POAC11-063

ISO 19906 ICE CRUSHING LOAD DESIGN EXTENSION FOR NARROW STRUCTURES

Mauri Määttänen[1], Tuomo Kärnä[2]
[1]Aalto University, Finland / NTNU, Norway
[2]Karna Research and Consulting, Finland

ABSTRACT

For ice crushing against a vertical structure the application of the new ISO 19906 ice load design code is limited to structures having their width larger than twice the ice thickness (larger than 2 aspect ratio). However, in sub-arctic environment many offshore structures fall well below this aspect ratio limit. To cover this handicap an adjustment to the ISO crushing requirement is proposed. Over 35 year long ice load design practice and subsequent in-field experience of Finnish aids-to-navigation is compared to ISO crushing load design. With decreasing aspect ratio the ISO approach would have resulted in unsafe design. The reason can be attributed to the too weak aspect ratio effect in the ISO database derived from measurements on wide structures. With a simple aspect ratio effect correction the ISO method can be extended also to narrow structures.

INTRODUCTION

ISO 19906 Arctic Offshore Structures ice load code was sent in December 2010 to the ISO member countries for final vote: accept or not to accept. The code development started in 2002, originally only for petroleum and gas structures in the Arctic, but soon the application area was expanded to cover sub-arctic waters and other than oil and gas related offshore structures as well. The initial starting point brought with it a comprehensive ice actions database for thick ice and wide structures. Due to the relatively sparse measurement database of well documented ice loads against offshore structures in sub-arctic regions, a lot of effort was given to utilize quite recent good quality data measured in the EU LOLEIF and STRICE projects from the Norströmsgrund lighthouse located in the Northern Baltic. These data were combined with the North American arctic data in order to have a unified crushing load design method.

While more temperate application areas were included the size of application structures diminished, especially the aspect ratio: the width of the structure at waterline divided by ice thickness. As the available good quality database did not include narrow structures, the ISO crushing load application area was limited to aspect ratios above 2. However, the data from Norströms-grund never reached close to this limit. The waterline diameter was 7.6 m including the load panels and during the measurement years the level ice thickness was less than 0.6 m - with thicker but weaker rafted ice being omitted. If narrow panel data from Norströmsgrund is used, the ice action geometry at panel width is close to 2-dimensional state giving less constraint compared to the three dimensional state of stress at low aspect ratios. Hence the real aspect ratio in the data for ISO crushing load is above 10.

The database on ice load measurements in offshore structures with low aspect ratio is sparse. Masterson et al. (2000), presented an overview on aspect ratio effects, including measurement data from Cook Inlet at aspect ratios below five, Blenkarn (1970), and a theoretical reasoning based on Prandtl's plastic limit analysis model. As the largest ice loads are expected at the ice failure transition zone from ductile the brittle, a plastic limit analysis is a questionable starting point. Field data on bridge piers, e.g. Neill (1976), on the other hand, is mostly related to ice discharge with rivers at high strain rates. The largest ice loads measured by telemetry system, e.g. 4.4 MN, Määttänen (1987), with an estimated aspect ratio close to one, but without the data of actual ice conditions, are not directly applicable for design database.

In Finland the first steel lighthouses collapsed in the early 1970's when the aspect ratio effect was not observed correctly. With this in mind the new ISO 19906 crushing ice load is now compared to the present in field proven successful practice in designing lighthouses and channel edge markers that have typical waterline diameter close to 1 m while the ice can be thicker. Hence aspect ratios below 1 are common. The comparison indicated that at low aspect ratios the ISO approach ends up into unsafe design. This paper presents the results of comparisons and a proposal to add a stronger aspect ratio effect to the ISO crushing load determination.

FINNISH DESIGN PRACTICE

The design practice in Finland for caisson type lighthouses at the beginning of the 1970's was based on an in field proven requirement of 1 MN/m horizontal ice load. This was doubled to 2 MN/m for much narrower steel lighthouses at waterline. However, this was not enough. The first steel lighthouses failed due to ice action in severe ice conditions in the Gulf of Bothnia, the first one, Kemi-1 during the first winter, and the sister lighthouse Nukkujan matala, after withstanding four winters. In addition four simpler steel channel edge markers failed as well.

