Ice

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Ice Guideline for Docks in the Lower Thames River
Technical Background: Final Approved Report

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CAO/Secretary-Treasurer
Lower Thames Valley Conservation Authority
100 Thames Street
Chatham, ON N7L 2Y8

Sent by email to: mark.peacock@ltvca.ca

Dear Mr. Peacock:

Thank you for your comments regarding my previous submissions. These have been addressed and I am pleased to submit this final, approved report.

Please do not hesitate to contact me with any further comments. Thank you.

Yours truly,

George Comfort

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Ice Engineering Technical Specialist
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1.0 Introduction and Objectives

1.1 Background and Objectives

It is well known that ice problems occur regularly in the lower Thames River. There is a long history of ice jams on the river; and in parallel, efforts have been made for more than four decades to investigate ice problems and potential solutions for mitigating them.

The Lower Thames Valley Conservation Authority (LTVCA) is often asked to make decisions regarding whether or not docks are permitted on the Thames River. The LTVCA has found that even robust docks suffer damage from flooding and ice push/jam events. A detailed approach is lacking for the LTVCA to make informed decisions regarding a given proposed dock.

The overall objective of the work proposed here was to produce an Ice Guideline that would assist the LTVCA in decision-making with respect to permitting for docks regarding ice issues. This report provides technical background to the Engineering Ice Guideline that was prepared (Comfort, 2021).

1.2 General Description of Project Scope

The work included the following:

(a) Information review – an extensive bibliography of relevant information was provided by the LTVCA, which included technical reports, conference papers, presentations made by the LTVCA, aerial photos for 82 docks in the lower Thames River from aerial surveys in 2015 and 2016, and more than 2000 photos and videos showing ice conditions. This was supplemented with other material as appropriate that is available in the literature.

(b) Ice environment definition – key ice properties such as the ice thickness and strength were quantified.

(c) Evaluation of the ice actions (loads, jams, pileups, etc.) that will be "seen" by a dock – this work started by assessing the ice-dock interaction modes, based on the available photos in combination with judgement. Next, the ice actions were quantified as appropriate. This included defining both horizontal and vertical ice loads.

(d) An evaluation of the likely effect of docks on potential ice jamming problems. This was done empirically, making use of the extensive experience of the LTVCA.

(e) Recommendations and conclusions – this included providing recommendations regarding the monitoring that should be done by the LTVCA.

(f) Engineering Ice Guideline – this was a concise document intended to provide detailed information for calculating ice loads. It was provided under separate cover.

1.3 Applicable Return Period for the Ice Guideline

1.3.1 Background

The return period or annual probability of occurrence is a very important issue as ice actions are environmental processes which vary in severity from year-to-year. The LTVCA provided the guidance that the Ice Guideline should generally err conservatively with respect to ice actions and issues as it wishes to avoid ice-related problems in the future (M. Peacock, LTVCA, personal communication).

The following inter-related issues must be considered:

(a) The return period or annual probability of occurrence for the design ice loads
(b) The safety or load factors that must be applied to the design ice loads.

1.3.2 Other Design Codes for Ice

Recognizing that no codes or guidelines are available that are directly applicable to ice problems for docks in the lower Thames River, other existing ice-related codes were reviewed.

<u>The Canadian Highway Bridge Design Code (CSA S6-19, 2019)</u> has been in common usage for bridges and other riverine structures for the past four decades. It does not provide specific guidance regarding the appropriate return period for ice actions. No doubt, this reflects the fact that the CSA S6 code was developed several years ago when probabilistic design was less-developed.

<u>The International Electrochemical Commission code (IEC 61400 - IEC, 2008)</u> was developed for offshore wind platforms. Specific overall guidance is not provided although IEC 61400 states that the 50-year ice thickness is to be used for calculating ice loads arising from impacts with moving sheet ice in “offshore” areas.

<u>The International Standards Organization (ISO) code for offshore oil and gas structures (ISO 19906)</u> is important because it was developed based on the consensus of worldwide ice experts. It was first published in 2010 (ISO, 2010), which was adopted as a Canadian standard by CSA (CAN/CSA-ISO, 2011). Recently it was updated with a FDIS (Final Draft International Standard) version (ISO, 2018). This code provides the only direct treatment to my knowledge. It specifies annual probabilities of occurrence for ice actions for various limit states (i.e., serviceability, ultimate, fatigue, and accidental), and exposure levels.

