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Ice loads on port structures in the Canadian Arctic

R. Frederking[1] and J. Brown[2]
[1] Ocean, Coastal and River Engineering, National Research Council Canada, Ottawa, Canada
[2] Ocean Coastal and River Engineering, National Research Council Canada, St. John's, Canada

ABSTRACT

The growth of communities and economic activity in the Canadian Arctic is resulting in development of new port facilities. Some guidance for these developments has been gained from observations of ice behavior and measurements of local ice forces at Nanisivik. The ice conditions at the site are first-year fast ice during the winter preceded by a 2-to-3-week freeze-up period. During the melt and summer seasons the ice conditions can be described as mobile pack ice, with occasional glacial ice inclusions. The combination of fast ice, a 3-m tide and the steel construction of the wharf leads to the formation of a zone of disturbed ice between the wharf and the first-year ice, complicating the application of existing guidance documents to ice force predictions. Global ice forces based on application of ISO 19906:19 Arctic offshore structures standard yielded an annual global load of 22 MN on a 23-m diameter cell and 75 MN on the 100-m-wide Nanisivik wharf. Extrapolating from the annual mean line load measured on a 0.54-m width, a global load of 10 MN on the 23-m diameter cell was determined. Ice load measurements on hydropower dams provide direction in interpreting ice pressure data over various scales on structures. Observations of ice conditions and measurements of ice loads at Nanisivik, together with dam experience, provide a basis for guidance on predicting ice loading on port structures in the Arctic.

KEY WORDS Ice force measurements; Ice conditions; Standards; Ice force predictions

INTRODUCTION

Communities in the Canadian Arctic are typically located on the coast and seaborne transport is an essential part of their existence. A key element of infrastructure supporting them is port structures through which goods and supplies are brought in, and resources and products shipped out. Most communities have no port structures and community resupply cargo is offloaded onto barges which transfer it to the beach. This is a perilous and time-consuming process.

Development of mineral resources in the Arctic necessitated industrial scale port structures that could facilitate the loading of ore or concentrates onto bulk carriers. The nature of port structures is dictated by the cargo they handle and the local ice conditions. The ice conditions and behavior generate horizontal ice loading due to drifting ice, thermal actions, currents and tides. A number of port facilities have been built over the past 50 years, and there are some case studies published, and a body of experience has been built. For the design of such structures, engineers have had to use judgement and limited experience. At a few sites investigations of ice behavior and ice loading have been documented. Most notable is Nanisivik, where ice observations and force measurements go back to the late 1970's, reviewed in Frederking (2022). Measurements of ice conditions and loads have also been reported for port structures in Svalbard (Marchenko,2018).

An assessment of standards with respect to application to ports was done by Frederking (2012). It examined national standards for offshore structures from Canada, Russia and the United States and an International ISO standard. The Canadian Highway Bridge Code (CSA, 2024) was also evaluated. The conclusion was that for structures the size of Arctic wharves, the ISO or Canadian offshore standards were most suitable. More recently Croasdale et al (2021) adapted ISO 19906:19 to predict loading on a nearshore structure. One other structure was examined, hydropower dams, since they are also exposed to ice. They are large gravity structures 10s to 100s of m in width, vertically faced, and subject to horizontal loads due to thermal ice actions and vertical loads due to water level changes associated with peak power production. Comfort et al (2003) reported on an extensive field and analytical study which developed analytical predictors for ice loads on dams. This work has been incorporated in a guidance document of the Canadian Dam Association.

Active research on ice loads on dams is underway in Sweden. Hellgren and Malm (2024) present a thorough and well documented review of static ice loads on concrete dams. A summary of 138 maximum annual ice load cases from measurements on 19 dams in 6 countries was reviewed, finding that ice thickness and water level variations were the primary factors effecting maximum ice loads. It identified a number of additional factors which were important in interpreting measurement results, for example; whether the load sensor was on the dam face or in the ice, size of the sensor, number of sensors. Similar to the CDA Dam Safety Guidelines, the objective of Hallgren and Malm's work is a design guide.

Guidance documents that could be used for port structures will be assessed, applied to the ice conditions at Nanisivik and then compared with measured ice forces at the site. This paper aims to advance the discussion concerning ice actions on port structures and the development of guidance documents for them.

