such a rubble field will control. For a sloping structure the design engineer might assume that applying the ISO equations for a sloping structure will give the correct design loads. But this would be wrong.

Figure 7 shows the stages of ice interaction for this case. In Stage 1, the ice fails in bending on a bare sloping face and rides up to the top of the slope. For 1 m thick ice acting on a 100 m wide barrier, the ice breaking load is 2.5 MN (for a 45 degree slope, friction of 0.15, and a flexural strength of 500 kPa). As the ice rides up to the top of the slope at say 7 m above the ice line, the load increases to 16.6 MN. On a wide structure, an ice deflector may be needed to avoid overtopping. In which case the ice falls back onto the oncoming ice and rubble builds up on the slope. In Stage 2, it is assumed that the ice keeps pushing through the ice rubble to continue to fail in bending on the slope. The sloping structure algorithm can still be used for this situation, but with a higher ride up height and rubble on top of the advancing ice. Using the ISO algorithm with a rubble height of 12 m and rubble angle of repose of 35 degrees gives a total global load of about 30 MN.

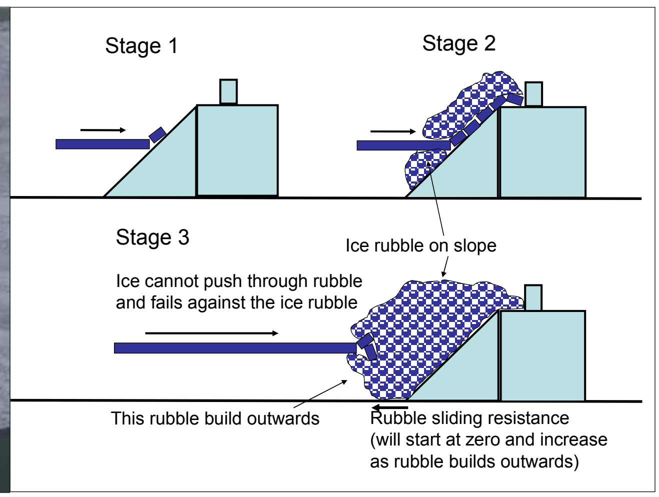

Figure 6. Rubble in front of a wide barrier

Figure 7. Stages in interaction

If the ice would always stop moving at this point, the above ice load would be the design load. However, most ice movements will cause the rubble to continue to build to the point where the ice no longer pushes through the ice rubble to fail on the steel slope. It starts to fail on the outside of the rubble pile in the "rubbling" failure mode. This is shown as Stage 3 in Figure 7. For a short period of time when the growing rubble field still has minimal sliding resistance, the ice load is that due to the rubbling process. If this is greater than the Stage 2 ice load, then the rubbling load will control.

Rubbling loads are similar to ridge building loads and have been investigated, but not with as much attention as crushing and pure flexural loads. A recent review of rubbling loads is in Croasdale (2009) which also references the background to the rubbling loads provided in ISO (2010). The ISO algorithm expressed as ice pressure is:

$$p = R\,(t^{0.25})\,(D^{-0.54}) \tag{12}$$

where p is the rubbling pressure in kPa; t is the ice thickness in m; D is the width of interaction in m and R is a coefficient derived from a best fit to the data. The value of R which gives the best fit to the measured data is about 2000. However based on the discussion in Croasdale et al. (1987), where measured data is reported and analyzed, an uncertainty factor of about 2 should be recognized. So R could be from 1000 to say 4000. Also note that in ISO, a conservative upper bound of R = 10,000 was suggested, especially for narrower widths. This was partly to account for uncertainties but also the possibility of a frozen – in condition, and also because for narrow widths the relationship was matched to be close to the crushing pressure. The rubbling load on rubble in front of a 100 m wide structure for 1 m thick ice is shown in Figure 8 for the full range of R values. Comparisons are also made to the maximum flexural load and to the crushing (for reference only – assuming a vertical structure).