The exposure levels depend on the consequences of a failure (e.g., potential loss of life, possibility for pollution); and whether or not the structure is manned with facilities for evacuation, as follows:

(a) L1, the most stringent exposure level, for manned platforms, for platforms with hydrocarbon storage, or platforms flowing hydrocarbons that cannot be shut in for the design environmental conditions;

(b) L2, an intermediate exposure level for unmanned or not normally manned platforms that do not store hydrocarbons.
(c) L3, the least stringent exposure level, for unmanned platforms and those not flowing or storing hydrocarbons.

For L1, L2, and L3 structures, ice and met-ocean loads are specified at the extreme-level (EL), with annual probability of exceedance of 10^{-2} (100-year return period). The abnormal-level (AL) loads are specified at an annual probability of exceedance of 10^{-4} (10,000-year return period) for L1 structures and at an annual probability of exceedance of 10^{-3} (1,000-year return period) for L2 structures. Abnormal-level loads do not apply for L3 structures. Generally, the Ultimate Limit State (ULS) criteria are satisfied by EL loads multiplied by a factor greater than 1, while Accidental (ALS) criteria are satisfied by AL loads multiplied by a factor of 1.

For ice loads on L1 structures, ULS checks are carried out for ice load combinations (where ice is the principal load) using a load factor of 1.35 on the EL value. For L2 structures, ULS checks are carried out for ice load combinations using a load factor of 1.10 on the EL value. While not provided in the ISO 19906 standard, a load factor of 0.85 on the EL value was estimated for L3 structures in the calibration of the standard (OGP, 2010).

The extreme level (100-year) ice load is first added together with associated met-ocean loads, live loads and dead loads multiplied by partial factors or combination factors, and then the sum is multiplied by the load factor. ISO 19906 provides default partial factors for combinations where ice is the principal load. Where the companion action is stochastically dependent, the factor is 0.9. Where the action is stochastically independent, the factor is 0.6. ISO 19906 also allows the user to consider joint probability distributions and thereby justify the use of other partial factors.

For ULS checks, the strength of each member or joint is divided by partial resistance factors (≥1) that are specified for steel structures in ISO 19902 (CAN/CSA-ISO, 2013). Different resistance factors are applied to different types of members. To meet the requirements of the ISO 19900 series of standards, the factored resistance should be greater than or equal to the factored load. For ALS, the resistance factor is normally equal to 1.

According to ISO 19902 (CAN/CSA-ISO, 2013), action and resistance factors for FLS in steel structures are both equal to 1.

1.3.3 Recommendations

The following recommendations are made for the Ice Guideline for Docks:
(a) Applicable return period for ice actions – this should be taken as 100 years.
(b) The safety factors that must be applied – this is a related issue of course. Recognizing that LRFD (Load and Resistance Factor Design) is typically used at present, it is my opinion that factors should be applied to both the loads, and the foundation or structural resistance, in accordance with the National Canadian Building Code.

2.0 Range of Applicability

Overall, this Ice Guideline is limited to technical matters related to ice actions and issues on docks in the lower Thames River. It is not intended to cover items that are to be addressed by policy.

2.1 Docks

2.1.1 Overview

This Ice Guideline is intended to be applicable to "recreational" docks, and not "industrial" ones. This removes sheet pile/retaining walls from consideration for the Ice Guideline. To obtain further information, aerial photos for 82 recreational docks in the lower Thames River were reviewed. These photos were obtained from the MNRF Swoop imagery taken in 2015 and 2016. Most of the docks were downstream of Chatham.

Dock configurations for the lower Thames River can be broadly divided into the following general categories:

(a) A single-piece dock that is placed along the shore – these docks tend to be generally rectangular. See Figure 2.1 for an example.
(b) A two-piece dock that consists of a walkway extending out from shore to a deck offshore, at the end of the walkway. See Figure 2.1 for an example.

Single-piece dock alongshore

Two-piece dock with walkway

Figure 2.1: Sample Docks in the Lower Thames River (photos courtesy of LTVCA)

With respect to ice actions, it is of interest to define the following overall dock dimensions:

(a) The length that the dock extends out into the river (termed the "offshore" length) – the offshore length averaged about 5.5m, with a range from about 1 to 12.5m. Figure 2.2

shows the dock with the largest offshore length. The offshore length has an important effect on the ice forces exerted on the dock components perpendicular to shore, in the downstream direction due to ice moving with the flow. This affects the normal forces exerted for impacts with sheet ice, and also the length which acts to "catch" pack ice forces during an ice run.

