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ICE LOADS FOR WIND-POWER FOUNDATIONS IN THE GULF OF BOTHNIA

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ABSTRACT
Ice loads measured on lighthouses in the Gulf of Bothnia can serve as guidance for design of foundations for wind-power generators. At some locations in the sea these structures must withstand high pressure from solid land fast ice as well as from ridges or other compacted ice masses that are drifting. Recommendations for design of offshore foundations around the Swedish coastline have recently been written by the authors. For the purpose of design, effective pressure as well as compressive strength is assumed to be independent of ice thickness. All structures should be designed for dynamic ice loads that are dependent on the natural frequency of the structure and the ice drift velocity. Increased effective pressure has earlier been indicated for high speed ice crushing both in field studies and compression tests. The presented results from ice load measurements on lighthouse Norströmsgrund support the suspicion that also design ice loads should increase with drift speed. This rate effect and other uncertainties about the worst case scenario for ice-induced vibrations suggest a more conservative design of wind-power foundations inside the dynamic ice zone.

INTRODUCTION
Ice conditions in the Gulf of Bothnia
Many hundred years of documentation shows that the Gulf of Bothnia has been ice covered, at least a short part of the winter, mainly in March. When studying sea ice in the Gulf of Bothnia one must distinguish between fast ice and moving ice. Fast ice is even level ice covers frozen to the coast and locked in by the extensive archipelago. It occurs mostly inshore from the 5-15 meters depth curve. This ice develops rather fast during the freezing period and will then be rather still during the rest of the ice season. Haapanen et al. (1997) point out that in the Eastern Gulf of Bothnia the land fast ice will stop moving when it has become thicker than around 0.3 m, and although it later in the season may become 0.8 m thick and sometimes up to 1.3 m it is assumed to lie still until it starts moving again in the spring. It is then deteriorated and the loads on structures may not be so large. According to Haapanen wind power plants should only be built in areas known to have land fast ice.

In contrast the moving ice in the central area is of dynamic nature and usually deformed. During severe storms it can move 20 – 30 km in a day. Ice floes of up to several kilometres diameter are interrupted by leads and wakes. In the middle of the winter the open water will freeze fast and new ice will form. The deformation process causes bands of ice fragments, hummocked ice and ice ridges. The compacted ice pack often freezes together and bands of thick ice, thicker than the snow covered fast ice, are formed.

Load from ice press

In a recently written recommendation for ice design of offshore structures in Swedish waters (Fransson & Bergdahl, 2009) much emphasis have been put on separations of different ice failure mechanisms. Assume first a scenario in which a large ice cover has been formed and grown thermally in thickness around a structure. We must then first consider the load at the onset of ice motion caused by e.g. thermal expansion, wind or on-setting currents. Static ice loads on a structure will often reach a maximum after the ice has been partly crushed and is about to move. If the contact between ice and the structure is smooth the stress distribution becomes rather uniform after a certain loading time due to viscous creep and creep crushing. According to plasticity theory the highest stress level is a function of yield strength of the ice and the degree of confinement around the structure. Static ice pressure is most likely independent on size of the pressure area if the confinement is constant. If this is the design situation it is possible to calculate ice loads on fixed structures with FE-analysis (e.g. Sand, 2008).

If the driving force is sufficient, ice floes are crushed against vertical structures when they are moving. The driving force in the Gulf of Bothnia comes from the wind and the drifting velocity is about 3% of the wind velocity, usually less than 0.6 m/s. The prevailing low-saline ice is extremely brittle even close to the melting point and thus brittle ice crushing is the most common failure mode. Fracture mechanical behaviour implies that the process is highly dynamic causing substantial vibrations to almost any structure in interaction. These vibrations may lead to ice-induced resonant oscillations on flexible structures. Such oscillations are only limited by the damping in the system and may cause a total collapse of an otherwise stable structure. The classical engineering approach to ice loads is empirical, e.g. studies of the variations of the effective ice pressure $p_{eff} = F/(Lh)$ defined as the ice load F divided with the contact width L and the ice thickness h. Even if the ice quality and temperature are kept constant it has been found that the effective pressure becomes quit different depending on load situation. This is a serious problem when writing recommendations and a source of dissension.