REVIEW OF STANDARDS AND APPLICATION TO NANISIVIK

A survey was made for design standards for port structures in ice affected areas. None specifically addressing such structures were identified. "Ice Navigation",(PIANC, 1984) addressed ice navigation in harbors. It was operationally oriented, treating ice control, traffic management and planning of facilities, but there was no guidance on ice loads on port structures themselves

For standards or guidance documents that could be adapted to apply for the case of ice actions on port structures the following categories of structures were identified; bridge piers, offshore structures and hydropower dams. Standards for bridges and offshore structures apply for dynamic horizontal ice interactions from river runs or wind and currents driving ice past a structure. Hydropower dams identify primarily thermal ice forces, and more recently loading mechanisms due to water level changes in reservoirs. The starting point for any addressing of ice loads is defining the various scenarios whereby ice can generate a force on the structure.

Ice conditions at port sites set the context for assessing standards. Port facilities, existing or planned, in the Canadian Arctic are in two general categories, those serving communities and those where industrial development is ongoing or planned. Most Arctic communities are located in protected bays, for example Cambridge Bay or Iqaluit, but some are at more exposed sites like Hall Beach. All these Arctic sites are in a marine environment where annual ice thickness can be up to 2 m, there are tides ranging from 30 cm to 7 m, currents, winds, low air temperatures and rapid temperature changes. The port structure itself may modify the ice conditions around it. This combination of environmental factors results in ice forces being generated on the structure and necessitates design to safely accommodate them. A few candidate standards or guides were identified and they will be reviewed here. ISO 19906:19 Arctic offshore structures (2019) is the most current offshore standard. The dam standards include the Canadian Dam Association Dam Safety Guidelines 2007 (Revised 2013) and the Norwegian guideline will be considered. There is also relevant current research in Sweden collecting performance data on ice loading on dams.

ISO 19906:19 Arctic Offshore structures

This second edition of ISO 19906 provides guidance on estimating ice forces on offshore structures. The global force, F_G is determined from

$$F_G = p_G\, h\, w \qquad (1)$$

where

p_G is the average ice pressure on the structure,
w is the width of the structure,
h is the ice thickness.

The average ice pressure p_G is given by

$$p_G = C_R\, \{(h/h_1)^n\, (w/h)^m\} \qquad (2)$$

where

C_R is an ice strength coefficient expressed in MPa,
h_1 is a reference thickness of 1 m,
m is an empirical coefficient equal to −0.16,
n is an empirical coefficient, equal to $-0.50 + h/5$ for $h < 1.0$ m, and to -0.30 for $h \geq 1.0$ m.

Clause A.8.2.4.3.2 Global actions due to ice crushing, in ISO 19906:19, provides guidance on regionally dependent values of the ice strength coefficient, C_R for analysis of ice forces. It also provides guidance on a probabilistic method for determining C_R in terms of exposure represented by the amount of ice moving past a structure and also return periods. Croasdale et al (2021) has used ISO 19906:19 for estimating forces on a nearshore structure where the ice movements are, however, much less than the movements in the source data on which the original values of C_R were determined. Table 1 takes data from Table A.8-4 in ISO 19906:19 to provide values of ice strength coefficient C_R for various return periods and exposure related to the distance of ice movement. It is anchored on a Baltic C_R of 1.8 MPa for a 100-year return period and 135 km annual ice movement, shown bold in Table 1. Nanisivik is in the Canadian Arctic, so the Beaufort value of C_R of 2.8 MPa would apply at this location. This base case value is 1.55 times the Baltic C_R value. The right-hand column of Table 1 is scaled accordingly for C_R Arctic. Following the approach of Croasdale et al (2021) and here using data for a 1-year return period (noted by *), a power function has been fit to the C_R data for ice movements, S, of 6, 135 and 653 km, yielding the following expression

$$C_R = 1.3\, S^{0.0913} \qquad (3)$$

The one-year return period data were used since at Nanisivik our 3 years of data only allows determining an annual value. Note, Croasdale et al (2021) used 100-year return period values, appropriate for a design case. ISO also provides guidance for adjusting C_R for the freeze-up and break-up periods, when lower ice strength might be expected, but that will not be used.

Table 1. Ice strength C_R dependence on exposure for Baltic and Arctic conditions

Ice Movement (km)	Return period (yr)	C_R (MPa) Baltic	C_R (MPa) Arctic
6	1	0.99	1.54*
6	100	1.45	2.26
135	1	1.34	2.08*
135	100	**1.8**	**2.8**
135	10,000	2.3	3.58
563	1	1.49	2.32*
563	100	1.96	3.05

A test calculation using ISO 19906:19 for Nanisivik conditions, assuming an ice movement, S, of 100 m, the distance from the wharf face to the shore, and using Eqn. (3) gives a C_R of 1.05 MPa. This is an annual ice strength. For ice thickness, h of 1.6 m, wharf cell diameter, w of 23 m, and C_R of 1.05 MPa, Eqn. (2) yields a global ice pressure of 0.6 MPa corresponding to a line load of 950 kN/m. Increasing the structure width to 100 m would reduce the line load to 750 kN/m. These line loads convert to a global load of 22 MN on a cell and 75 MN across the100-m-wide wharf.