(b) The length that the dock extends along the shore of the river (termed the "alongshore" length) – the alongshore length averaged about 10.9m, with a range from about 1 to 124m. Figure 2.2 shows the dock with the largest alongshore length. The alongshore length affects the ice loads produced on the "alongshore" part of the dock by ice moving in the direction of the river flow such as the shear forces exerted on the dock for impacts with sheet ice, and the shear forces resulting from pack ice forces during an ice run.

Dock with max. offshore length (i.e., 12.5m)

Dock with max. alongshore length (i.e., 124m)

Figure 2.2: Selected Docks in the Lower Thames River (photos courtesy of LTVCA)

Although the LTVCA does not have a record of the docks which suffer damage, and dock owners are not required to report this, three of the docks could be identified as having suffered ice-induced damage (V. Towsley and J. Homewood, LTVCA, personal communications).

(a) 6816 Riverview Line (Figure 2.3) – this location is on an "outside" bend in the river. The dock is 9m x 3.5m in size. It was built to be raised and lowered so that in winter, only the 4"-6" concrete-filled steel posts supporting the deck would be exposed to ice. The steel posts were bent by the ice to the point that, within a couple of years, they were no longer usable as supports for the dock. This structure is no longer present at the site.

(b) 106 William Street North (Figure 2.3) – this location is on an "inside" bend in the river. The dock is 12.5m x 3.5m in size. This dock is maintained by the owner who is a contractor. Regular maintenance is required due to damage suffered during ice events.

(c) 0 Riverview Drive (Figure 2.4) – this location is on an "outside" bend in the river. This is the municipal dock on Riverview Drive by the Kiel Drive Bridge. The dock is 124m x 2.5m in size, with a 4.5m x 4m walkway. The dock was found to be damaged at its far west end (see arrows in Figure 2.4) following the 2019 ice jam (J. Homewood, LTVCA, personal communication). The deck was damaged and it is not known if the piles supporting it were damaged as well.

6816 Riverview Line

106 William St. North

Figure 2.3: Docks with Ice-Induced Damage (photos courtesy of LTVCA)

Figure 2.4: Dock with Ice-Induced Damage (photo courtesy of LTVCA)

2.1.2 The Components of a Dock

"Recreational" docks can be considered to have the following components:

(a) The abutment – which connects the dock to shore. This might be concrete for example.
(b) The support for the dock – for example, this might be piles or cribs. Although cribs are not likely to be allowed by DFO/MNRF (J. Wintermute, LTVCA, personal communication), they were included in the Ice Guideline for completeness.
(c) The superstructure – the Ice Guideline is limited to open decks. Other potential additions such as a canopy or a deckhouse were beyond the scope of the Ice Guideline. These would be governed by policy (M. Peacock. LTVCA, personal communication).

Because all of the existing docks are vertical, this Guideline is limited to vertical structures.

The Ice Guideline provides separate guidance for each of these dock elements as a given case may not involve all three components. For example, some docks might get taken out in winter, leaving only the piles exposed to ice. Furthermore, the Ice Guideline considers the effects of dock layout, for docks that are either: (a) perpendicular to the shoreline; or (b) parallel to it.

Anchored docks are a complex case as many scenarios are possible. Furthermore, an anchored dock has flexibility that allows it to absorb some ice movements without failing, depending on the scope of the mooring system. This is particularly true for vertical loads as the water level changes in the river are limited. This is not true for horizontal loads as large ice movements do occur. To avoid undue complexity, anchored docks were not covered explicitly in the Ice Guideline except to state that the anchors and mooring system must be adequate to withstand the horizontal and vertical ice loads on the deck, as given in subsequent sections.

2.2 Geographic Region

The Ice Guideline's area of jurisdiction extends from the mouth of the Thames River up to Communication Road, which is near the eastern city boundary for Chatham. Furthermore, the Ice Guideline's area of jurisdiction is limited to the lower Thames River, and it excludes the tributaries (i.e., various creeks and canals) that feed into the river.

2.3 Dikes

Dikes are a very important consideration as about half of the river shoreline in the area of jurisdiction for the Ice Guideline is diked. Most of the dikes are along the shore although some are up to about 100 m back. This issue is complicated because the various dikes have different ownerships. The LTVCA does not want to have any construction on dikes (M. Peacock, LTVCA, personal communication).

Dikes are out-of-scope for the Ice Guideline as they will be covered by policy (M. Peacock, LTVCA, personal communication).