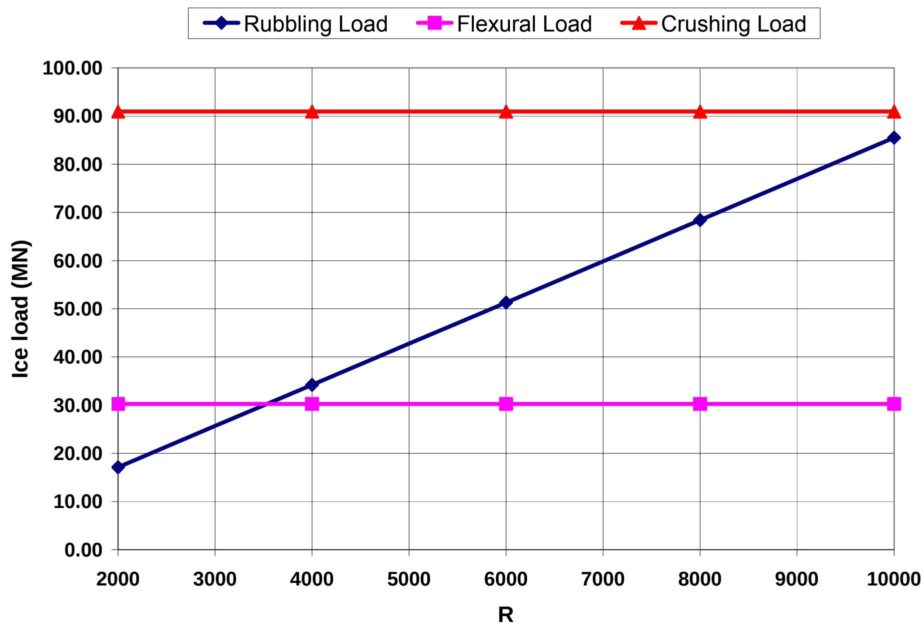

Figure 8. Comparison of loads on a 100 m barrier for a range of R (coefficient in the rubbling equation)

For the Caspian Sea region, the author recommends an upper bound R value of between 6,000 and 7,000. This is derived by using the same ratio as obtained by comparing Cr in Eq. 1 between Arctic and Temperate regions (i.e. 1.9/2.8 = 0.68). Using 6,800 precisely for R gives a rubbling load of 58 MN. Recognizing the logic discussed earlier, 58 MN would be the design ice load (deterministic) for the example with a 100 m barrier subject to 1m ice maximum thickness. This is because it is higher than the 30 MN obtained using the ISO algorithm for sloping platforms for this structure. It should also be noted that the same logic of scenario development can be included in probabilistic models using appropriate ranges of input values. Such an approach is described in Stuckey et al (2011).

CONCLUDING REMARKS

This paper has described three examples in which platform shape and configuration require careful application of the new ISO 19906 in order to avoid erroneous loads and designs.

In the first example of thick multi year ice, some improvements in the ISO algorithm to better fit the way thick ice is expected to interact with a sloping structure are proposed. These will reduce the loads on sloping structures compared to ISO. However, ride up and clearing of thick ice is uncertain and overhanging decks should be avoided unless having sufficient clearance for the ride up of thick ice. Because of uncertainties in ice crushing pressures for thick ice and cyclic excitation in crushing; and ride up heights and clearing of thick ice on sloping structures, the trade offs between sloping and vertical structures still require very careful assessment.

In the second example, a new method is presented for use when a platform is partially protected by ice barriers. This method will lead to lower loads than would be predicted using only the crushing formulae in ISO, which would be conservative in this situation.

In the third example of a wide sloping structure in shallow water, the application of the ISO sloping structure methods without recognizing the effects of ice rubble may lead to underestimation of design loads. This paper has shown that when the ice switches to a rubbling mode against the rubble in front of the structure, the peak load on the structure will generally be higher than predicted using the sloping structure algorithm (even though eventually with continued rubble growth, the net load on the structure will trend lower).

This paper is not a criticism of ISO (the author was intimately involved in its development). But it is recognized that not all situations can ever be covered in a general standard, and that extra thinking and improved methods are always needed. The paper is offered in that spirit, hoping that the content and discussion will lead to improved applications of ISO 19906.

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