Refinements to ice load methods for nearshore structures

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ABSTRACT
Nearshore structures are defined as those subject to an ice regime which is stable for the middle period of the winter. The "Limit Stress" ice load is the product of structure width, ice thickness and ice strength (ice pressure). In this kind if ice regime, if ice thickness and ice strength distributions for the whole winter period are used, the approach will usually over-estimate design ice loads. Conversely, if ice loads are based on the ice being stable for the whole winter, the ice load will be under-estimated. This approach recognizes three separate winter periods each having distinct characteristics of ice thickness, ice mobility and ice strength. They are: 1) Freeze-up: The ice is growing in thickness; it can be highly mobile and it is cold and hence of maximum strength. 2) Stable (landfast): The ice attains maximum thickness but strain rates are usually limited to the creep regime giving lower effective strength. 3) Break-up: The ice becomes mobile again; it can be close to maximum thickness but will be weaker due to warmer ice. An additional factor is the effect of limited ice movement due to either a nearshore location or shallow water. This paper shows how ice loads for each period can be calculated using the methods in ISO 19906. Controlling ice loads for design are discussed for nearshore Arctic structures in first year ice. The method results in design ice loads about three to four times lower than if maximum winter thickness is combined with the Arctic strength coefficient.

KEY WORDS**:** Ice; Loads; Nearshore; Docks; Platforms.

INTRODUCTION and APPROACH

The nature of ice regimes can vary according to distance from shore and water depth. In general, away from the constraints of land and in deeper water, the ice cover can be in constant motion driven by winds and currents. This is called pack ice in which the ice cover consists of discrete floes, often large. Pressure ridges form between floes in converging ice. Structures located in pack ice can be subject to mobile ice throughout the ice season. Ice loads are usually determined by using the thickest ice of the winter and its maximum strength. The length of ice moving past the structure will also be large (many tens or hundreds of km depending on specific location). This large ice motion when used in a probabilistic model (combing thickness and strength distributions) will lead to a higher load at a given level of probability than if the ice motion is small. This issue will be discussed later under the topic of "exposure".

Closer to shore and in shallower water the ice is different. In this regime the ice cover can be stable for most of the winter (e.g. landfast ice). In fact there are three separate winter periods each having distinct characteristics of ice thickness, ice mobility and ice strength. These periods are shown conceptually in Figures 1 to 3 and are:-

1) Freeze-up: The ice is growing in thickness but it can be broken up during storms and be highly mobile; it is cold and hence of high strength.

2) Mid-winter, stable ice (landfast): During this period the ice attains maximum thickness but strain rates are usually limited to the creep regime giving lower effective strength.
3) Break-up: The ice becomes mobile again; it can be close to maximum thickness but is often thinner due to warming temperatures which also weaken the ice.

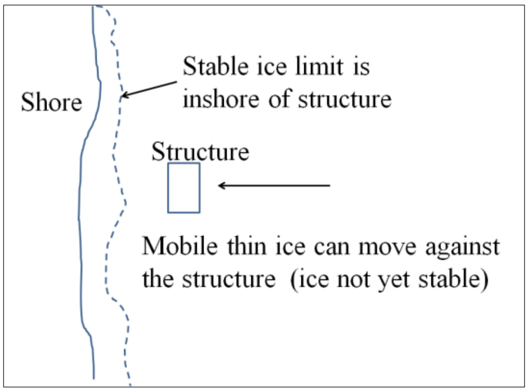

Figure 1: Freeze-up period: Structure is subject to mobile, thin, cold ice actions