Canadian Dam Association Dam Safety Guidelines 2007 (2013 Edition)

The Dam Safety Guideline is a high-level document, identifying thermal expansion of the ice cover and dynamic forces at breakup as factors that could cause damage or failure of dams. More detailed guidance is provided in the CDA Dam Safety Guidelines: Technical Bulletins, which accompany the Guidelines. For thermally-driven static ice loads the Hydrotechnical Considerations Technical Bulletin specifies 150 kN/m as an ice load for stability analysis of concrete dams. It identifies a number of factors influencing ice loads, including reservoir water level fluctuations. Quoting from the Bulletin "… at many sites thermal loading alone may be less than the traditional 150 kN/m value, but when combined with certain fluctuations in water level may also produce much higher total ice loads." It also states ice loads are very site specific and dependent on reservoir operation. It further refers to Canadian Electricity Association Technologies Inc. (CEATI) Ice Load Design Guide (CEATI, 2003), stating that when site-specific characteristics and reservoir operating water level information are available, design values of static ice loads can be determined. The guide is a culmination of almost a decade of field measurements of environmental and reservoir conditions and ice pressures at dams in Canada. The work identifies water level variation as an important factor in ice loading. Predictive algorithms worked well for thermal loads but less well for loads produced by a combination of water level and ice temperature changes. It provides a computer program for calculating ice loads for design, with cautions on going too far outside the range of conditions on which the program was based.

Comfort et al (2003) provides a good background for the design method in CEATI Ice Load Design Guide (CEATI, 2003). The approach is empirical and can only be applied confidently within the range of experience. Of interest, the paper identifies the cycle frequency (0.5 to 2 cycles per day) and water level amplitude (5 to 50 cm per cycle) to classify three categories of loading; (i) large amplitude and low frequency, (ii) small amplitude and low frequency, and (iii) small amplitude and high frequency. This third category saw the highest line loads, 350 kN/m for frequent cycling (1 or 2 per day) and small amplitudes (~0.2 m).

Norwegian Guideline for loads and dimensioning (for Dams)

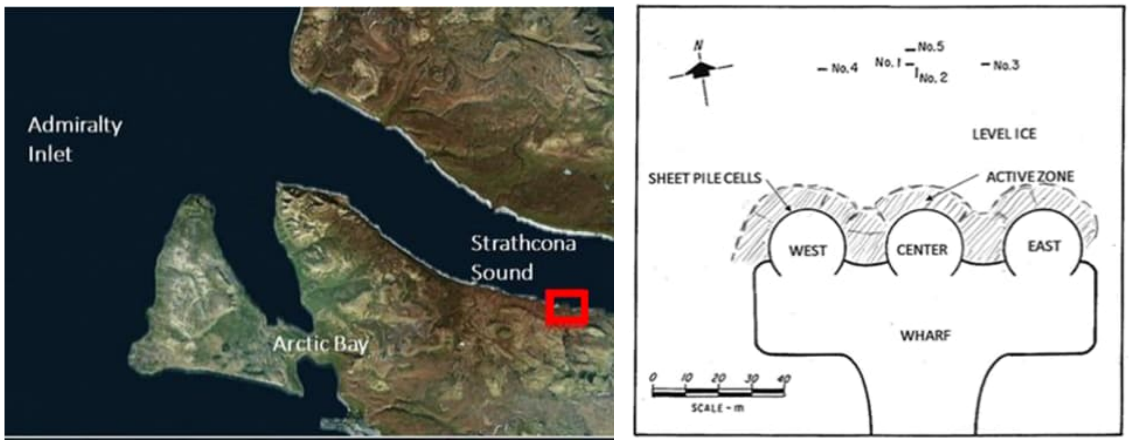
The guideline recommends an ice load of be between 100 kN/m and 150 kN/m throughout Norway. It also identifies cases where there are frequent water level variations, the total ice pressure can be significantly greater than the thermal ice pressure. It advises this be done in cases with daily variations greater than +/- 0.2 m. For this case it recommends a line load (units kN/m) dependent on ice thickness, *h*, in m, of the following form

$$P_{max} = 250\, h^{1.5} \qquad (4)$$

Applying this standard for 1.6 m thickness ice at Nanisivik gives a line load of 500 kN/m. Alternatively, applying an average thickness of say 3 m for the ice directly acting on the wharf, yields a line load of 1300 kN/m.

