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FULL SCALE ACTIONS FROM FIRST YEAR RIDGE INTERACTIONS WITH FIXED STRUCTURES

Åse Ervik[1]
[1]Centre for Sustainable Arctic Marine and Coastal Technology, Norwegian University of Science and Technology, Trondheim, Norway

ABSTRACT

The objective of this paper was to study full scale actions from first year ice ridges on fixed structures. The first part is a review of reported full scale global loads and associated failure modes from ice ridges compared to level ice, on three fixed structures. The instrumented structures are the Molikpaq, the piers of the Confederation Bridge and Nordströmgrund lighthouse. The highest ridge loads on Nordströmgrund lighthouse and the piers of the Confederation Bridge were associated with crushing and combined crushing/bending respectively. On Molikpaq crushing of first year ridges was not reported. In the second part of this paper data is analyzed. A limit force analysis was performed to estimate a critical ice ridge length of approximately 9km for crushing to occur on the Molikpaq compared to 20m on Nordströmgrund lighthouse. Accordingly some Nordströmgrund data were analyzed to compare global loads derived from load panels and tilt. A ratio between panel load and tilt was found for a quasi-static 5m deep ridge interaction with the instrumented side of the lighthouse. For the ridge a ratio of 8.2 kN/μradians was derived, compared to 12kN/μradians for level ice both ratios without uncertainties. The different ratio indicates that load panels underestimate ridge keel loads. The analysis also showed that it is not possible to obtain a unique ratio between global load and tilt for ridges, due to the stiff bottom foundation that makes the tilt sensitive to changes in point of action i.e. ridge keel depth.

INTRODUCTION

Actions from ice ridges is assumed to establish dimensioning loads on infrastructure and offshore installations in ice-infested areas, when icebergs are not present. In the past decades great effort has been put into predicting ice ridge loads. A study by Timco and Croasdale (2006) shows that ice ridge loads on a vertical structure predicted by twenty-one ice experts ranged with a factor of five. The study shows that research on ice ridge structure interactions is still needed. This paper begins with a review of full scale first year ice ridge loads on three instrumented fixed structures. The structures are the Molikpaq (CAN), the piers of the Confederation Bridge (CAN) and the Nordströmgrund Lighthouse (SWE). The purpose is to investigate ice ridge load levels and associated failure modes compared to level ice, measured on fixed structures.

The second part of this paper is an analysis of some ridge interaction data. Global loads derived from load panels and tilt are compared, for this analysis data from Nordströmsgrund lighthouse are used. Finally a limit force analysis is performed to compare the minimum ice ridge length for crushing to occur on the three structures.

Structure geometry, instrumentation and location

Ice actions depend on the type of interaction. In the following the three structure geometries, instrumentations and locations are presented. Nordströmgrund lighthouse is a vertical structure and Molikpaq is close to vertical. The piers of the Confederation Bridge on the other hand are conical which favors breaking of ice in bending. Both Nordströmgrund lighthouse and the Confederation Bridge piers are narrow structures while the Molikpaq is a wide structure (Table 1). All the structures are fixed to the sea bed in the bottom foundation, but free to rotate and deflect in all other parts limited by the structure stiffness.

Table 1. Some key structure and location parameters

	Molikpaq	Confederation Bridge	Nordströmgrund Lighthouse
Structure width (MWL) [m]	90	14.2	7.6
Incliation (MWL) [°]	82	52	90
Dominant ice drift dir.	NE	NW (SE tides)	NE

*MWL mean water level

Full scale data is obtained by instrumenting the structures with load panels, accelerometers, tiltmeters, optic sensors (laser, EM, ULS) and video coverage. In addition weather data and dairies are documented. Global loads on the Molikpaq and Nordströmgrund lighthouse were found by load panels (Timco et al., 2000),(Bjerkås, 2006) , tiltmeters were used to find global loads on the Confederation bridge piers after 2003 when load panels broke (Brown, 2007).

In addition to measuring load and responses some ice parameters were measured. At Molikpaq ice velocities and ice ridge sails were estimated from videos. At Nordströmgrund ice velocities and direction were estimated form videos, wind speed/directions and air temperatures by a weather station. Ice thickness above water was found with laser, below water an electromagnetic device (EM) was used. For ridge keels EM footprint data is too coarse, an upward looking sonar (ULS) gives more precise ridge profiles. At Nordströmgrund a ULS was installed in 2000 but broke early in 2001. Based on linear regression between available ULS and EM data at Nordströmgrund; maximum keel depths from ULS was approximately 3 times the EM maximum (Bjerkås, 2006). At the Confederation bridge a weather station records wind speed/direction and air temperatures. Since the Confederation Bridge is 13km long; wind loads must be subtracted from tilt measurements to find ice loads. Ice drift speeds were measured by an acoustic doppler current profiler and ice thickness is measured with ULS.