Ice crushing experiments with transparent indenters have shown that high pressure zones develop at the centre of the contact area (Joensu & Riska, 1988). The maximum pressure in these small zones is probably limited only by pressure melting. Average pressure over a large contact area is typical less than 1/10 of these peak pressures. The impact of a strong pressure gradient on the contact area seems to be the key to brittle crushing. Fransson & Stehn (1993) proposed that the load from ice edge crushing is limited due to horizontal cleavage cracks in front of a vertical structure. The effective pressure under similar stress concentrations is then proportional to $h^{-0.5}$. Such dramatic dependence of the ice thickness can be found just by plotting the results from field measurements. Major fracturing is however only one of many mechanisms that are involved when an ice sheet is passing a structure. For narrow structures the aspect ratio is the most important factor and must always be considered when selecting the effective pressure. Wide structures (wider than usual foundations) imply that a larger volume of ice is involved in the crushing process and one might expect some type of size effect. It is also possible that the ice thickness has an effect on the effective pressure and this question is closely linked to the influence of pressure area. Full scale measurements have shown that the effective pressure decreases with pressure area but this is more likely to be a result of non-simultaneous pressure peaks on different contact spots on the structure.

FULL-SCALE MEASUREMENTS ON LIGHTHOUSE NORSTRÖMSGRUND, IN THE GULF OF BOTHNIA

Static pressure

In the European research project "Validiation of Low Level Ice Forces on Coastal Structures" (LOLEIF), ice loads on the lighthouse Norströmsgrund in the Gulf of Bothnia were measured simultaneously on nine panels covering about half the periphery (LOLEIF database, 2008). When data from the season 2000, was reanalysed it was found that the highest pressure over the whole winter (625 kN/m) was reached April 3 at the onset of ice movement. The local ice thickness was measured to 0.7 m in direct contact with the lighthouse foundation but the average level ice was probably much thinner.

Ice crushing

Results from LOLEIF also showed that the dynamic ice loads most of the time were uncorrelated on pairs of load panels that were separated from each other. One interesting problem was how to calculate the global ice load on the cylindrical structure. The panels could only measure compressive load perpendicular to the surface and they did not cover all the ice action. These shortcomings made global load estimations quit unreliable, but measured loads could be divided with the assumed contact width and load readings were well synchronized due to the used sampling method with parallel a/d converters. A log-log plot of measured ice pressures is shown in Figure 1 as a function of contact width *L*. On 1 m contact width a maximum pressure of 380 kN/m was estimated, whereas the pressure decreased to 165 kN/m for 10 m contact width. The typical level ice thickness was measured continuously with an echo-sonar to about 0.25 m during this period. Thicker ice was also in contact with the lighthouse but these ice fields were broken into smaller floes.

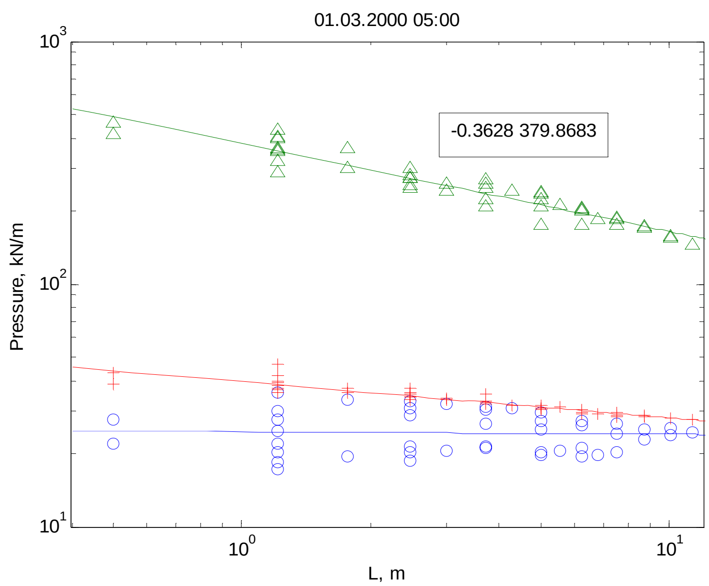

Figure 1. Example of analysed ice crushing event, where 8 panels were sustained to ice pressure. Max pressure (triangle), Standard deviation (+), average pressure (o).