NANISIVIK WHARF EXPERIENCE

Investigations of ice conditions and interactions with the wharf at Nanisivik began in 1975. A number of projects to measure ice forces on the wharf have been conducted and results of two successful projects, 1985-86 and 2017-20 will be summarized here. The wharf at Nanisivik is located on the south coast of Strathcona Sound about 20 km east from its outlet to Admiralty Inlet (Figure 1 a). Admiralty Inlet is at the northern end of Baffin Island, and connects to Lancaster Sound and the Northwest Passage. The width of the sound is about 5 km and it extends another 20 km to the east. The ice is first-year, freeze-up starts in mid-October and becomes landfast at a thickness of 30 cm 2 to 3 weeks later. Ice thickness by the end of December reaches about 70 cm. These thicknesses have been determined from the Canadian Ice Service's (CIS) weekly Regional Ice Analysis charts (https://iceweb1.cis.ec.gc.ca/Archive/page1.xhtml) and from site visits in the 1970s and 80s. A maximum ice thickness of about 1.6 m is attained in May. Some years a trace of multiyear ice or the occasional iceberg were frozen into the ice cover of Strathcona Sound. The maximum tidal range at the sites is almost 3 m. The wharf comprises three vertically-sided sheet pile cells 23 m in diameter, 38 m on centre, and provides 13 m water depth at low tide (Figure 1b). The wharf extended out about 100 m from shore. The combination of fast ice and tides resulted in the formation of a tidal ice feature, semi-circular in form, between each cell and the adjacent first-year ice. These three ice features, identified by 'ACTIVE ZONE' in the figure, had a hinge-like connection with the first-year ice, and were wedged between the first-year ice 'LEVEL ICE' and the wharf face. The 'active zones' had a slip-stick motion at the interface with the wharf. At extreme high tides these zones were flooded and at low tide sloped downwards from the wharf at up to 10°. The width of these zones grew to a maximum of about 10 m at the end of winter and were over 5 m in thickness at the midpoint. Surface flooding at high tide and freezing explained the thickness being greater than the level first-year ice. On-site observations for over a decade showed the same features forming every winter. It is likely similar ice features will develop at other locations with landfast ice, significant tides and a vertically-sided wharf.



(a) (b)

Figure 1. Location of Nanisivik wharf on Strathcona Sound (red box) (a), and schematic showing locations of ice pressure-measuring panels installed adjacent to the wharf, winter 1985-86 (b).

There were two field programs of successful ice pressure measurements at Nanisivik, 1986 and 2017 through 2020.

1986 Ice pressure measurements: An array of five ice pressure measuring panels, numbered 1 to 5, was frozen into the landfast ice about 50 m off the face of the wharf (see Fig 1 b). They were 1-m wide, 1 or 2 m in depth and were divided horizontally into 0.5-m deep segments. Panel pressure on each 0.5 m^2 segment were logged at 15-minute intervals, and additionally ice temperatures through the ice cover for the period January 21 to May 20. Results of these measurements have been reported previously, Frederking and Sayed (1988), and Frederking (2021). Measurements indicated that the majority of the ice pressure was transmitted in the top 0.5 m of the ice cover. The pressure from each segment was summed to calculate a total load measured by the panel and interpreted as a line load on a 1-m width. Table 2 reports the maximum line load experienced by the three panels oriented parallel to the wharf face. All three individual panel maxima occurred within a couple hours of each other. Because of the near simultaneity of the loads, it was assumed an average of the line loads over greater widths than the panels themselves could be calculated. Averages of groupings of Panels 3, 4 and 5 were used to represent global line loads over widths of 25 and 50 m, similar to the scale of the wharf, are also presented in Table 2. The average line load over 25 and 50 m is successively lower than the maximum line load from one panel, inferring a size effect. The average line load of Panels 3, 4 and 5 is presented in Figure 2 as a time series together with air temperature. This provides a qualitative basis for assessing the effect of temperature on ice pressure. Five episodes, noted by ellipses in Figure 2, highlight periods of high line loads. Each one generally occurs after a rapid air temperature rise. These loading events lasted several days and the peaks lasted several hours, so they can be judged thermal in nature. There is an apparent relation between line load and air temperature, but quantifying it is beyond the scope of this paper. A detailed examination of individual panel time series showed oscillations of 25 to 75 kN/m at tidal frequency (Frederking 2021), so the panels were also responding to tide.