Molikpaq was (1984-1986) located in the Beaufort Sea, experiencing heavy ice conditions including old ice features. The Confederation Bridge crosses the Northumberland Strait in Canada and the Nordströmgrund lighthouse is located outside Luleå in Sweden, both are located in temperate areas only experiencing first-year ice features. Based on this; loads from first-year ice ridges were expected to be dimensioning, at least for the temperate structures. Location of the structures are shown in Figure 1.

Classification of ice features

In this paper actions from ice ridges and level ice are compared. WMO (1970) classify ice as either deformed or undeformed, where undeformed ice is level ice while deformed ice is

Table 2. Instrumentation and monitoring, Molikpaq; Timco et al. (2000) and Timco et al. (2005), Confederation Bridge; Brown et al. (2009), Brown (2001), Nordströmgrund lighthouse; Bjerkås (2006) and Schwarz and Jochmann (2001)

	Molikpaq	Confederation Bridge	Nordströmgrund Lighthouse
Load panels	yes (1984-86)	yes (1997-2003)	yes (1987-1989) (1998-2003)
Location panels	SE, E, NE, N	NW	NE, E
Max panel depth [m]	3/6m	2m	1.5m
Response measurements	4 16 (12th April 1986) Extensometer and 10 strain gauges (1984-86)	Tiltmeters, accelerometers	Tiltmeters (1986) (2003), accelerometers (1973-1989) (2001-2003)
Video	yes (1984-86)	yes (1997-)	yes (1979) (2001-2003)
Other instruments	-	upward looking sonar (ULS) (1997-), Acoustic Doppler Current Profiler (1999-2000)	Laser, electromagnetic device(EM) (2001-2003), ULS (2000-2001)

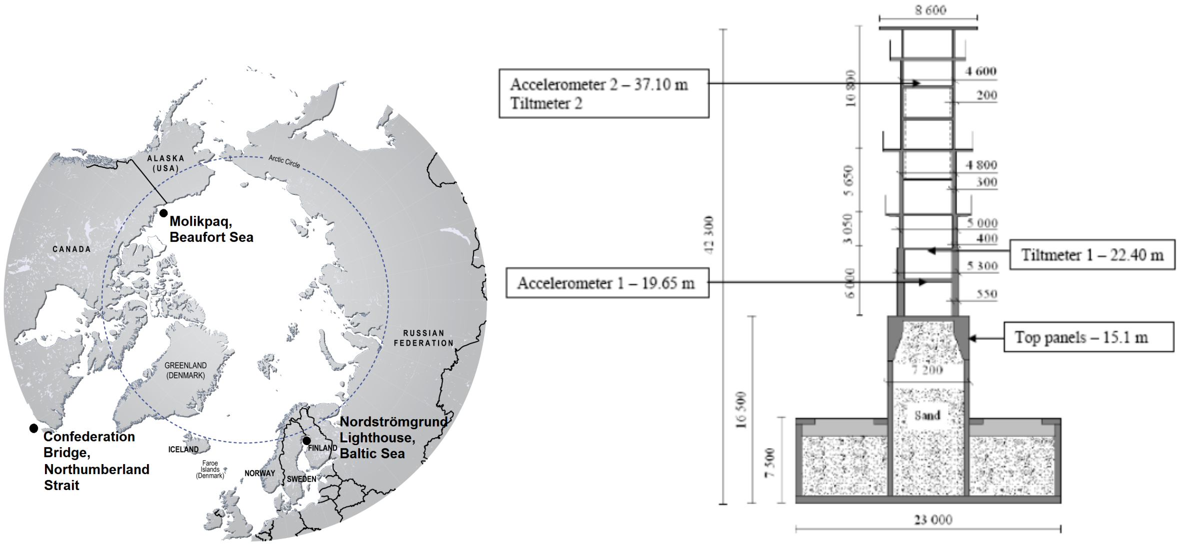

Figure 1. To the left:Map showing the location of the Molikpaq, the Confederation Bridge and the Nordströmgrund lighthouse (Ahlenius, 2005). To the right: Nordströmgrund lighthouse (1998-2003) Bjerkås et al. (2013).

both rafter and ridged ice. Level ice is thermally grown ice. When visually studying ice it is seldom possible to distinguish level ice from rafted ice, therefore ice thickness should be measured manually and compared to thermodynamic estimates in order to distinguish between undeformed and deformed ice.