In 1975 more stringent deterministic design requirements for narrow steel aids-to-navigation were set. The structures with a circular cross section had to withstand horizontal ice loads based on an average level ice pressure p = 2.25 MPa, and multiplied by the aspect ratio effect, which is based on measurements by Korzhavin (1962), and expressed by the equation of Afanasiev (1972):

$$F = pwh\sqrt{1+5\frac{h}{w}} \tag{1}$$

where w is waterline diameter and h level ice thickness. Compared to the original design, Eq. 1 with aspect ratio D/h=1 would have increased the design ice load 2.45 times.

The last Finnish caisson lighthouse, with waterline diameter of 5.8 m, was constructed in 1975 to replace the steel lighthouse Kemi-1 that failed in spring 1974. Thereafter only narrow offshore steel lighthouses (and other aids-to-navigation structures) with waterline diameter around 1 m – about the same as the expected maximum level ice thickness – have been built at the cost of less than one third compared to a caisson type foundation. A total of more than 100 of these structures have already experienced cumulatively more than 2000 winters without any failure due to static ice load while designed according to Eq. 1. Some first generation fixed bottom founded channel edge markers experienced also fatigue failures due to ice-induced vibrations, but this was cured at the beginning of 1980's as the requirement to design for dynamic ice loads was adopted. The ISO 19906 dynamic ice load design criteria in crushing are based on these design principles.

To compare the design ice loads provided in ISO 19906 (Eqs. A.8-20. A.8-21) to the present Finnish aids-to-navigation structures design practice, over 80 design cases are plotted as a function of aspect ratio in Fig 1. The structures are located along the Finnish fairways at water depths from 4 to 16.5 m. The included structures are either at moving ice zone or at the land-fast ice zone where, however, occasional level ice movements can occur. As the level ice at the land-fast zone is thicker the aspect ratio will be smaller. The ice data is based on long-term statistics, Palosuo et al. 1982 covering years 1920-1980, and Seinä, 2010, for extension up to year 2010. The data points in Fig. 1 are based on ice thicknesses varying from 0.40 to 0.80 m for moving ice and from 0.65 to 1.20 m for land-fast ice.

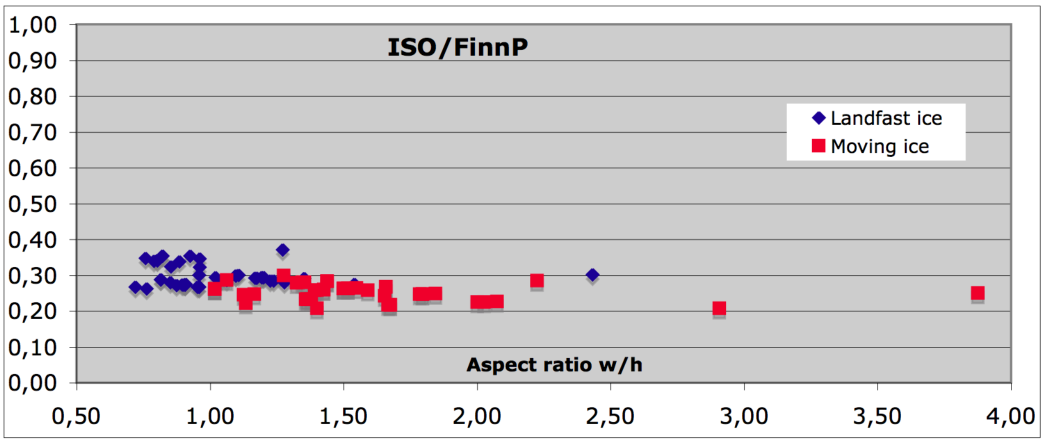

Figure 1. The ratio of ISO crushing load to Finnish practice

The ISO ice load predictions falls in average to less than one third from those according to the in-field proven successful design practice. Even though the ISO limits the aspect ratio above 2, there are still many data points that suggest too low design loads. The resulting ISO ice crushing load being less than 1:3 from the Finnish design practice is too small to be explained by the fact that none of the design cases in Fig. 1 have suffered damage due to excessive ice action, an indication of too conservative design.