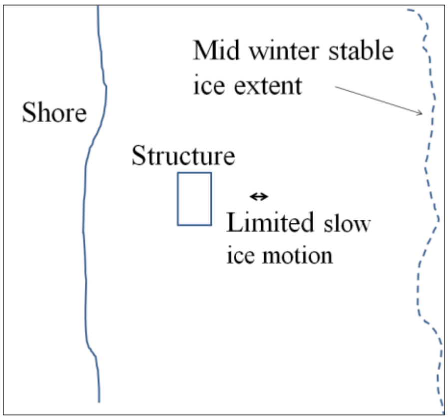

Figure 2: Midwinter: Stable ice; slow, limited ice motion; cold thick ice

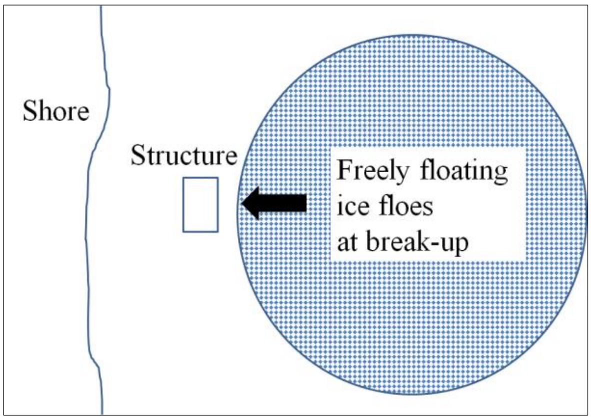

Figure 3: Break-up: Freely moving ice floes; large ice movement; warm ice

In calculating ice loads, if the same approach as that for pack ice is used (combining maximum thickness with maximum strength or strength based on many interactions), the calculated ice load will be conservative. A better approach is to look at each period of the winter as a separate scenario and then determine the one which controls. Methods and typical examples now follow.

ICE LOADS DURING FREEZE-UP

Thickness

A critical input to this calculation is the maximum ice thickness at the end of freeze-up just before the ice becomes stable. This may vary from year to year and will be different from location to location depending on shoreline geometry and the presence of offshore features such as islands or platforms as well as grounded ice. One approach to thickness determination is to use historical satellite images to assess when the ice is stable and then use weather records of freezing degree days to estimate thickness. Another approach is to use historical measurements of thickness and visual observations either from vessels or from shore. In the authors' experience in the Canadian Beaufort Sea, a rule of thumb was that the ice had to be about 0.5m thick for it to be landfast out several km from shore. In a recent study for an

Arctic dock, satellite images and ships records were used to determine the thickness of stable ice transition. For the region of Tasiujak (formerly Eclipse Sound), which includes Pond and Milne Inlets in Canada, the data indicated a mean thickness at the end of freeze-up to be 0.32m with a standard deviation of 0.11m. The extrapolated 100-year value was conservatively estimated as 0.6m.

Global Ice Loads

In this exercise the structure is a dock type structure or platform with vertical sides such that the ice failure mode will be crushing. The physics of ice crushing is complex with non-simultaneous failures occurring in various micro-modes such as spalling to the upper and lower surfaces with small high pressure zones rapidly growing and decaying across the contact zone. No theoretical models based on pure physics are proven, so the current methods are based on the empirical treatment of measured data combined with plausible adjustments for different geometries and conditions. The accepted methodology is outlined in ISO 19906 (2019) for wide structures, where the global ice pressure averaged over the thickness of the ice and the structure width is given as,

$$p_G = C_R \left(\frac{h}{h_1}\right)^n \left(\frac{w}{h}\right)^m \qquad (1)$$

where p_G is the global average ice pressure in MPa; w is the structure width in metres (m); h is the ice thickness in m; $h_1$is a reference ice thickness of 1m; m is a coefficient equal to -0.16; n is a coefficient equal to -0.50+h/5 for h< 1.0m and to -0.30 for $h \geq$ 1.0m. In ISO 19906, C_R = 2.8 for Arctic regions (= 2.4 for sub-Arctic regions: = 1.8 for temperate regions). In this exercise structure widths ranging from 50 to 200m are used. For this scenario with an end of freeze-up ice thickness of 0.6m and a value of C_R = 2.8, Eq. 1 gives the loads for various structure widths as shown in Table 1.

Table 1: Global loads at the end of freeze-up period

Level ice crushing	ISO 19906	C_R = 2.8		
		m = -0.16		
Structure width (m)	End of freeze up thickness (m)	n	Arctic cold p (MPa)	Global load (MN)
20	0.6	-0.38	1.94	23
50	0.6	-0.38	1.68	50
100	0.6	-0.38	1.50	90
200	0.6	-0.38	1.34	161

Effects of Exposure on the Ice Loads

The loads in Table 1 would apply to a structure such as an offshore platform with many tens or hundreds of km of annual ice motion. This is because the strength coefficients in the ISO formulation are based on measured data on structures in moving ice with many interactions. Ice motion against nearshore structures will generally be limited by the shoreline behind the structure which stops the ice. Even an offshore loading terminal, depending on shoreline shape, can be subject to limited ice movement during freeze-up. It is therefore important to consider this effect in designing nearshore structures. In the latest ISO 19906 (2019), a method is included to account for the amount of ice motion ("exposure" is the term used).