Table 2. Maximum line load in first-year ice in 1986 at Nanisivik site

Panel arrangement	Panel 3	Panel 4	Panel 5	Panels 3&5	Panels 4&5	Panels 3&4&5
Loaded width (m)	1	1	1	25	25	50
Line load (kN/m)	**230**	165	138	**182**	151	**176**

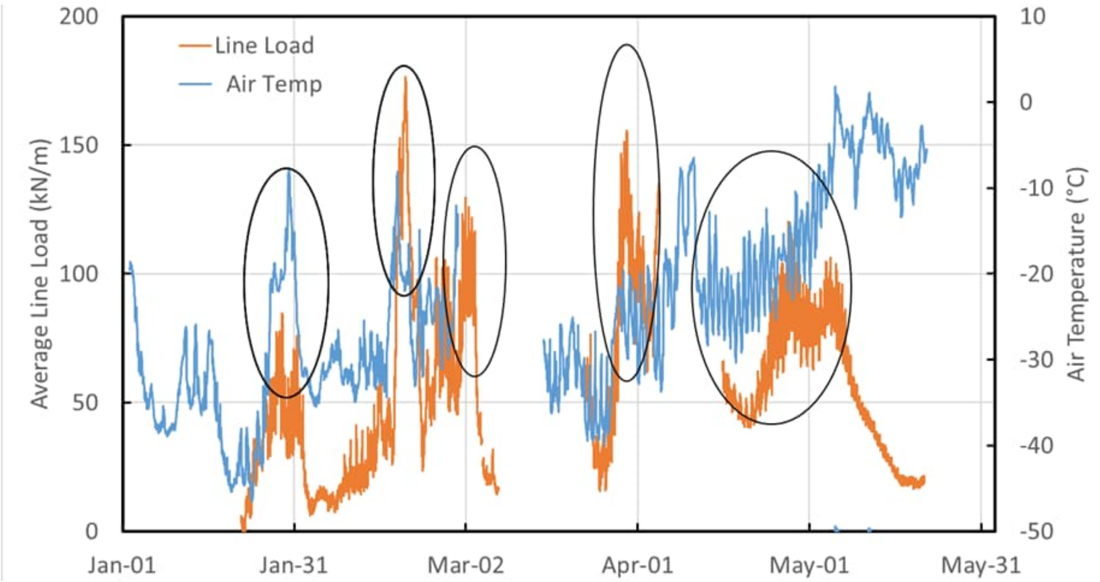


Figure 2. Average line load and air temperature at Nanisivik in 1986

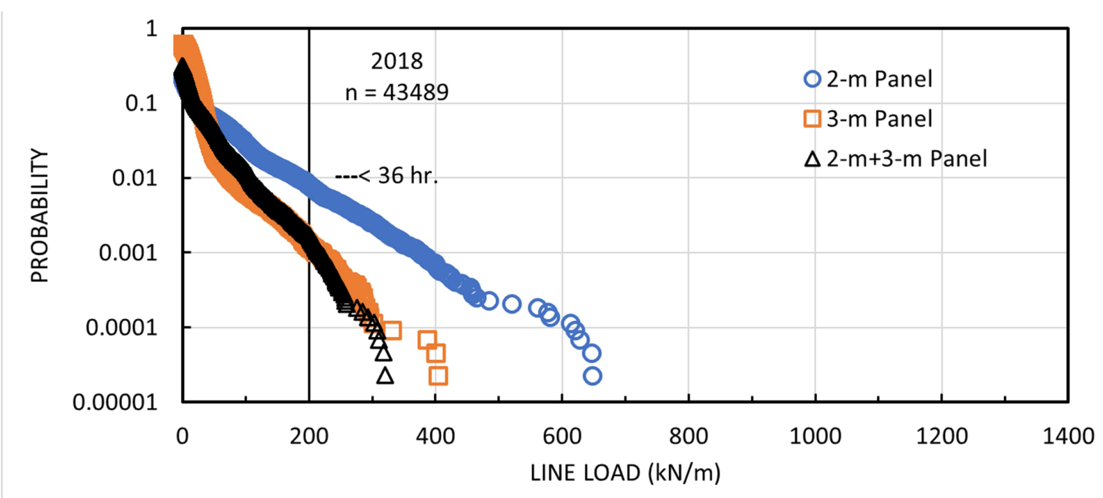
2017-2020 Ice pressure measurements: A recent program at Nanisivik measured ice pressures at the interface between the wharf and the ice. The program logged data continuously for the period September 2017 to January 2021. Brown et al (2022) reported on the three winters of measurements. The system had two load panels attached to the face of the wharf to measure ice pressures at the interface. Each panel had an active area that is 270 mm wide and the upper panel had an active height of 2 m while the lower panel had an active height of 3 m. Note that the panel width was limited by the width of the sheet piles used in construction of the wharf. The panels were divided into 0.5 m high zones. The mid-point of the 2-m panel and top on 3-m panel corresponded to mean tide. The top of the 2-m panel was 1.22 m below the top surface of the wharf. The 3-m panel had a pressure transducer at the bottom to determine the tide level. A complete scan of all channels was logged every 5 minutes in the 2017-18 season and every 2 min 30 sec for subsequent years. More details on the instrumentation can be found in Poirier et al, (2019). Time series plots of all panel zones for the three seasons, shown in Brown et al (2022), indicated that the loading on the panels was very localized and intermittent. Even at the scan rate of 2.5 minutes no dynamics were noted in the signals and loading event durations were from an hour to several hours. It was very rare for two zones to be simultaneously loaded. The top zone of the 2-m panel experienced loading less than 5 % of the time, and the lower zones less, only about 1% of the time. The bottom 3 zones of the 3-m panel did not experience any load, and were not included in any subsequent analysis. The loading record reflected tidal effects with maximum loads during rising tides. Loading was exclusively in the January through May period. Poirier et al (2019) observed that larger loads were observed at lower temperatures, but no quantitative relation could be determined between load and temperature.