The same analysis was done for all events where a minimum of 7 panels were involved in the ice action. Maximum pressures for 16 events during the winter 2000 are shown in Figure 2. Ice pressures increased until March 15 when a large lead broke up close to the lighthouse. After that date ice pressures were constantly smaller than 200 kN/m when measured on 10 m width. The highest pressure estimated that season on 1 m width was 1000 kN/m on March 5. As can be seen from Figure 1 there is a substantial scatter of the individual panel pressures (*L*= 0.5m and 1.2m) around the perimeter of the foundation and the local pressures are somewhat underestimated. It is also important to consider that the travelling length of the ice sheet on a registered event was typically less than one km.

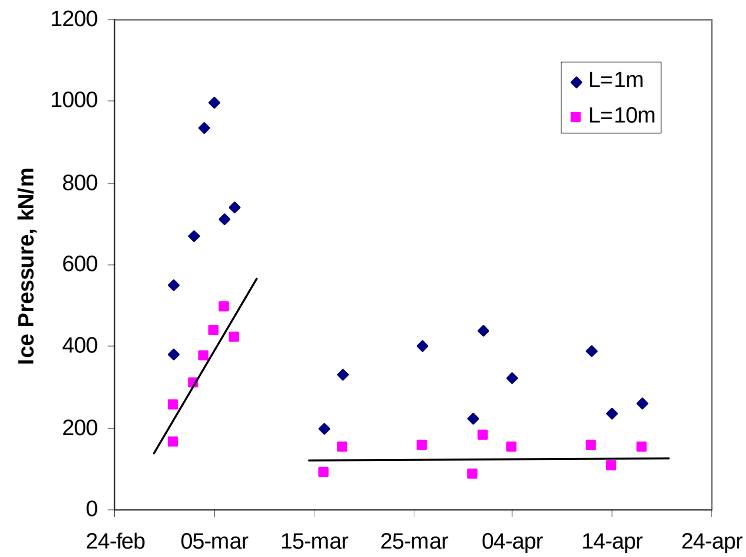

Figure 2. Seasonal variations of the empirically calculated maximum ice pressures on 1 m contact width (blue) and on 10 m (red with a line).

Ice-induced vibrations

Measured ice pressure and corresponding lighthouse displacement during the season 2000 were often small and probably limited by bending, splitting of floes or collapse of weak ice or inhomogeneous ice. When the moving ice floes were thick and strong enough and the velocity was over a critical value, continuous ice crushing resulted in vibrations of the lighthouse and the load peaks were reached nearly simultaneously on all panels. The measured oscillating pressure were then characterised as a saw-tooth curve where the force dropped faster than it was build up. For wider structures this high frequency variation was superposed a quasi-static load level usually referred to as ice extrusion pressure. The structure was then always in contact with the ice edge. A good example of measured ice pressure variations due to ice-induced vibrations is shown in Figure 3.