3.0 The Ice Environment and Ice Design Criteria

3.1 Ice Information Sources

The ice information sources included the following:

(a) An extensive set of more than 2000 photos and videos dating back as far as 1979.
(b) Several presentations and briefing notes describing the ice jamming process and the ice jam risk (e.g., Wintermute, 2015).
(c) Ice thickness data from the LTVCA – the annual maximum ice thickness was provided for winters from 1977 to 2015, a period of 39 winters. As well, the LTVCA provided copies of the analyses that it has done over the years relating for example, the ice thickness to the Freezing Degree Days (FDDs).

3.2 The Ice Regime

In general, the ice regime can be divided into the following periods:

(a) Freeze-up – the ice is thin but relatively strong at this time. It is known that freeze-up ice jams can occur at some sites, but because the LTVCA's experience is that the most severe jams occur in late-winter, freeze-up jams were discounted here.
(b) Mid-winter – the ice is essentially static during this period, and ice temperature changes are the main (practically the only) mechanism for generating ice forces. It is noted that in "light" winters (about 25% of the LTVCA's record – described subsequently); the maximum ice thickness was nil, which shows that the "mid-winter" period doesn't always occur. This is normal for southern locations. However, it is evident from the LTVCA photos that for the winters which were not "light", there must have been a "mid-winter" period as the river's ice cover consisted of a solid sheet which was broken up in several stages in spring as the ice began to move. These ice conditions are the most severe ones for generating ice loads in mid-winter. However, thermal ice loads are typically much less than those produced by mechanical ice failures at the dock (e.g., crushing, shear, flexure, ice jamming, etc.), which would occur during breakup (discussed later).
(c) Break-up – large ice movements occur during breakup, as the ice cover continually breaks up into smaller and smaller ice pieces. At this time, the key ice properties are the ice thickness and the ice strength, which are discussed in the sections that follow. Similar considerations would be involved for the other relevant strengths such as flexure and shear, which limits the vertical forces exerted by "jacking" on piles.

3.3 Ice Thickness

3.3.1 Focus of Investigation

For the Ice Guideline, it is most useful to focus on the annual maximum ice thickness as the ice loading events of concern would occur in late winter when the ice has reached its peak thickness. The ice would be effectively at its maximum thickness, although some thickness decay may be present in some cases (i.e., later breakups). However, the ice thickness decay would be hard to predict given that the timing of the breakup events varies; and that the state-of-the-art is not well-developed for predicting ice decay. Thus, this report is focussed on the annual maximum ice thickness.

It is noted that the LTVCA has performed other analyses (e.g., relating the ice thickness to the freezing degree days). They are useful as they allow the ice thickness to be estimated over the duration of the winter. Also, they provide one approach for evaluating the return period of various ice thicknesses.

However, the analyses in this report were focussed on the data provided to define the annual maximum ice thickness. This avoids potential uncertainties related to modelling ice thickness growth using FDDs. Furthermore, the period of record is 39 years long which is extensive enough to obtain reliable results in my opinion.

3.3.2 The Annual Maximum Ice Thickness

The annual maximum ice thickness over the past 39 years has averaged 0.24m, ranging from nil to 0.58m. It is noteworthy that for about 25% of the winters, the ice thickness was nil (Figure 3.1). This was considered in establishing the design ice thickness.