To interpret the measurement data in terms of global loading on the wharf, a time series of total loading on each panel was determined by summing the individual panel zone loads, similar to Brown et al (2022). This was converted to a line load dividing by the panel width 0.27 m. At each time step a summation of the 7 active panel zone loads was made to generate a time series of line load on a 0.54 m width. Probability distributions for each winter (January through March) are provided in Figure 3. Note the measurement system did not register any loads during the October-December period, so are not included. The distributions illustrate how infrequently the line load exceeds 200 kN/m, also indicated by the 36-hour line at 10^{-2} probability for the 150-day period, to illustrate how rare loads exceed this level. For the 2-m panel for all three winters the 10^{-2} line load limit was the same, 200 kN/m, only the peaks were different. It is also noteworthy that the near vertical tails of the distributions indicates that even the 'peaks' are 'flat' and have short durations, about an hour.

Table 3 summarizes the maximum line loads for the three measurement widths available, 0.27 and 0.54 m in 2018-2020 and 1 m in 1986 to facilitate comparisons. An annual mean of the 2018-2020 is also provided to facilitate comparison with predictions of annual line loads using various standards and guidelines.

Table 3. Maximum annual line loads (kN/m) in first-year ice at Nanisivik site

	2-m Panel	3-m Panel	Sum 2-m & 3-m Panels	Panel #5 (1986)
Panel width (m)	0.27	0.27	0.54	1.0
1986	---	---	---	240
2018	647	404	320	---
2019	1328	591	658	---
2020	543	290	264	---
Mean of annual max	840	430	415	---