Limit scenarios and failure modes

It is important to distinguished between load limiting mechanisms and failure modes. There are three recognized load limiting mechanisms. They are limit stress, limit force and limit momentum. Ice load is limited by stress when ice fails directly against the structure (in crushing, bending, buckling, creep or shear), this requires sufficient driving forces. If the driving forces from the wind and current are insufficient to fail the ice or if inhomogeneities in ice sheet causes the ice to fail adjacent to the structure surface; driving forces limits the ice load i.e. a limit force mechanism. If the momentum of the ice is insufficient the ice will come to halt and the ice load is limited by momentum or energy.

The mode of which the ice fails against the structure controls the load level. Recognized failure modes are crushing, bending, creep, buckling, splitting and spalling (ISO19906, 2010). For ridges other failure modes are also reported such as ridge spine failure, failure behind the ridge (Timco et al., 2000) and dodging (Kärna and Jochmann, 2004). The dodging failure was described for a ridge with a sail hight of 2m on the 1st of April 2002 (Kärna and Jochmann, 2004):"Instead of a ridge penetration, the drift direction changed for a while. Then the structure found the boundary between the level ice and the rafted ice.". Timco et al. (2000) and Bjerkås (2006) also differ between local and global failures. Where local failures occur continuously over the whole structure width while global failures occur on a concentrated part of the structure. The failure mode that produces the highest load is crushing since the crushing strength is generally the highest strength in sea ice.

REVIEW OF GLOBAL LOADS AND FAILURE MODES

Failure modes and global loads both dependent on structure geometry and ice parameters; when designing the Confederation bridge between 20 and 25 parameters were used to find design ice loads (Brown et al., 2009). Table 3 gives a summary of maximum loads and failure modes of ridges compared to level ice.

The maximum reported first year ridge load on Molikpaq was 89MN associated with a global failure behind the ice ridge. On Molikpaq crushing of first year ridges was not observed. For level ice the maximum global load found was 131MN. The level ice failure mode was unknown, but the second largest level ice load (110MN) was caused by crushing of level ice with a thickness of 1.2m (Timco and Johnston, 2004). Molikpaq, being in the Arctic, encountered old ice features in addition to first year ice, crushing of level old ice produced the overall highest loads up to 466MN. Wright (1986) reports that strong dynamic vibrations were sometime associated with crushing of old ice features.

Some of the Nordstömgrund data are not yet analyzed, but the highest ridge load reported until today is 3MN occurred during crushing of a ridge of 9m depth. During the interaction the ice velocity decreased to zero and dynamic accelerations up to 1m/s^2 were registered. The largest quasi-static ridge load reported is 1.3MN for crushing of a ridge keel of 6m (Bjerkås, 2006). The highest level ice load reported to this date is 3.5MN measured during crushing of level ice with dynamic accelerations up to 2m/s^2 (Bjerkås et al., 2013). For large ice ridges dodging was sometimes reported at Nordströmgrund lighthouse. In Figure 2 the full time series from 30th of March is shown, a dodging event is seen from 18.00-19:30. For large ice ridges limiting mechanisms seems to be important, it is stressed that a comprehensive study of all Nordströmgrund data is not yet done, and should be carried out to validate what caused extreme loads.