Practically all the data points in this paper derived from the Finnish aids-to-navigation structures present compliant structures. No additional ice load increase due to compliance effect, as proposed by Kamesaki et al. (1996), is taken into account in utilizing ISO crushing load design, or Finnish practice. Hence the comparisons are at even basis.

FAILED OFFSHORE STRUCTURES IN THE NORTHERN BALTIC

In order to judge from the practical experience whether ice load design requirements are correctly set one needs to know both the loads and the true structural capacity. The loads have a large statistical variation from year to year. In most cases the properties of structure and foundation have less statistical variation. A successfully designed structure with a typical structural factor of safety 1.5 will not indicate how close to its deterministic design load it has been. E.g. the infield experience of using Eq. 1 in Finnish aids-to-navigation structures gives only an indication of a too stringent design. But a detailed failed structure “post mortem” analysis including both the loads and structural performance gives a more solid fix at which side of the design envelope the structure in question has been.

Only nine reasonably documented failure cases could be found for comparison, six from Finland and three from Sweden, Table 1. In most cases after the failure the true ice thicknesses were measured. Exceptions are Kemi-1 and Nukkujan matala where the ice thicknesses are based on the general ice thickness in the area. In the first Finnish steel aids-to-navigation structures the failure mode was plastic buckling of the foundation pile close to the sea bottom. The reason for under-dimensioning was mainly due to the non-sufficient aspect ratio effect. In channel edge markers AR1, R3 and L64 an additional factor was the unexpected movement of thick land-fast ice. Even if the applied structural safety of 1.5 is fully utilized, the ISO ice load design would not have been adequate to prevent failures. With Björnlack and Borussiagrundet the rafted ice thickness exceeded even the long term statistics of level ice thicknesses.

Table 1. Structures failed under ice action in the Northern Baltic

	Failure year	Water depth	Landfast ice	Moving ice	Ice at failure	w MWL	Failure load	$Finn_{MOVING}$	$F_{LFISO}(K3)/F_{FAILURE}$	$F_{MISO}(K3)/F_{FAILURE}$	$F_{ISO}/F_{FAILURE}$	w/h	Failure mode
Failed struct.		m	m	m	m	m	MN	MN	-	-	-	-	
Tainio	1966	9,0	0,80	0,45	0,80	3,50	6,00	4,54	1,00	0,52	0,72	4,4	Sliding
Kemi-1	1974	12,0	1,00	0,80	0,93	1,18	4,40	4,45	1,22	0,89	0,44	1,3	Plastic buckling
Nukkujan matala	1974	11,0	1,00	0,80	0,90	1,18	4,40	4,45	1,22	0,89	0,43	1,3	Plastic buckling
AR1 Ristilänsi	1974	11,5	1,10	0,45	0,90	1,12	4,40	1,97	1,36	0,40	0,41	1,2	Plastic buckling
RM3	1974	8,5	1,10	0,45	0,95	0,90	3,70	1,70	1,46	0,43	0,43	0,9	Plastic buckling
L64	1974	5,2	1,10	0,45	0,95	1,30	4,40	2,18	1,46	0,43	0,49	1,4	Plastic buckling
Nygrån	1969	5,0	1,00	0,80	0,90	2,50	4,00	7,26	1,82	1,32	0,89	2,8	Breaking
Björnlack&Borussiag	1985	6,9	1,00	0,80	1,40	2,90	10,9	8,05	0,70	0,51	0,55	2,1	Sliding