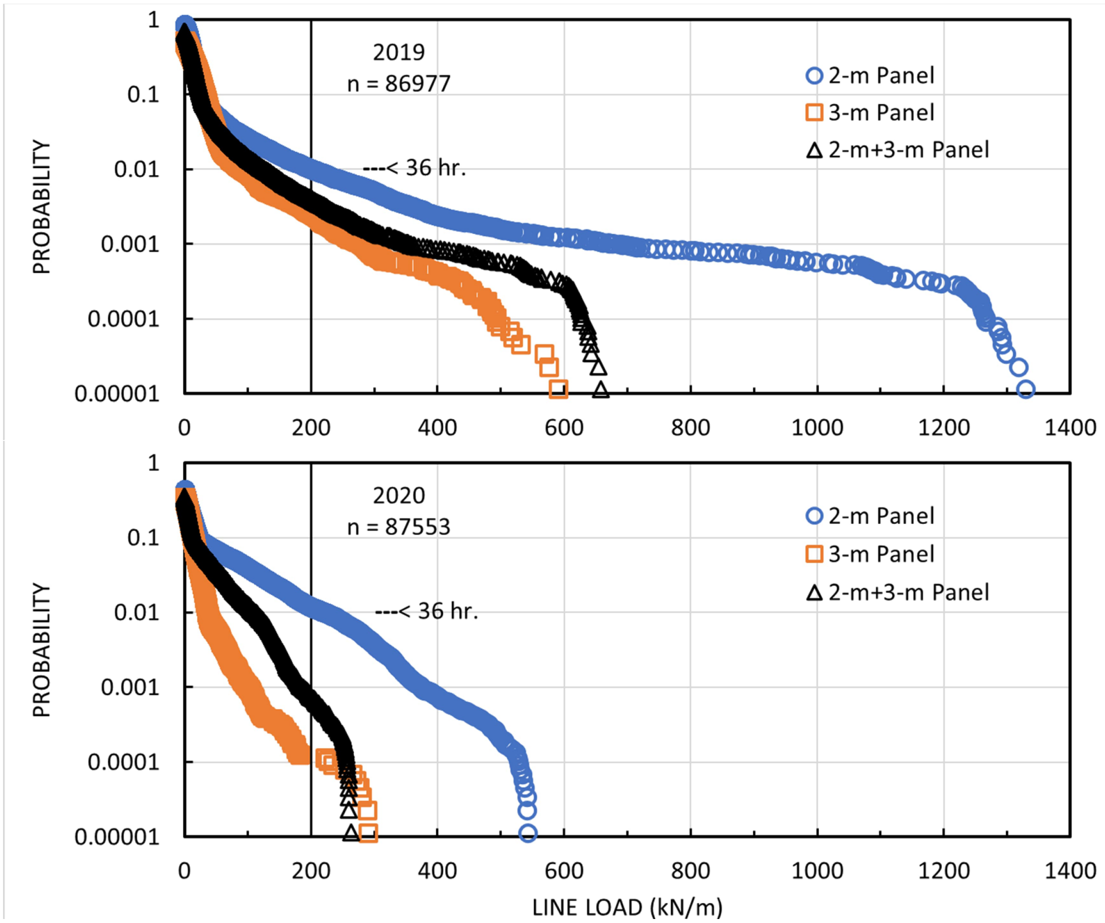


Figure 3. Line load for each panel and two panels summed and for each measurement season

DISCUSSION AND GUIDANCE SUGGESTIONS

The wharf at Nanisivik modifies the natural ice conditions, forming a zone of ice up to 10 m wide by 5 m thick immediately adjacent to the wharf (ACTIVE ZONE in Figure 1(b)). Something similar has been seen elsewhere in the Arctic. Løset and Marchenko (2009) reported that at Svalbard an ice bustle 3 m in diameter 2 m deep formed on an 0.8-m-diameter steel pile. A zone of ice thicker than the first-year ice was also observed in the area between the piles underneath the wharf. Tide range at the site was about 2 m. It can be expected that any wharf in the Arctic will likely modify the preexisting natural ice conditions by its presence, particularly in a tidal environment and landfast ice.

The measurement data obtained at Nanisivik from both field measurement programs are plotted in Figure 4 to show the influence of the panel width on the line load. The field data are the annual maxima for each actual panel width (6 data points for the two 0.27-m-wide panels for 3 years and 3 data points for the two panels combined, 0.54 m width). For the 1986 program, 'effective' panel widths of 25 and 50 m were 'created' by averaging the line load and applying it for the distance between panels. For 2018-20 an effective panel width of 540 mm was generated by summing the 2-m and 3-m panel results for each season. The prediction of ISO 19906:19 for nominal widths corresponding to 1 m, 23 m for the cell diameter and 100 m for the wharf width are also indicated in Figure 4. The average of the 3 maximum annual line loads for a 0.54-m panel width was 415 kN/m, noted by '0.54-m mean' in Figure 4. Applying 415 kN/m to the 23-m-diameter cell yields a global load of 10 MN, substantially less than the 22 MN prediction using ISO 19906:19.