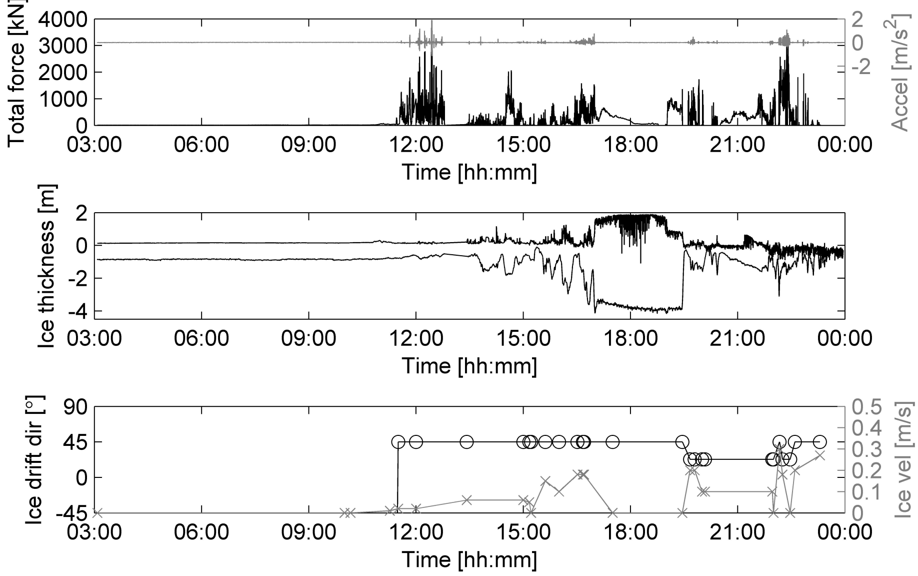

Figure 2. Extreme events from the 30th of March including dodging of and ice ridge. In the bottom plot x marks ice drift velocity and o marks ice drift direction.

Brown et al. (2009) reported the highest ice loads and associated failure modes measured until 2009 on the two center piers of the 13km long Confederation Bridge. The highest ridge load measured was 8.3MN associated with a continuous failure. The failure seemed to be a combination of crushing and bending. The highest level ice load was 8.9MN also associated with a combination of bending and crushing failure.

ANALYSIS AND DISCUSSION

In the second part of this paper some data are analyzed, first an attempt is made to compare panel loads to tilt measured at Nordströmgrund for a quasi-static ice ridge event. This is done in an attempt to investigate if tilt can be used to obtain global ice ridge loads. Accordingly limit ridge building forces are applied to estimate the critical ridge lengths for limit stress to occur on the three structures.

Analyses of tilt and panel loads on Nordströmgrund lighthouse

Global loads on Nordströmgrund lighthouse were originally derived from load panels. Loads from level ice heading from east would be captured by load panels fixed on the N-SE of the lighthouse reaching 1.5m below mean water level (MWL). However, load panels are not capable of obtaining total loads from ridges which reach deeper than 1.5m below MWL.

Frederking (2005) calibrated tilt data from a quasi-static level ice event with heading from the east, he found a ratio between global load and tilt of 12kN/μradians. Arguing that once

Table 3. Full-scale actions from first year ice features. Highest load reported from first year ice ridge (F_{MaxR}) compared to highest overall load reported from first year ice (F_E) .

Maximum ice ridge event	Molikpaq (Timco et al., 2000)	Confederation Bridge (Brown et al., 2009)	Nordströmgrund (STRICE data 2002, Bjerkås (2006))
Date/time [dd.mm.yyyy/hr.min]	NA	29.02.2008/09.29	30.03.2003/22.15
Failure mode	Failure behind/spine	crushing and bending	crushing
h_i [m]	0.8	0.6	0.75
h_k [m]	NA, h_s ca. 1.0	6.6	9*
F_{MaxR}[MN]	89	8.3	3.0
Ice drift [m/s]	0.10	0.00	0.18
Drift direction [°]			23
Maximum level ice event	**Molikpaq (Timco and Johnston, 2004)**	**Confederation Bridge (Brown et al., 2009)**	**Nordströmgrund (STRICE data, Frederking (2005))**
Date/time [dd.mm.yyyy/hr.min]	NA	04.04.2003/07.02	30.03.2003/12.27
Failure mode	NA	crushing and bending	crushing
Mean h_i [m]	2.0	0.58	0.75
F_E [MN]	131	8.9	3.5
Ice drift [m/s]	0.01	1.31	0.02
Drift direction [°]			0
Ratio $\frac{F_{MaxR}}{F_E}$	0.68	0.93	0.86

*approximate keel depth from EM-data times 3, a relation found by linear regression between ULS and EM (Bjerkås, 2006)

calibrated; tilt could be used to find total global loads regardless of the ice drift direction. He assumed that the foundation and lighthouse stiffness was omni directional and that wind loads were negligible. The data was filtered with a 3sec moving average. In the following an attempt is made to compare this ratio to a ratio for an ice ridge.