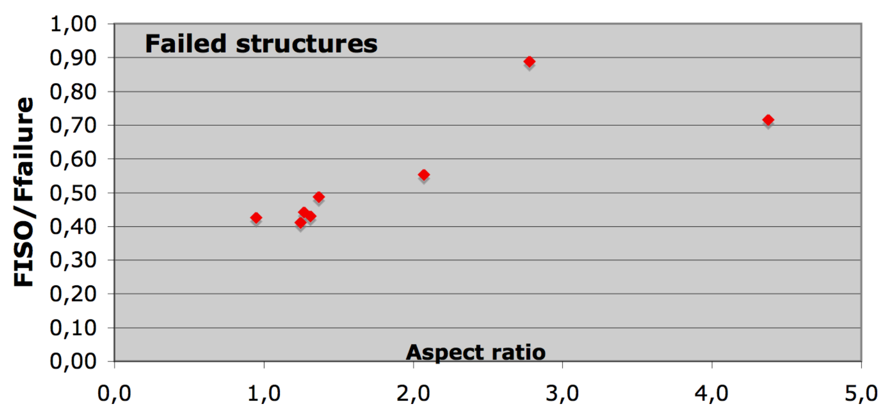

Figure 2. The ratio of ISO crushing load to the structural failure load

EARLIER DATA ON THE ASPECT RATIO EFFECT

Early studies on the loads due to ice crushing were made in the 1970s on narrow structures. Comparisons were made between the loads using a coefficient *k* that describes the effect of the aspect ratio. Afanasiev et al. (1972, 1973) used data that yielded this coefficient as given earlier in Eq. 1.

Further data published by Schwarz et al. (1974), Saeki et al. (1979) and Mirzoev (1992) is presented in Figs. 3 and 4. In Saeki's data both the ice thickness and the width of the structure varied. The ice thickness influences the global pressure independently from the aspect ratio. Therefore, Saeki's data will be represented by his model, which states that the global pressure varies with the aspect ratio *w/h* as

$$k_{SA} = C\sqrt{\frac{h}{w}} \qquad (2)$$

where *C* is a constant. All data on the aspect ratio parameter *k* were normalized to give for the aspect ratio value of $w/h = 1$, a value of $k = 2.45$ as in Afanasiev's model. Regardless of possible scale effects due to thin ice in scale model test measurements in Fig. 3, also these data sets verify the similar aspect ratio dependence that has been learned in full-scale data.

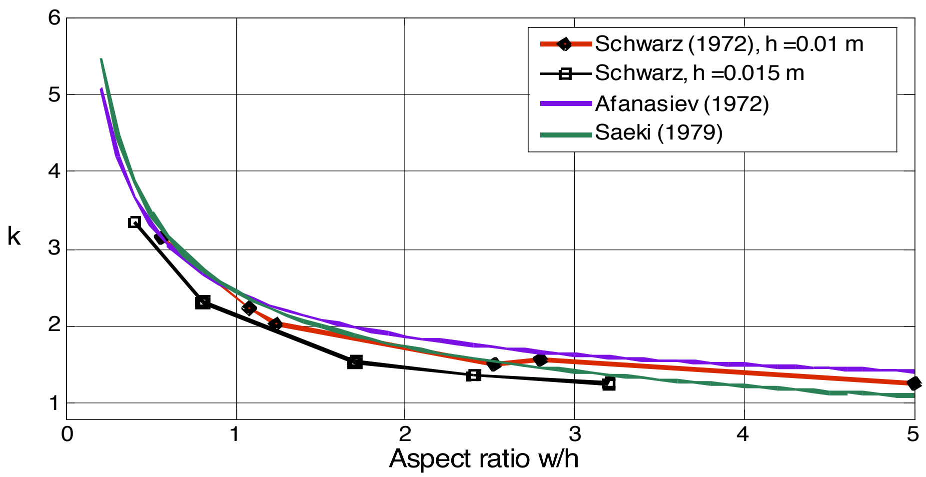

Figure 3. Schwarz's scale model data, ice thickness *h*=10 and 15 mm, correlation to Afanasiev and Saeki models.