The main reason why ice loads can vary with the amount of ice movement is because of the nature of ice as a brittle natural material at high strain rates. As the ice moves, a series of load cycles occur (events). For each load cycle, the load builds up to a load peak and then fails. These peaks are not equal because the ice contains many cracks and flaws so that effective ice strength is very variable. The more load peaks that are included in a series, the probability of a higher value increases. Therefore, the more the ice movement, the higher the load peak that will be captured.

The empirical methods which are based on measured data tend to use the upper envelopes of the measured data implying that many events will not attain the ice loads predicted by them. This does not matter if there are thousands of ice events per year because at least a few of those events will correspond to the upper envelope of the measured data. However, if the structure is in a location with only a few ice events per year, then the probability of attaining an ice load equivalent to the upper envelope defined by the empirical method is reduced. In other words, the ice load is a function of "exposure" which is a function of the number of ice events per year. The number of ice events per year is a function of the amount ice movement past the structure.

To account for this phenomenon, a full probabilistic analysis of ice loads can be undertaken (using variable strength as a statistical input). In ISO 19906 (2019), the issue of exposure is discussed, and examples are given. Results for the Baltic region are shown in Table 2.

A quote from ISO 19906 follows.

"In Reference [130], a probabilistic method is proposed for including the effect of exposure on C_R using temperate data from the Baltic Sea. Exposure was represented in terms of the distance moved by the ice past the structure. Using this approach, C_R values can potentially be scaled based on exposure and applied to different regions of interest."

Table 2: Effect of exposure on strength coefficient (from ISO 19906 2019)

Distance moved by ice (km)	Return period	C_R (MPa)
6	1 year	0.99
6	100 years	1.45
135	1 year	1.34
135	**100 years**	**1.8**
135	10,000 years	2.8
563	1 year	1.49
563	100 years	1.96

The values in Table 2 relate to the Baltic for which the nominal value of C_R is stated as 1.80 for a 100-year event. It can be seen that this is attained with an exposure equivalent to a distance moved by the ice annually of 135km. If the ice only moved 6km, the C_R value would be reduced to 1.45 which is a reduction in the expected load of 20%. (Factor of 0.8)

When considering a dock on the shoreline, it can be appreciated that the amount of ice motion against the dock from offshore is limited by the shoreline behind and adjacent to the dock. Even if the dock is located at the end of a short causeway, a typical distance behind the dock to the shore can be a small as say 100m. For a large ice sheet or floe moving against a dock or terminal a distance S from shore, the amount of ice failing against the dock is also about S. The information given in ISO 19906 on reduction in C_R with lower exposure can be analyzed to look at more limited interaction distances. The 100-year values of C_R are plotted against distance in Figure 4. (This is a log – log plot to give a linear relationship)

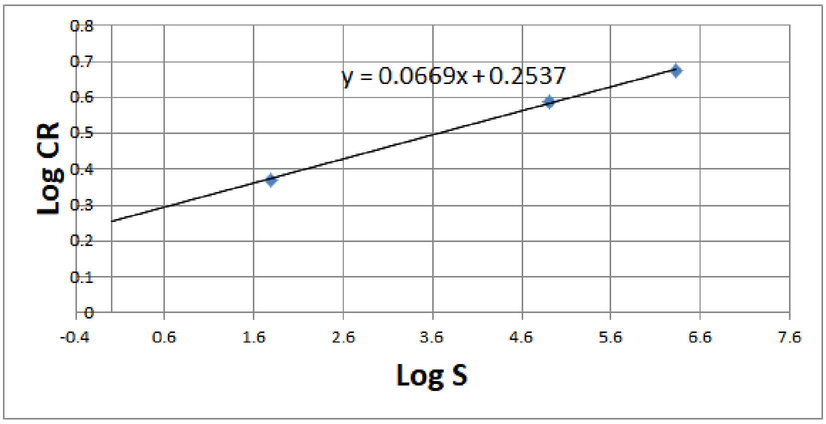

Figure 4: Ice strength coefficient (C_R) vs distance moved during the interaction (S)