Based on the calibration done by Frederking (2005), eight quasi-static ice ridge events from the 2003 STRICE- data were analyzed. The maximal ratio between global panel load and tilt was found for an approximately 5m deep ridge. The ratio was 8.2kN/μradians, this value is lower than the value for level ice, suggesting that the total ridge load is not captured.

The ratio above is based on loads measured at MWL, however the actual load point of action for a ridge depends on the ridge depth. In the following estimate the ridge load is approximated by a linearly distributed load with a resultant force F acting at a water depth of $1/3h_k$ (Figure 3). If the lighthouse is approximately a cantilever beam with varying cross section (see Figure 1 and Figure 3) the tilt is given by the equation of rotation of an elastic cantilever beam with two cross sections 1 and 2 in Equation 1.

$$\theta = \frac{F[(l_2+l_1)^2 - l_1^2]}{2EI_2} + \frac{Fl_1^2}{2EI_1} \tag{1}$$

where F is the resultant ice load, $l_2 = 7.5m$ is the length of the bottom foundation, l_1 is the distance from the bottom foundation to the load F ($l_1 RI \approx 1/3 h_k$, $l_1 LI \approx MWL$), E is the elastic modulus of the lighthouse. The second area moment is $I = d^4/64$, where d is the diameter, $d_2 = 23m$ and $d_1 = 7.5m$. Now by changing $l_1 LI$ to $l_1 RI$ according to Figure 3 tilt from the same load for a 5m deep ridge and level ice is compared.

By applying Equation 1 tilt is reduced by approximately 40% for the ridge compared to level ice, due to the change in point of action and the large bottom foundation. As a result the ratio between global panel load and tilt for a 5m deep quasi static ridge should be approximately 20kN/μradians. This estimate needs validation by more advanced numerical tools. Further this analysis shows that it is not possible to find a unique ratio between global load and tilt for ridges.

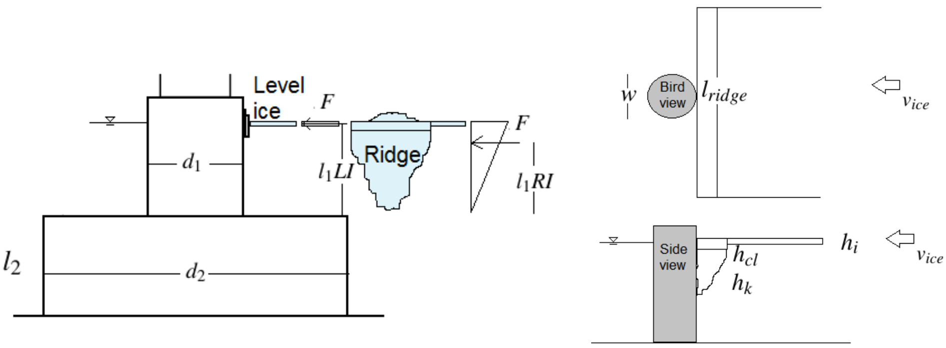

Figure 3. To the left; Simplified level ice and ridge interaction with Nordströmgrund lighthouse. To the right; a ridge interaction seen from above and the side. To illustrate ridge limit ridge building force.

Limit force estimate of critical ridge length

Limit stress is typically applied to estimate dimensioning extreme quasi-static ice loads. In the following a limit stress analysis is applied to estimate minimum ice ridge lengths for crushing to occur on the three structures review in the beginning of this paper. Limit stress requires that the global load from an ice ridge acting on a structure, is lower than the global ridge building force action on the parent ice sheet, illustrated in Figure 3. This is expressed in Equation 2 and 3. It is assumed that the driving forces from the drag and wind are small compared to the ridge building force (Croasdale, 2009).

$$F_i > F_{cl} + F_k + F_s \tag{2}$$

F_i is the ridge building force, F_{cl} is the force from the consolidated layer, F_k is the keel load and F_s is the sail load. Sail loads are assumed to be negligible and are left out of this analysis, this gives Equation 3