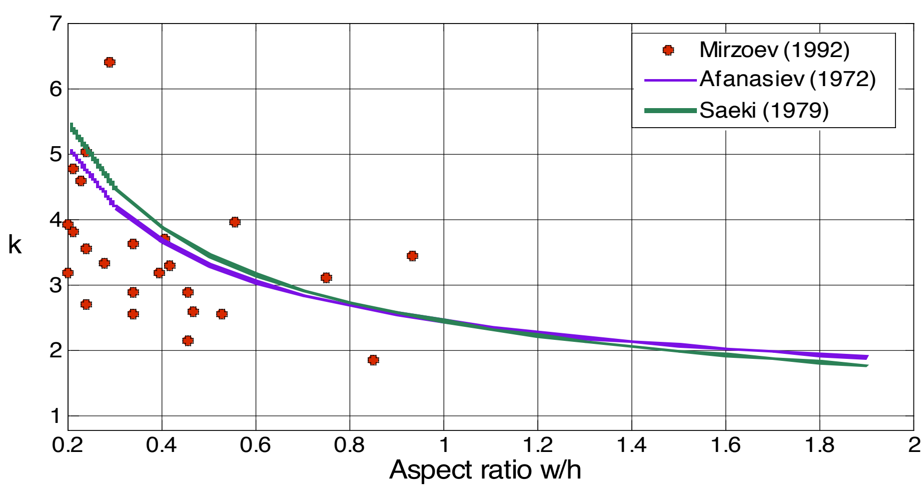

Figure 4. Mirzoyev's sea ice full-scale data, *h*=350 – 500 mm, correlation to Afanasiev and Saeki models.

According to ISO 19906, the global pressure varies with the aspect ratio as $w/h^{-0.16}$. The data shown in Figs. 3 and 4 reveal that the real aspect ratio effect is significantly stronger in the range of $w/h < 2$.

ASPECT RATIO EFFECT ENHANCEMENT

Both the successful and failed structures in the Northern Baltic indicate a severe danger of ISO 19906 determined ice crushing load to result into unsafe structural design in the case of low aspect ratio applications – even at the range of ISO validity above aspect ratio $w/h>2$. In sub-arctic climate many structures are at the aspect ratio range $w/h\approx 1$. To cover these pitfalls a modification is proposed to the ISO crushing load equation by adding the classical Afanasiev's aspect ratio effect and making it to decay exponentially with increasing aspect ratio, the third term in Eq. 4.

$$F_G = p_G \, h \, w \tag{3}$$

$$p_G = C_R \left(\left(\frac{h}{h^*}\right)^{-0,5+\frac{h}{5h^*}} \left(\frac{w}{h}\right)^{-0,16} + e^{\frac{-w}{3h}} \sqrt{1+5\frac{h}{w}} \right) \tag{4}$$

with the symbols as in ISO 19906:

p_G effective ice pressure, MPa;
w structure width under ice action, m;
h ice thickness, m;
h^* reference thickness = 1.0 m;
m experimental constant = -0.16;
n experimental constant
= $-0.50 + h/5$ while $h < 1.0$ m
= -0.30 while $h \geq 1,0$ m
C_R ice reference strength, MPa, for subarctic climate.
=1.8 MPa circular cross section
=2.0 MPa straight wall