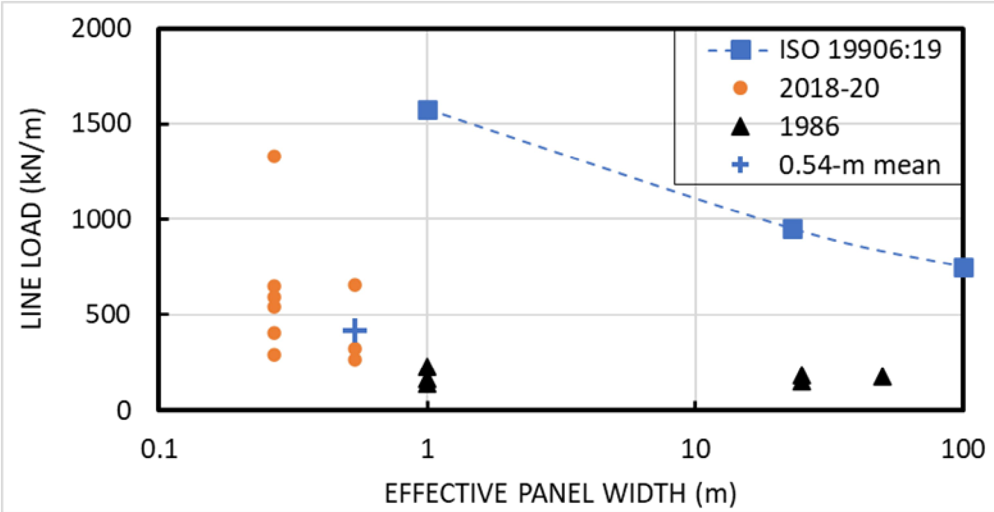


Figure 4 Annual maximum line load measurements as a function of panel width and ISO-based line load predictions at Nanisivik

Marchenko (2018) reported on ice pressure measurements on a wharf in Svalbard. The site was protected, in a fjord. Small pressure cells, 150 mm by 250 mm, were attached to the wharf. Ice conditions around the wharf were disturbed by the presence of the wharf but in a different manner than at Nanisivik. The tide range in Svalbard was smaller and the wharf was supported on 0.8 m dia. piles with an enclosing sheet pile skirt. Ice pressures were generally low, 0.1 to 0.3 MPa and linked to diurnal tides. There were 2 high ice pressure events each lasting about 2 hours and reaching peaks of 0.9 and 1.3 MPa. For comparison, at Nanisivik the maximum annual pressures on a zone 0.27 m wide by 0.5 m were 1.02, 2.76 and 1.02 MPa in 2018. 2019 and 2020, respectively.

Measurement programs underway at the Rätan dam in Sweden (Hellgren et al, 2022) provide useful insights on instrumentation for ice load and ice pressure measurements and interpretation of results from them. Instrumentation included large load panels 1 m by 3 m on the dam face that measured total ice load on them. Additional instrumentation in dummy panels on the dam face used several small ice pressure cells (150 mm by 250 mm wide) from which local pressures were extrapolated to line loads on these panels. Ice thickness at the site was slightly greater than 1 m. Maximum annual line loads from 5 winters by the large panels were in the range 150 to 200 kN/m. Maximum peak values measured with the pressure cells were in the range 1000 to 1500 kPa, similar to that of Marchenko (2018). Converting the pressure cell results to line loads, values between 200 and 1000 kN/m were determined. This experience on dams indicates a factor of 5 reduction in line load as the measurement width increases by a factor of 5 (200 mm to 1m width). Using the guidance of ISO 19906:19 a further reduction by at least a factor of 2 could be expected, so a line load of 500 kN/m could be applied for global load on a 100 m wide structures.

The work on dams in Sweden and Canada identify water level change as an important factor in ice loading on dams (Comfort et al, 2003 and Hellgren and Malm, 2024). Stander (2006) has identified a mechanism to connect ice pressure variations of 200 to 400 kPa to reservoir water level changes. Stander et al (1988) and Frederking (2021) have also proposed mechanisms relating ice pressures to tidal action. Quantifying such a relation remains an area requiring work.

Suggested guidance for proposed port structures:

1. Survey local conditions; evolution of ice conditions, use CIS regional charts and a tool like CASRAS (Sudom et al, 2023) to quantify ice regime development (concentration, floe size, thickness) for freeze-up, fast ice period, break-up, summer drift ice; also tide, currents, weather.
2. Consider how the proposed port structure will modify the ice conditions and ice loading mechanisms.
3. For periods when drifting ice generates loads, ISO 19906:19 can be used following guidance in Croasdale et al (2021), noting that the extrapolated movement amount is much shorter than measurement experience.
4. For periods when ice is landfast, consider mechanisms such as tidal jacking and measurements at Nanisivik, Svalbard and dams for guidance on ice pressures and loads.
5. Measurements of ice pressures on hydropower dams provide guidance on extrapolating small scale ice pressure data to larger scale global ice load estimations.
6. Additional analysis of the thermal effects on line loads observed at Nanisivik is warranted to understand the degree to which underlying loading mechanism are understood and captured in the design standards.

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