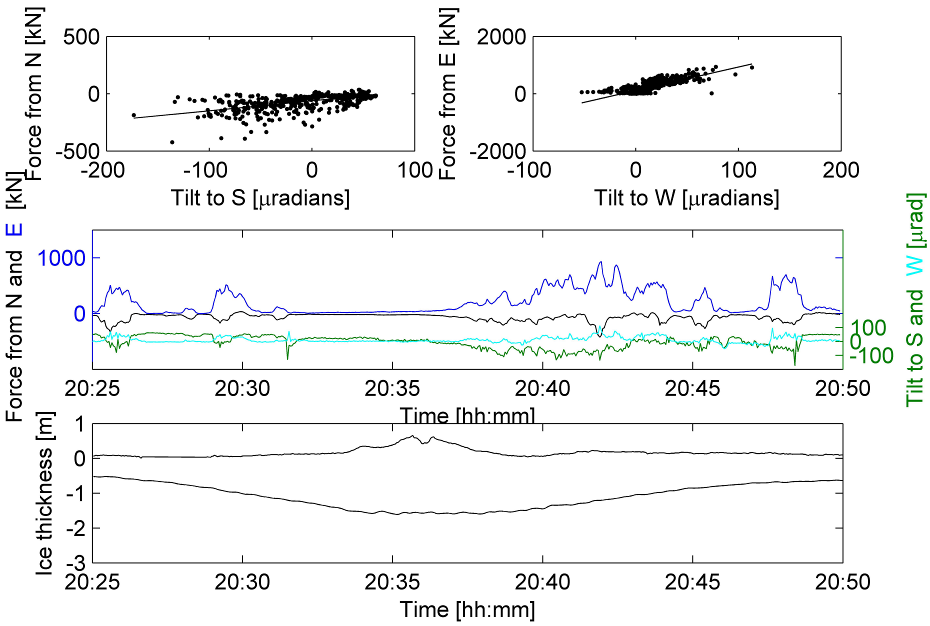

Figure 4. Tilt vs force on the 19th of March 2002 from an ice ridge event, thickness was measured with EM. N (North), S (South), E (East) and W (West).

$$p_i l_{ridge} > p_{cl} w h_{cl} + p_k w h_k \tag{3}$$

p_i is the ridge building force per unit ridge length, l_{ridge} is the length of the ridge, p_{cl} is the ice crushing pressure of the consolidated layer, w is the structure width, h_{cl} is the consolidated layer thickness, p_k is the pressure from the ridge keel and h_k is the keel depth. Ice crushing occur when the ridge length is above a critical length given by Equation 4.

$$l_{ridge} > \frac{p_{cl} h_{cl}}{p_i} w + \frac{p_k h_k}{p_i} w \tag{4}$$

In ISO19906 (2010) the crushing pressure of consolidated layer p_{cl} is given according to Equation 5.

$$p_{cl} = C_R \left(\frac{h_{cl}}{h_{ref}}\right)^n \left(\frac{w}{h_{cl}}\right)^m \tag{5}$$

C_R is a reference strength depending on the area (Beaufort Sea $C_R = 2.8$, Temperature areas $C_R = 1.8$), m is a constant, n is a constant depending on the ice thickness and h_{ref} is 1m. I believe m is a constant used to describe non simultaneous failure over the consolidated layer similar to the Equation ($p_{cl} = A_k D^m h^n$) by Bjerkås (2004), he suggests $-0.3 < m < -0.1$ in ISO19906 (2010) $m = -0.16$.

The reference crushing strength (C_R) in ISO19906 (2010) is 2.8MPa for the Beaufort sea. This value was based on first year and old ice data (ISO19906, 2010). Timco and Johnston (2004) measured ice pressured from first year ice on structures in the Beaufort sea and found that "the maximum Global Pressure measured for all types of ice loading events never exceeded 2 MN/m^2". Based on this; I have changed C_R to 2 for the estimation of critical first year ice ridge length in the Beaufort Sea (Table 5).

In ISO19906 (2010) the rubble keel pressure (Equation 6) is estimated by a passive failure Mohr Coulomb model based on Dolgopolov et al. (1975). In the model the rubble fails simultaneously on shear plans inside the rubble. The original model of (Dolgopolov et al., 1975) was based on observations from model scale tests on ice rubble and the last group in Equation 6 was replaced by $1+2h_k/3w$. The rubble keel pressure p_k is given by Equation 6.

$$p_k = \mu\left(\frac{h_k\gamma_e\mu}{2} + 2c\right)\left(1 + \frac{h_k}{6w}\right) \tag{6}$$

$$\mu = tan\left(45 + \frac{\phi}{2}\right) \tag{7}$$

$$\gamma_e = (1-\eta)(\rho_w - \rho_i)g \tag{8}$$

where μ is the passive pressure coefficient, ϕ is the internal angle of friction at failure, c is the average keel cohesion, w is the structure width and γ_e is the effective buoyancy. Typical values for these ridge parameters are presented in Table 4 based on ISO19906 (2010).