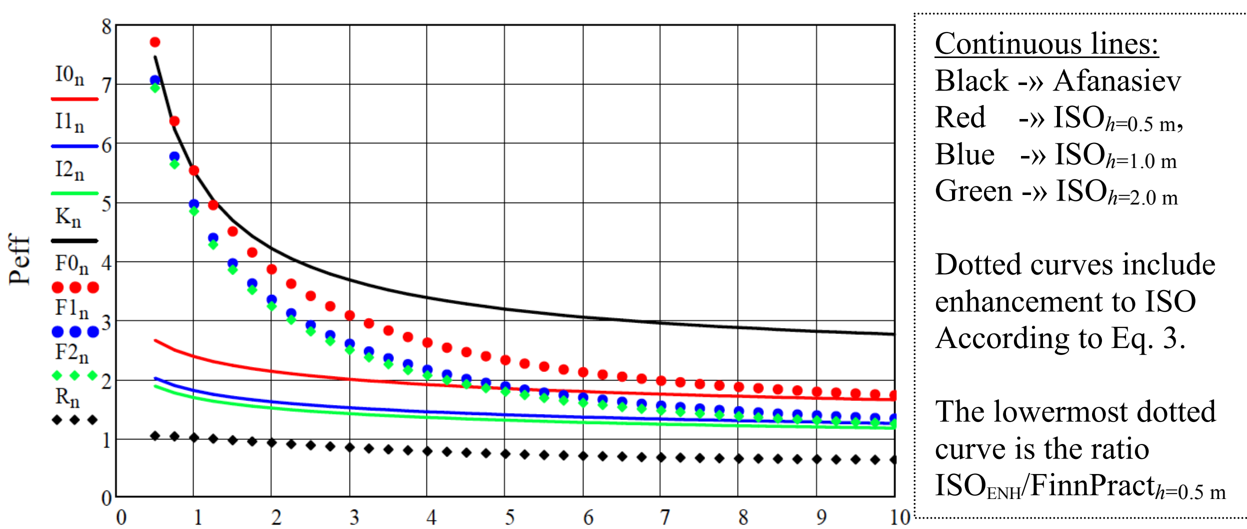

Figure 5. Effective pressure vs. aspect ratio *w/h*.

Fig. 5 presents the effect of enhancement in Eq. 4 as a function of aspect ratio *w/h* for three ice thicknesses *h*=0.5, 1.0 and 2 m. The reduction of effective pressure 2.25 MPa in the Afanasiev equation to the reference strength C_R=1.80 MPa in the enhanced ISO crushing load equation results from the fact that the original ISO crushing load already includes some aspect ratio effect. At aspect ratio *w/h*=1, depending on ice thickness, almost the full classical aspect ratio effect is achieved. At aspect ratio *w/h*=10 the effect of enhancement has no significant effect. At the ISO application range lower limit *w/h*=2 the increase in the effective pressure p_G is already significant.

For arctic structures there is only a minor increase in the design ice load due to the proposed enhancement. First, with thick ice the ISO crushing load built in size effect reduces effective crushing pressure, cf. Fig. 5, secondly, in the Arctic the typical aspect ratios are larger than 5, and thirdly, no thick ice full scale data are available for low aspect ratios. With this in mind the proposed enhancement opens the ISO crushing load application to all structures in arctic and subarctic regions.

With the aspect ratio enhancement the comparison of ISO to the present Finnish design practice in Fig. 1 changes to that in Fig 6. Now with small aspect ratios the ISO ice crushing load prediction is only slightly reduced from the level that the established infield proven Finnish practice has utilized. As there has not been any failures in these offshore structures after about accumulated 2000 winters under ice action it can be concluded that a small reduction also in Finnish practice design ice loads is justified.

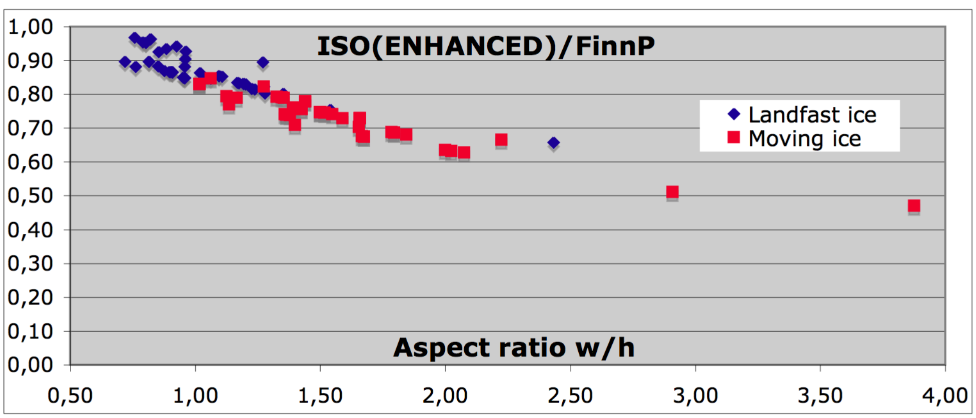

Figure 6. The $ISO_{Enhanced}$ ice load/FinnPractise design ice loads

Table 1 gives also the ratios of enhanced ISO design ice loads to the “post mortem” calculated structural failure loads both at moving level ice and land-fast ice thicknesses. The predicted enhanced land-fast ice load exceeds in all but in Björnlack and Borussiagrundet cases the estimated true failure load. The predicted enhanced moving ice loads in all but in the Nygrån case are smaller than failure load in thinner moving ice. This raises a question whether the structures should always be designed for land-fast ice thickness regardless of what is the probability of land-fast ice movement. The analysis of failed structures clearly demonstrates that at low aspect ratios the original ISO crushing load is not adequate but with the proposed enhancement and with choosing the land-fast ice thickness the enhanced ISO crushing load is safe.