The equation for the log – log plot is

$$Log\ C_R = 0.0669\ (LogS) + 0.2537 \quad (2)$$

For a length of interaction of 100m, the value of C_R is 1.1. This is compared to the 100-year value with extensive movement of 1.8 which implies a reduction factor of 0.61. It is assumed that this can be applied to an Arctic situation with C_R value with extensive motion of 2.8 to give a reduced value for C_R of 1.71. The global loads at the end of freeze-up in Table 1 are modified for limited exposure in Table 2.

Table 2: Ice loads for end of freeze-up (accounting for limited ice movement)

	Ice movement distance (m)		10,000	1000	500	100
	Exposure factor		0.84	0.72	0.68	0.61
Structure width (m)	End of freeze up thickness (m)	Global load from Table 1	Global load	Global load	Global load	Global load
		(MN)	(MN)	(MN)	(MN)	(MN)
20	0.6	23	19.4	16.7	15.9	14.3
50	0.6	50	42.0	36.0	34.4	30.8
100	0.6	90	75.2	64.4	61.5	55.2
200	0.6	161	134.5	115.3	110.1	98.9

ICE LOADS DURING MID-WINTER UNTIL BREAK-UP

At the end of the freeze-up period in regions close to shore and in sheltered inlets, the ice becomes “landfast”. However, so-called “landfast ice” can move under thermal strains, ice jacking (as cracks refreeze) and under wind stress. These ice motions are however at low strain rates. Because ice creeps at low strain rates, slow motions are associated with lower ice pressures than when ice moves faster during freeze-up and break-up. Therefore, this period will usually not influence the design ice load.

In ISO 19906 it is suggested that *“For a preliminary assessment of thermal actions, indicative values in the range of 150 kN/m to 300 kN/m can be used regardless of the ice thickness. Thermal actions in freshwater ice are larger in magnitude than those in sea ice”.*

Even using the upper value of 0.3MN/m, an example load on the 200m structure is 60MN which is lower than the loads shown in Table 2. Therefore, this scenario is unlikely to govern.

ICE LOADS DURING BREAK-UP

Overview

In a typical Arctic landfast ice area, the break-up period starts with ice decay due to above freezing temperatures and solar radiation input. As break-up progresses, the nearshore area usually becomes ice-free while ice is still present offshore albeit primarily large broken floes. The ice can be quite mobile due to the actions of winds and currents.

A typical image of large ice floes at break-up is shown in Figure 5. This is for ice in Frobisher Bay but the situation is similar in many Arctic areas. Floes from 500m to 2000m wide and larger are possible. Although not always the case, in a deterministic ice load assessment, it is reasonable to assume that a large floe with sufficient kinetic energy will be driven into the structure and fully envelop it to give the "Limit Stress" condition. If data is available on floe sizes and velocities for a specific location, then a probabilistic analysis can be conducted which may give some relief on the deterministically calculated loads. These deterministic loads should be based on the expected ice thickness and strength at break-up.

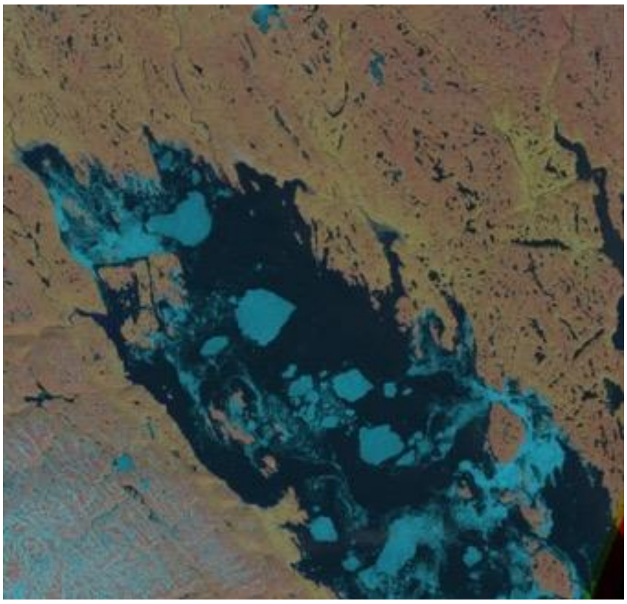

Figure 5: Satellite Image of Ice Conditions in the Northern end of Frobisher Bay on July 16, 1990

Ice Thickness at Break-up

Typical ablation of Arctic ice is shown in Figure 6. It can be seen that thickness at break-up is less than the maximum winter value. These data are for Pond Inlet but similar data exists for other places and represent a typical Arctic location.