For conical structures a load reduction due to bending failure is expected. ISO19906 (2010) only consider bending of level ice, in the absence of such formulas crushing is considered also for the conical piers of the Confederation bridge.

The ridge building force per unit ridge length is expressed by Equation 9 which is an empirical formula from ISO19906 (2010). The value of R depends on the ice thickness, in ISO19906 (2010) the expression for $Rh_i^{1.25}$ is equal 2, obtained by curve fitting data of 1m thick ice for structure widths greater than 100m. I have used $2 = A = Rh_i^{1.25}$, Equation 9.

$$p_i = Rh_i^{1.25} l_{ridge}^{-0.54} = Al_{ridge}^{-0.54} \tag{9}$$

Finally; the critical ridge length for limit stress is estimated by Equation 10 and presented in Table 5. Ridge parameters are taken from Table 3 and 4. For Nordströmgrund parameters were based on the ridge that caused the largest quasi-static load of 1.3MN. h_{cl} was never measured and is therefor estimated by $h_{cl} = 1.8h_i$ based on measurements by Høyland (2000). For Molikpaq h_k was neither measured, it is estimated by $h_k = 4.5h_s$ based on Timco et al. (2000).

Table 4. Ice ridge parameters used in this estimation (ISO19906, 2010).

Parameter	ϕ [°]	c [kPa]	ρ_w $[kg/m^3]$	ρ_i [kg/m^3]	η [-]
	30	7	1025	920	0.3

$$l_{ridge}^{0.46} > \left(p_{cl} h_{cl} + p_k h_k \right) \frac{w}{A} \tag{10}$$

The ridge loads calculated from the analytical models in Table 5 are between 1.5 and 6 times the measured loads.

Table 5. Table over critical length l_{ridge} together with ridge loads F_{cl}, F_k and $F_{tot} = F_{cl} + F_k$. Ridge sizes are taken from Table 3. h_{cl} was not measured for any of the structues and for Molikpaq h_k was also not measured, these values are estimated.

	Molikpaq	Confederation Bridge	Nordströmgrund lighthouse
w [m]	90	14.3	7.6
h_i [m]	0.8	0.6	0.3
h_{cl} [m]	1.44	1.08	0.54
h_k [m]	4.5	6.6	6.1
n	-0.34	-0.38	-0.44
C_R MPa	2*	1.8	1.8
F_{cl} [MN]	118	18	6
F_k [MN]	12	3	2
F_{tot} [MN]	130	21	8
l_{ridge} [m]	9000	200	20

*Adjusted down to 2 from 2.8 to only account for first year ice ridges.

CONCLUSIONS

In this paper actions from first year ice ridges on fixed structures has been studied. The first part of this paper was a review on full scale global loads and associated failure modes on three fixed structures, actions from first year ridges and level ice were compared. The three instrumented structures was the Molikpaq, the piers of the Confederation Bridge and Nordströmgrund lighthouse. In the second part of this paper some ice ridge structure interaction data were analyzed. Data from Nordströmgrund lighthouse were used to obtain a ratio between global panel loads and tilt for ridges compared to level ice. Finally a limit force analysis was performed to estimate minimum ice ridge lengths for crushing to occur on the three fixed structures.

From this work the following conclusions were made:

- The highest ridge loads on Nordströmgrund lighthouse and the piers of the confederation bridge were associated with crushing and combined crushing/bending respectively, while on Molikpaq crushing of ice ridges did not occur. Measured full scale global ice ridge loads were in the same order as loads from level ice for all three structures.

- From a limit force analysis it was estimated that the critical ridge length to produce local crushing was 9km on Molikpaq compared to 20m for Nordströmgrund lighthouse and 200m on the piers of the confederation bridge.
- From full scale data of a quasi-static 5m deep ice ridge iteration with the Nordströmgrund lighthouse; a ratio between global panel load and tilt was found. The ridge ratio obtained was 8.2 kN/μradians compared to 12kN/μradians for level ice derived by Frederking (2005). The low value indicates that load panels underestimate ridge loads. Additionally; an analytical estimate suggest that the same load from a 5m deep ridge would give approximately 40% less tilt than level ice due to the change of point of action and large bottom foundation. As a result a general ratio between global load and tilt cannot be obtain for ice ridges. For ice ridges; advanced numerical tools (FEM,DEM) are needed to obtain global loads from tilt.