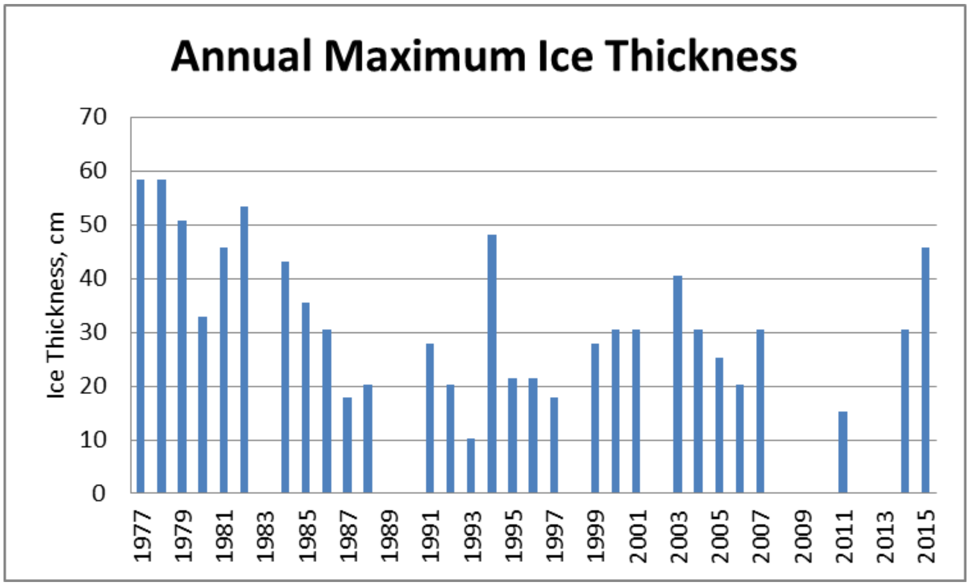


Figure 3.1: Annual Maximum Ice Thickness

3.3.3 Relationship between the Thickness and Winters with “Bad” Flooding

The LTVCA provided context regarding which winters had “bad” flooding (i.e., 1979, 1981, 1984, 1985). This is useful as it helps to explore the relationships. However, it was difficult to establish trends as:

(a) there is not a clear correlation as "bad" flooding is not directly correlated to thicker ice; and;
(b) there is an overall trend of decreasing ice thickness with time over the approximate 1977-1988 period.

For simplicity, it is recommended that the design ice thickness in the Ice Guideline be based directly on the data.

Statistical analyses were carried out using a commercial statistics program (Easy Fit Professional version) to determine the best-fit distribution. Overall, the program identified the Uniform distribution as the best-fit one, with the Johnson SB being second-best. The Johnson SB distribution was selected as it provided a good degree of fit while providing a distribution that was physically credible (Figure 3.2).

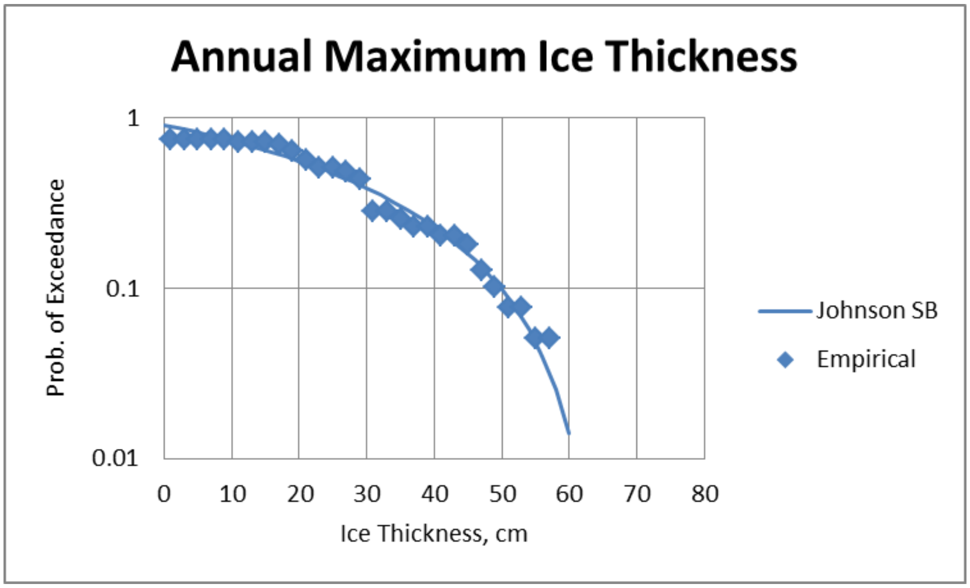


Figure 3.2: Annual Maximum Ice Thickness

This analysis predicted that annual maximum ice thicknesses of 0.50, 0.59 and 0.61m would have return periods of 10, 50 and 100 years respectively.

3.3.4 Possible Effects of Climate Change

The data seem to indicate an overall trend of reducing ice thickness with time (Figure 3.1). However, the trend is weak and the results are quite scattered, indicating that the results are subject to significant variability. This makes it quite uncertain to incorporate the potential effects of climate change. In my opinion, this potential trend (of ice thickness vs time) is too weak and scattered to incorporate into Ice Guideline reliably.

It is recommended that the Ice Guideline be developed based on the ice thickness data presently available, without taking into account potential effects of climate change. This will simplify the Ice Guideline, making it easier to use; and furthermore, this approach most likely errs conservatively.

3.4 Ice Strength

3.4.1 Focus of Investigation

This issue is complex because the relevant ice strength depends on the ice failure mode.

Also, the ice strength varies during the winter. At breakup, when severe loading events occur, the ice would be somewhat deteriorated, so its strength would be reduced.

This is illustrated using the ice crushing strength as an example, which is relevant for vertical structures where the ice fails in crushing. The CSA S6 Highway Bridge code (CSA, 2019) has four ice strength categories in it with qualitative descriptions for each as summarized in Table 3.1.