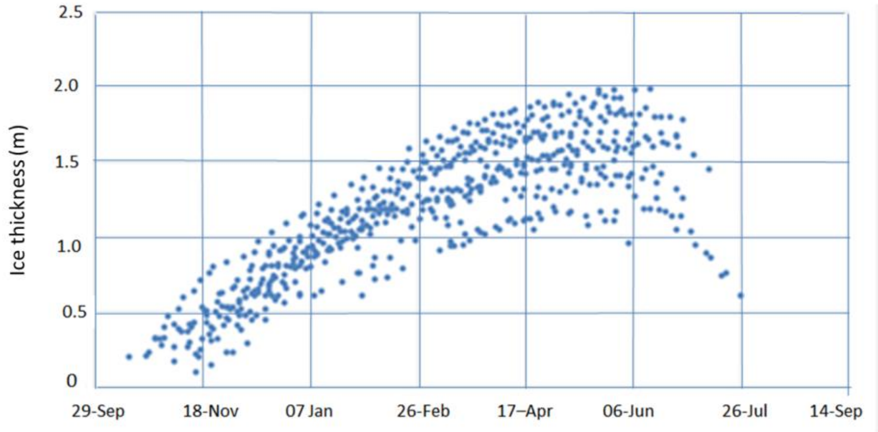

Figure 6: Ice thickness data for Pond Inlet, Canada (1964-1993)

A detailed analysis of ice thickness data has been conducted for Pond Inlet. The 100-year maximum thickness is 2.05m. Break-up at Pond Inlet usually occurs after about July 10th. Table 3 shows the data available for those years with measurements after July 10th. The winter maximum thickness and thickness just before break-up are shown together with a thickness reduction factor. The average reduction factor is 0.69.

Table 3: Thickness reductions at break-up (Pond Inlet, Canada)

Year	Max h (m)	h (m) (July 10 on)	Reduction factor
64-65	1.4	0.9	0.64
67-68	1.4	0.6	0.43
84-85	1.9	1.25	0.66
85-86	1.65	1.45	0.88
86-87	1.9	1.5	0.79
87-88	1.5	1.1	0.73
		Average	0.69

Applying this factor to 2.05m gives a 100-year thickness for design at breakup of 1.4m.

We can also reference the work of Timco and Johnston (2002), who studied ice ablation and strength reductions. Their measurements at Resolute in 2001 are shown in Figure 7. These indicate maximum winter thicknesses of about 1.5m that year and the last thickness measured at about 0.8m, which is a reduction factor of 0.53. If this is applied to the “100-year” value of 2.05m, a thickness of 1.1m results. In this example the more conservative value of 1.4m is used.

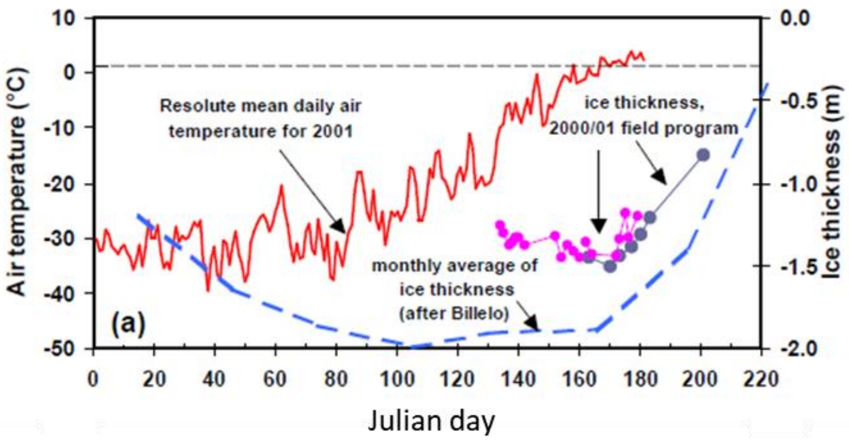

Figure 7: Measurements of ice thickness at Resolute by Timco and Johnston (2002)