CONCLUSIONS

The limitation of ISO ice crushing load application only for aspect ratios above two leaves almost all sub-arctic offshore structures outside the possibility to utilize ISO 19906 code. Also the measurement data, which are the base for ISO ice load design below aspect ratio 10, is questionable due to lack of true three-dimensional geometric similitude.

At aspect ratios close to one, comparison to the established Finnish design practices for aids-to-navigation structures, the analysis of failed structures in the Gulf of Bothnia, and scale-model test data indicated that the ISO 19906 does not observe the aspect ratio adequately in its crushing load equation.

A simple enhancement, adding an exponentially with aspect ratio decaying Afanasiev aspect ratio term into the ISO crushing load equation results in a robust crushing equation that covers the whole aspect ratio range from below one to infinity. This removes the limitation of aspect ratios and makes the ISO 19906 ice crushing code applicable to all structures from arctic to sub-arctic regions.

The unlikely movement of thicker than statistically determined land-fast ice has been the most common reason for the failed structures. The proposed enhanced ISO crushing load based on land-fast ice thickness would have been adequate to prevent most of these structures. In any case more reliable moving ice thickness data at land-fast ice zone is needed.

REFERENCES

Blenkarn K. A, 1970: Measurement and analysis of ice forces on Cook Inlet structures. Proc 2nd OTC, Houston Texas, Vol.2, pp. 365-378.

Afanasiev, V.P., Dologopolov, I.V. and Shvayshteyn, Z.I., 1972: Ice pressure on separate supporting structures in the sea. CRREL Translation 346. April 1972. 20 p.

Afanasiev, V.P., 1973: Ice pressure on vertical structures. Technical Translation 1708. National Research Council Canada. Ottawa. Canada. 6 p.

ISO 19906, 2010: Petroleum and natural gas industries - Arctic offshore structures.

Kamesaki, K., Yamauchi, Y. and Kärnä, T., 1996: Ice force as a function of structural compliance. Proc. 13th IAHR Ice Symposium, Beijing 1996. Vol. 1, pp. 395-402.

Korzhavin, K., 1962: “Action of Ice on Engineering Structures”, Draft Translation 260, US Army CRREL, Hanover, NH

Masterson D., and Spencer P., 2000: Ice force versus aspect ratio. Iutam Symposium ”Scaling Laws in Ice Mechanics and Ice Dynamics”, Fairbanks, AK, USA, 13-16 June, 2000.

Mirzoev, D.A., 1992: Ice resistant structures for hydrocarbon development in shallow-water areas. VNIPI Morneftegaz, Moscow, 1992, pp. 80-91.

Määttänen, M., 1987: Ten Years of Ice-Induced Vibration Isolation in Lighthouses. Proc. 6th International Offshore Mechanics and Arctic Engineering Symposium, Houston, Texas, March 1-6, 1987, Vol. 4, pp. 261-266. The American Society of Mechanical Engineers.

Neill C., 1976: Dynamic ice forces on piers and piles. An assessment of design guidelines in the light of recent research. Canadian Journal of Civil Engineering, Vol. 3, pp. 305-341.

Palosuo E., Leppäranta M. and Seinä A., 1982: Formation, thickness and stability of fast ice along the Finnish coast. Research Report No 36. Winter Navigation Research Board.

Saeki, H., and Ozaki, A., 1979: Ice forces on piles. Proc. IUTAM Symposium "Physics and Mechanics of ice. Copenhagen, August 6-10, 1979. Ed. Per Tryde, Springer, Berlin 1980. pp. 342-350.

Schwarz, J., Hirayama, K.I. and Wu, H.C., 1974: Effect of ice thickness on ice forces. Offshore Technology Conference, Houston, TX, USA, Paper no OTC 2048.

Seinä, A., 2010: Ice service. Proc. ICT services for environmental safety and security in the Baltic Sea. Helsinki, 12 April 2010.