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REFERENCES

Ahlenius (2005). Arctic map, political, http://www.grida.no/. 2005.

Bjerkås (2004). Global design ice loads' dependence of failure mode. *International Journal of Offshore and Polar Engineering*, (Vol. 3 No. 3).

Bjerkås (2006). Ice actions on offshore structures, with applications of continuous wavelet transform on ice load signals. *Doctoral thesis for the degree of philopophiae doctor, NTNU*.

Bjerkås and Bonnemaire (2004). Ice ridge-structure interaction, Part II: Loads from ice ridges and their surronding ice sheets. *Proceedings of the 17th International Sumposium on Ice*. pp122-129.

Bjerkås, Meese, and Alsos (2013). Ice induced vibrations - observations of a full scale lock-in event. *Proceedings 23rd International Offshore and Polar Engineering Anchorage*. pp1272-1279.

Bonnemaire and Bjerkås (2004). Ice ridge-structure interaction, Part I: Geometry and failure modes of ice ridges. *Proceedings of the 17th International Sumposium on Ice*. pp114-122.

Brown (2001). Four years of ice force observations on the Confederation Bridge. *Proceedings of the 16th International Conference on Port and Ocean engineering under Arctic Conditions (POAC)*. pp285-299.

Brown (2006). Confederation bridge - an innovative approach to ice force. *Proceedings of the 2006 Annual Conference of the Transportation Association of Canada*.

Brown (2007). Analysis of ice event loads derived from structural response. *Cold Regions Science and Technology*, (47). pp224-232.

Brown, Tibbo, Tripathi, Obert, and Shrestha (2009). Extreme ice load events on the Confederation Bridge. *Cold Regions Science and Technology*. 14p.

Croasdale (2009). Limit force ice loads-an update. *Proceedings of the 20th International Conference on Port and Ocean engineering under Arctic Conditions (POAC)*, (30).

Dolgopolov, Afanasiev, Korenkov, and Panfilov (1975). Effect of hummocked ice on piers of marine hydraulic structures. *Third International Symposium on Ice Problems, IAHR*, (Vol. 3 No. 3).

Frederking (2005). Tiltmeter application at Nordströmgrund lighthouse - STRICE project. *Proceedings of the 18th international conference on Port and Ocean engineering under Arctic Conditions*, (Vol 1). pp399-408.

Høyland (2000). Consolidation of first-year sea ice ridges. *Journal of geophysical research*, (Vol. 107, NO C6, 3062).

ISO19906 (2010). Petroleum and natural gas industries - arctic offshore structures. 412p.

Kärna and Jochmann (2004). Field observations on ice failure modes. *Proceedings of the 17th International Symposium on Ice*.

Schwarz and Jochmann (2001). Four years of ice force observations on the Confederation Bridge. *Proceedings of the 16th International Conference on Port and Ocean engineering under Arctic Conditions (POAC)*. pp669-683.

Tibbo, Obert, Shrestha, Tripathi, Mayne, and Brown (2009). Year twelve of the Confederation Bridge ice monitoring program. *Procceedings of the 20th International Conference on Port and Ocean engineering in Arctic Conditions (POAC)*. pp47-57.

Timco and Croasdale (2006). How well can we predict ice loads? *Proceedings of the 18th IAHR International Symposium on Ice*. pp167-174.

Timco, Croasdale, and Wright (2000). An overview of first-year sea ice ridges. *Canadian Hydraulic Centre - technical report*, (5-112). p157.

Timco and Johnston (2004). Ice loads on the caisson structures in the Canadian Beaufort Sea. *Cold regions science and technology*, (No 38). pp185-209.

Timco, Johnston, and Wright (2005). Multi-year ice loads on the Molikpaq: May 12,1986 event. *Proceedings of the 18th International Conference on Port and Ocean engineering under Arctic Conditions (POAC)*, (pp453-462).

Timco, Wright, Johnston, and Frederking (1999). First-year ice ridge loads on Molikpaq. *Proceedings of the 4th International Conference on Development of the Russian Arctic Offshore*. pp172-179.

WMO (1970). WMO sea ice nomenclature. *World Meteorological Organization*, (Tech rep NO 259.TP.145). pp1272-1279.

Wright (1986). Winter ice interactions with an arctic offshore structure. *IAHR International Symposium on Ice Problems 1986*, (Vol. 3 pp49-73).