Ice Strength Reduction

The next key issue is the crushing pressure applied during this period. Equation 1 (from ISO 19906) will continue to be used, but with some adjustment to the strength factor C_R.
ISO 19906 allows an adjustment for C_R based on a comparison of strength for the scenario in question with the implied strength of cold Arctic ice (for which C_R=2.8 applies).

It is well proven that ice strength reduces with higher temperature and porosity. With sea ice, porosity is dominated by brine volume which for a given salinity also increases with higher temperature. Table 4 is reproduced from ISO 19906 (2019) for the adjustment of strength.

The ISO method suggests dividing the ice thickness into layers, developing temperatures and salinities for each layer for the scenario being examined, then calculating C for each layer. The average of C through the thickness is the strength index, σ.

Table 4: Ice strength coefficient vs brine volume (ISO 19906: Table A.8-5)

Brine volume	0.001	0.010	0.025	0.050	0.100	0.200
C (MPa)	8.4	6.0	3.4	1.6	1.0	0.8

Brine volume can be calculated using Eq. A6-7 in ISO19906 (2019) and is a function of ice temperature and salinity. At break-up when the ice becomes mobile it is assumed that the ice has become isothermal through its thickness with a typical temperature of -2^{o}C. A typical salinity for sea ice is 6 parts per thousand. Using these values gives a brine volume of 0.15. Looking at Table 4 indicates that the corresponding value of C is about 0.9MPa. For the assumed uniform temperature profile at break-up, the average strength index σ will be the same as this value of C. In ISO it is further stated that the value of σ which corresponds to a C_R of 2.8MPa is 2.86MPa. Therefore the reduction factor on the Arctic C_R value of 2.8 at break-up in this case will be = 0.9/2.86) = 0.32.

ISO also states that in-situ borehole jack tests can be used as a strength index. Such tests were conducted by Timco and Johnston (2002). Their measurements at Resolute in the Canadian Arctic are shown in Figure 8. These results would justify an even lower strength factor than the 0.32 value. In the data plot, the borehole strength by early July was about 0.1 of its mid-winter strength.

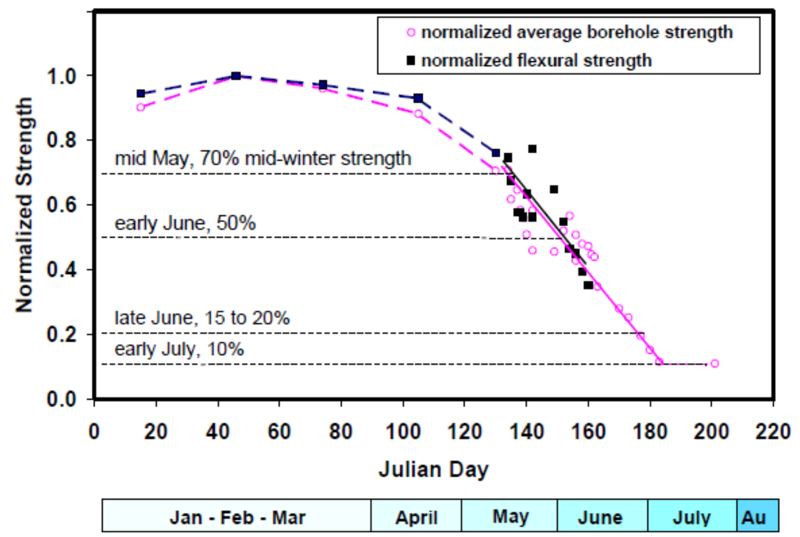

Figure 3: Comparison of normalized ice borehole strength and calculated flexural strength as a function of the Julian Day

Figure 8: Sea ice strength reduction at break-up (Resolute – Canadian Arctic) (Timco and Johnston, 2002)

To be conservative the strength reduction factor of 0.32 is retained so the value of C_R for Arctic cold ice of 2.8 is effectively reduced to 0.90 at break-up. The ice loads for this scenario based on a value of C_R of 0.90 and an ice thickness of 1.4m are shown in Table 5.