Table 3.1: Ice Effective Strength Categories in CSA S6 (CSA, 2019)

Ice Description	Ice Strength, kPa
Ice breaks up at melting temperatures and is substantially disintegrated	400
Ice breaks up at melting temperatures and is somewhat disintegrated	700
Ice breaks up or ice movement occurs at melting temperatures and is internally sound and moving in large pieces	1100
Ice breaks up or ice movement occurs at temperatures considerably below the melting point of the ice	1500

The ice strength varies by about a factor of about 4 among them. To keep the Ice Guideline simple, and to avoid analyses related to the timing of breakup events, it is recommended that the ice effective crushing strength be taken as 1100 kPa. This will add some conservatism to the Ice Guideline as no doubt, a lower strength might be appropriate in some cases.

Similar considerations would be involved for the other relevant strengths such as flexure and shear, which limits the vertical forces exerted by “jacking” on piles (discussed in subsequent sections). The ice at freeze-up is stronger than that at breakup, owing to the prevailing air temperatures for those periods. Ice flexural strengths of 500 kPa and 250 kPa would be reasonable values for freeze-up and breakup respectively in my opinion.

3.4 Other Important Ice Parameters – Annual Frequency of Ice Loading Events

This affects the probability that a dock will “see” a given loading event. This parameter was included in the analyses by evaluating its effect on the ice thickness, which has an important effect on the ice loads. This was considered by referring to:

(a) annual maximum ice thicknesses for the lower Thames River– these data indicated that the annual maximum ice thickness was nil for 10 of the winters over a 39-year period of record. Clearly, the breakup loads would be much reduced for these winters.
(b) local knowledge which is reflected in the extensive set of photos and videos (i.e., more than 2000) provided by the LTVCA.

For this report, the design ice thickness was determined using the equation below.

$$P_{\text{design ann\_max thick}} = P_{\text{non-zero event}} * P_{\text{ann max thick for all non-zero events}} \qquad [3.1]$$

where:

$P_{\text{design ann\_max thick}}$ = the annual probability of a given annual maximum ice thickness
$P_{\text{non-zero event}}$ = the probability that the annual maximum ice thickness will be non-zero
= 0.74 (i.e., 29 non-zero values out of a 39-year record)
$P_{\text{ann max thick for all non-zero events}}$ = the probability for the annual maximum ice thickness (Figure 3.2)

Taking the annual frequency of events into account, the design ice thicknesses was reduced to 0.47, 0.58 and 0.60m for return periods of 10, 50 and 100 years respectively.

4.0 Ice Loading Scenarios

4.1 Overview

The ice actions of concern vary with the period in the winter as well as the type of dock structure.

4.2 The Abutment for the Dock

The ice loading mechanisms of concern for the abutment include the following:

(a) Intact sheet ice moving horizontally against or along it – This would occur during “ice breakout” at spring when an essentially intact ice sheet is moved past or against the abutment; and this is the first step in ice breakup. The ice forces generated by this scenario are governed by:

   a. The ice properties – thickness and strength. Note because these movements may occur in any horizontal direction, the ice forces will be controlled by the ice strength in both crushing and shear.
   b. The geometry of the abutment – the ice forces will be controlled by the “offshore length” that the abutment protrudes out into the river as well as by the “alongshore length”. The offshore corners of the abutment require special attention as the ice may “catch” a corner, leading to higher ice forces there.

(b) Ice jam or pack ice moving against it or past it in any horizontal direction – this will occur later on during the breakup process. The abutment geometry (offshore and alongshore length, orientation to the river, etc.) will have an important effect on the ice loads.

   The ice properties are also important although detailed understanding is not presently available regarding the relationship between the ice properties and the ice loads. The most generally-accepted methods involve empirical approaches. For example, CSA S6-19 defines the ice jamming pressure on a bridge pier as 5 or 10 kPa, depending on whether or not clear span is less than or more than 30 m respectively. Other methods (developed for sea ice) also utilize an empirical approach.

(c) Vertical ice movements caused by water level changes – This case will exert purely vertical loads that will be controlled by the load to fail the ice, through bending and the formation of radial and circumferential cracks. It is expected to be a minor loading case if the ice is melted free from the abutment at breakup. However, it is unclear that this would happen in all cases so it has been included in the overall evaluation.

4.3 The Supporting Structure

The supporting structure can be broadly subdivided into fixed structures (e.g., piles or cribs); and anchors and flotation cells for floating docks.