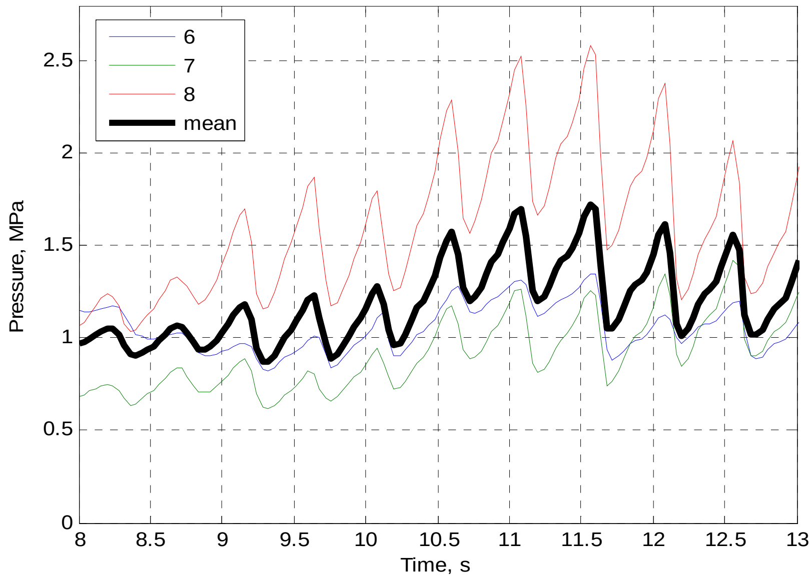

Figure 3. Oscillating ice pressures on three load panels at Lighthouse Norströmsgrund, April 10, 1999. Ice thickness = 0.7 m. (Fransson & Lundqvist, 2006).

Uncertainties about the representative ice thickness *h* may have caused several misinterpretations of the effective ice pressure. It was e.g. not possible to trace any clear dependence of ice drift velocity on the effective pressure even though the ice induced vibrations were triggered above a critical velocity. When the total load was divided only with the actual contact width there was a clear trend as shown in Figure 4.

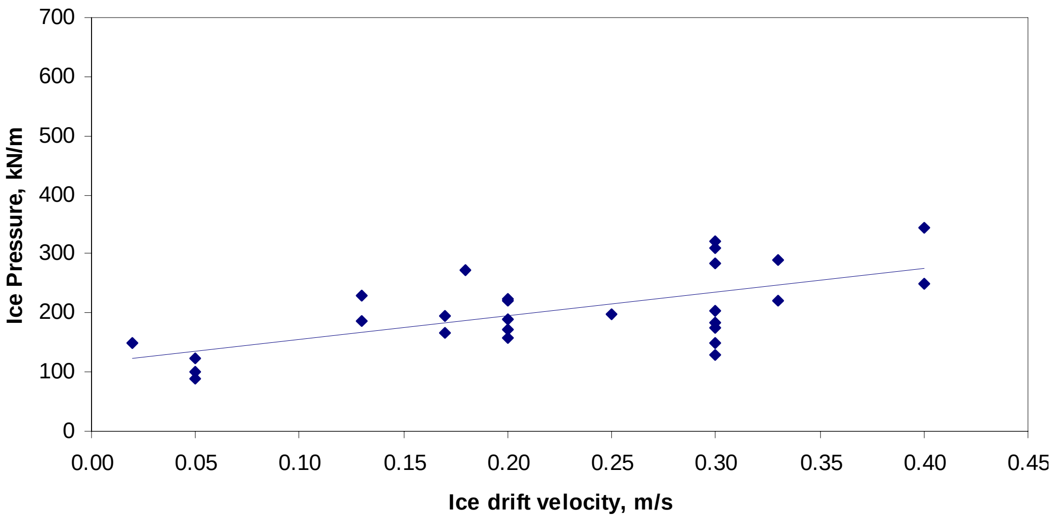

Figure 4. Obtained velocity effect on measured ice pressures winter 2000. Obtained pressures at zero velocity have been omitted (LOLEIF database, 2008).

Rate effects on strength in compression tests have also been studied at very high strain rates (Jones, 1997). It is often assumed that the ice strength increases for strain rates that are higher than 10^{-1} s^{-1} even though iceberg ice showed a decreasing trend (Jones, 2006). Compression tests at such a high speed were basically uncontrolled fracturing with severe stress concentrations, but it is interesting that the brittleness of different ice types may govern the trends.

High-speed ice crushing

At high penetration speed most of the experienced rate effects originate from indentation tests where the structure instead of the ice sheet has been moved. These findings are not directly applicable because of the different inertia effects but comparisons can be made. In a series of field tests in Luleå Harbour 2008, inspired by the work of Kärnä et al. (1993), loads from ice crushing against a 300 mm vertical steel pipe was measured (Fransson et al. 2008). The structure was mounted in front of an ice breaking tug boat, see Figure 5.

Figure 5. Test set-up for registration of ice loads, installed on the tug boat Viscaria.