An exposure factor reduction can also be incorporated using the same rationale as in the freeze-up period; that is, the amount of motion possible before the floe is stopped by the shoreline. These loads are also shown in Table 5. In this scenario, additional checks can also be made using the "Limit Energy" approach to calculate the distance to stop the floe. In this example, to be consistent with the freeze-up cases, the same ice movement values are used to assess exposure effects. Invoking Limit Energy can only reduce these distances.

Table 5: Ice loads for break-up (also accounting for limited ice movement)

Break up		Strength factor	0.32	See derivation based on temp. and brine volume			
		Cr	0.90	With exposure effect Ice movement distance (m)			
		n	-0.3				
		m	-0.16	10,000	1000	500	100
			Factor	0.835	0.716	0.684	0.614
Structure width (m)	Thickness (m)	Arctic warm	Load	Load	Load	Load	Load
		p (MPa)	(MN)	(MN)	(MN)	(MN)	(MN)
20	1.4	0.53	14.82	12.4	10.6	10.1	9.1
50	1.4	0.46	32.00	26.7	22.9	21.9	19.6
100	1.4	0.41	57.28	47.8	41.0	39.2	35.2
200	1.4	0.37	102.53	85.6	73.4	70.1	62.9

SUMMARY OF COMPARISONS AND CONCLUSIONS

First it is useful to look at how the loads for each period through the winter compare without the exposure effect. This is done in Table 6. These loads are deterministic but using nominal "100-year thickness values" for the end of freeze-up and break-up.

Table 6: Summary of global loads for the three ice periods of the winter

Global Loads (MN) (deterministic)				
Structure width (m)	Period			Max h & C_R
	Freeze -up	Stable	Break-up	
20	23	6	15	64
50	50	15	32	139
100	90	30	57	248
200	161	60	103	445

Also shown in the table is a column labelled "Max *h* and C_R". These are loads based on using the maximum level ice thickness during the winter combined with the Arctic value of C_R of 2.8. Using such loads would be incorrect for nearshore structures which experience stable ice during the mid-winter period. Table 6 shows that the freeze-up period is likely to give the controlling ice load for design. In this example the load is based on an ice thickness at the end of freeze-up of 0.6m. This compares with this region's 100-year value for first year ice of 2.05m. If such a thickness was used by an uninformed user in Equation 1 the apparent design load would be about three times higher. As reviewed in ISO 19906, if a probabilistic approach is used for the ice strength coefficient then its value will be a function of the number of ice events. These are a function of the annual amount of ice movement past a structure, an effect called exposure. For a nearshore structure exposure can be limited by the presence of the shoreline or just by event probability. A summary of loads including this effect for a nearshore Arctic structure is given in Table 7. (An exposure distance of 500m is used).

Table 7: Global loads with an exposure correction (500m of ice motion)

Global Loads (MN) (exposure correction - 500m)				
Structure width (m)	Period			Max h & C_R
	Freeze -up	Stable	Break-up	
20	16	6	10	64
50	34	15	22	139
100	62	30	39	248
200	110	60	70	445

In this case, the design ice loads are about four times lower than the use of Eq. 1 with maximum winter thickness and the ISO specified winter strength value for the Arctic. A significant part of the reduction is because the ice movement against nearshore structures (such as a dock) can be limited by the shoreline behind the structure. This obviously depends on the specific location and should be assessed accordingly. If during the ice movements of freeze-up and break-up it is considered that several events of ice motion against the structure could occur, then it is the annual total ice motion that should be used in Eq.2. It should also be noted (as discussed in Palmer and Croasdale, 2013 – Ch.5.6) that in shallow water the build-up of grounded ice rubble can also reduce ice mobility and corresponding exposure to ice loads.

The level of strength reduction at break-up is subject to some uncertainty. The borehole jack data implies a very significant lowering of strength (lower than the value of 0.3 actually used in this work). It can be noted that the strength reduction could be as high as 0.5 before the load at freeze-up no longer controls the design ice load. There is an opportunity for further research in the area of ice loads at break-up. Ideally this would be sets of measured ice load data on actual platforms through this period.

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