For docks with fixed structures (e.g., piles or cribs), the ice loading mechanisms include the following:

(a) Horizontal movements of an ice sheet – these would occur during “ice breakout” at spring when an essentially intact ice sheet is moved past the dock; and they are the first step in ice breakup. This process would exert horizontal loads on the structures. The ice failure process depends on the shape of the piles or cribs. For vertical ones, the ice will fail in crushing. If the structures are sloped, flexure will act to relieve the ice load, as ice is much stronger in compression than bending. However, the slope must be less than about 60° for this effect to start to be significant. Hence, unless a dock proponent was going to put cones on the piles (as an example); the ice loads on the piles or cribs will be governed by crushing.

(b) Vertical movements of the ice sheet due to water level changes – these cause “jacking” on structures, and exert vertical loads on them. The maximum ice force is governed by the load to fail the ice through cracking, notably by forming radial and circumferential cracks.

(c) Horizontal movements of an ice pack – this case was considered for completeness although it is practically certain that horizontal movements of an intact ice sheet would exert higher loads.

4.4 The Deck of the Dock

The ice loading mechanisms of concern for the deck include the following:

(a) Ice jams and moving pack ice – this imposes forces that are mainly horizontal, although ice can “pack” under the deck and push it up. The ice forces are controlled by:
   a. The deck size – The “length” that it projects out into the river is very important as it controls how much of the jamming force is “collected” and concentrated onto the deck. The “depth” of the deck (into the water) also has some effect.
   b. The ice properties – the detailed relationship between the load and the ice properties is not well understood, and most methods for predicting ice jam loads (or the ice ridge-building load which is a similar process) involve an empirical approach. For example, CSA S6 defines the ice jamming pressure on a bridge pier as 5 or 10 kPa, depending on whether or not clear span is less than or more than 30 m respectively. Other methods (developed for sea ice) also utilize an empirical approach.

(b) Water level changes – these induce purely vertical forces, which, in the limit, are controlled by the force to fail the ice being uplifted through cracking and flexure.

5.0 Horizontal Ice Loads

5.1 Ice Loading Scenarios

Ice horizontal forces may be produced by the following mechanisms:

(a) Ice temperature changes, which induce thermal loads on a structure
(b) Impact of level ice sheets with the structure
(c) Ice jamming

These mechanisms may affect various parts of a dock, as summarized in Table 5.1.

Table 5.1: Summary of Applicable Mechanisms for Creating Horizontal Forces

Component	Thermal Loads	Ice Jamming	Impact of Sheet Ice (note 1)
Abutment	Present in mid-winter	Present at breakup	Present at breakup
Supports (piles, cribs)	Present in mid-winter	Present at breakup	Present at breakup
Deck or Walkway	May be present in mid-winter, if deck is frozen into the ice (Note 2).	Will be present at breakup (Note 2).	Present at breakup, if the deck elevation is such that ice contact occurs (Note 2).

Notes:

1. An impact may occur during an ice run when large ice floes are carried downstream by the river flow. A similar ice loading could occur in the early stages of breakup, when the intact ice sheet is first broken loose and moved out, causing it to fail against structures frozen into it.
2. A water level rise typically occurs at breakup which acts to elevate the ice sheet, thereby affecting which parts of a dock are in contact with the ice.

5.2 Thermal Ice Loads

Thermal loads will be the primary ones for the mid-winter period. A line load of 150 kN/m is typically used as a design value for static ice loads on hydro-electric dams in Canada, for all ice thicknesses. Table 5.2 summarizes the peak loads measured during a 20-year field program undertaken in Canada to measure ice loads on dams (e.g., Comfort et al, 2003; 2012). In total, ice loads were measured at 11 sites in 4 provinces in Canada. For the case where negligible water level changes occurred, the peak measure line load was 85 kN/m.

As an overall conclusion, a conservative estimate for the thermal loads exerted on docks in the lower Thames River is 150 kN/m.

It will be shown subsequently that thermal loads are not the governing ones, as the loads due to ice impact are considerably greater.