In one of the tests series the velocity was kept as constant as possible and the steel pile was pushed for 10 minutes in smooth and uniform level ice. This test procedure was repeated at three different velocities at different dates with changed ice conditions. Load record and corresponding distribution for test number 12 are shown in Figure 6, and a summary of the results is given in Table 1. The recorded ice load was characterized as a harmonic vibration at abt. 40 Hz in test 12 when the steel structure was pushed in 0.25 m thick level ice at a speed of about 0.3 m/s. Average load level, standard deviation and maximum load is given in Table 1 for the period when the speed and thus the vibration was relatively uniform.

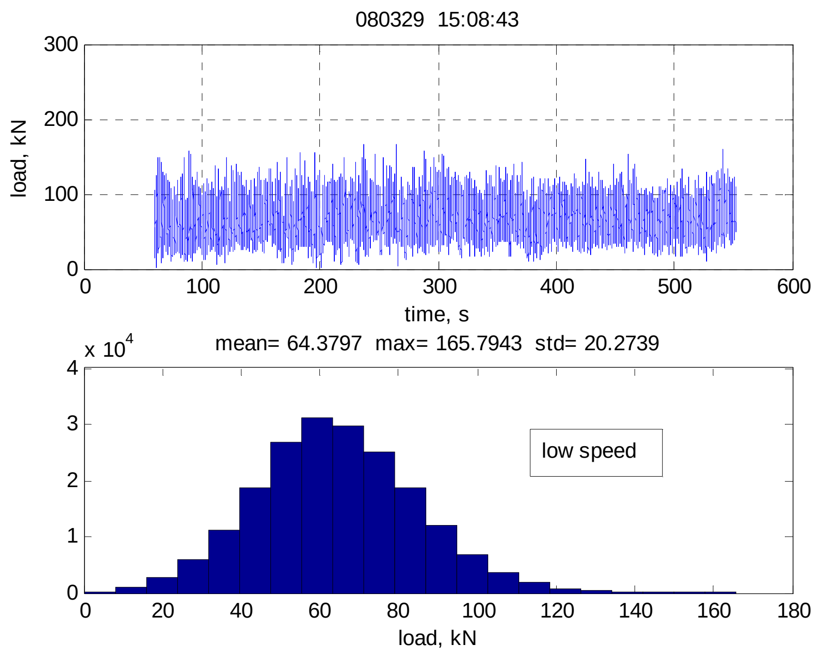

Figure 6. Ice load record from ice crushing tests number 12.

Table 1. Summary of ice crushing tests with constant velocities for 10 minutes.

Test No.	Date yymmdd	Speed m/s	Ice Thickness cm	Mean kN	Std kN	Max kN
12	080329	0.3	25	64	20	166
13		0.6		75	23	209
14		1		98	30	266
19	080410	0.3	25	55	28	248
20		0.6		82	34	277
21		1		101	31	250
23	080425	0.3	15-20	18	8	74
24		0.6		24	10	82
25		1		35	18	183

DISCUSSION

During the measuring seasons 1999-2004 the ice strength usually decreased with ice thickness and the average ice temperature in the thick ice became close to zero. Several dynamic effects made the thicker and older ice-cover in the Gulf of Bothnia less homogeneous and many crack systems were kept unfrozen. In a more severe winter, ice may grow to its maximum thickness without these flaws. For design it is therefore not motivated to use a lower effective pressure or compressive strength for thick ice in the northern parts of the Baltic Sea. It is then important that the selected design ice thickness is based on good statistics of the thermally grown ice cover and not on measured ice thickness that may include rafted or hummocked ice. The results from the icebreaker indentation tests indicate a general trend of increasing mean load levels with speed but the maximum load did not always follow the pattern. Snow on the ice or changing ice brittleness was a factor that may have affected the fracturing mechanism and thus the velocity trend. Results from similar field tests with a concrete indenter (Kärnä et al.1993) also showed that the effective pressure increased with velocity. The data-points indicate a maximum at 1.5 m/s but it seems unlikely that full-scale ice loads will start to decrease above such a high drift velocity.

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