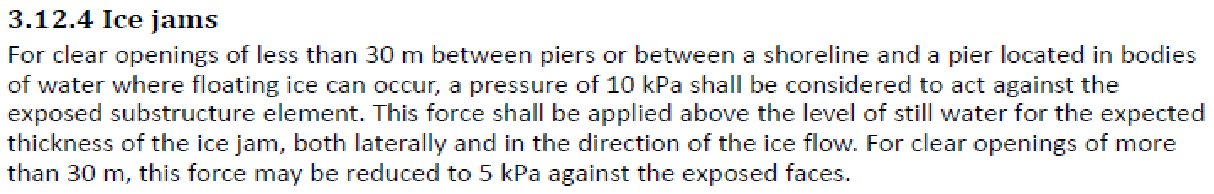
Table 5.2: Peak Static Ice Loads Measured at Hydro-Electric Dams in Canada

Case	Site	No. of Years	Peak Load, kN/m
Negligible Water	Paugan GS, Que.	3	70
Level Changes	NRC Basin, Ont.	1	47
Occurred	Seven Sisters GS, Man.	1	62
	Pine Falls GS, Man.	2	61
	MacArthur Falls GS, Man.	2	85
	La Gabelle GS, Que.	2	38
	Beaumont GS, Que.	2	13
Significant Water	Arnprior GS, Ont.	6	210;213 (2 winters)
Level Changes	Otto Holden GS, Ont.	3	65
Occurred	Seven Sisters GS, Man.	4	324; 374 (2 winters)
	Churchill Falls GS, Lab.	1	89
	Barrett Chute GS, Ont.	1	82

Legend: GS: Generating Station

5.3 Ice Loads Produced by an Ice Jam

The Canadian Highway Bridge Design Code (CSA S6) provides information for determining ice jamming forces (Figure 5.1).



3.12.4 Ice jams

For clear openings of less than 30 m between piers or between a shoreline and a pier located in bodies of water where floating ice can occur, a pressure of 10 kPa shall be considered to act against the exposed substructure element. This force shall be applied above the level of still water for the expected thickness of the ice jam, both laterally and in the direction of the ice flow. For clear openings of more than 30 m, this force may be reduced to 5 kPa against the exposed faces.

Figure 5.1: Ice Jam Forces (CSA, 2019)

A pressure of 10 kPa is recommended for calculating ice jam forces on docks in the lower Thames River. To provide initial information, exploratory calculations were done to determine ice jamming line loads presuming that the ice jam extends through the full water depth:

(a) Water depth of 3m: Ice jam line load = 30 kN/m
(b) Water depth of 4m: Ice jam line load = 40 kN/m
(c) Water depth of 5m: Ice jam line load = 50 kN/m

As will be shown subsequently, these loads are much lower than those produced by the impact of a level ice sheet. Consequently, they are not likely to be the governing case, although they must be checked as part of the design process.

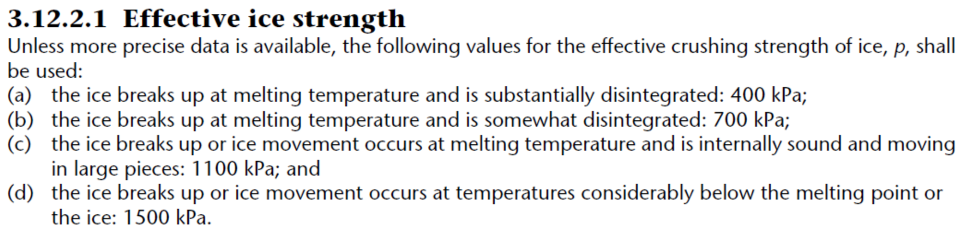
5.4 Ice Loads Produced by the Impact of a Level Ice Sheet

5.4.1 The Calculation Approach in the Canadian Highway Bridge Design Code (CSA S6)

The calculation approach in CSA S6-19 (CSA, 2019) is considered to be most relevant one available for sheet ice impact loads on docks in the lower Thames River. It has been extensively used for bridges, which is considered to be analogous. It should be recognized that the development process for the CSA S6-19 algorithms included several years of extensive field measurements of ice loads on bridges. This technical foundation is unique and not included in the basis for many other formulae in the literature.

Key aspects of the calculation process in CSA S6-19 are summarized in Table 5.3.

Table 5.3: Summary of the Key Components in CSA S6 for Calculating Ice Impact Loads

Item	Approach
Ice load due to bending failure, F_b	$F_b = C_n \sigma t^2$ [5.1] where: $C_n = 0.5 \tan(\alpha + 15°)$ α = the angle between the pier face and the horizontal σ = the ice strength, which is to be selected from the values below
Ice load due to crushing failure, F_c	$F_c = C_a \sigma t w$ [5.2] where: C_a = aspect ratio coefficient = $[(5t/w) + 1]^{0.5}$ w = the pier width t = ice thickness
Ice bending to crushing transition, F_{bc}	$F_{bc} = [(C_n + \sqrt{66})/72]\, \sigma w^2$ [5.3]
Ice strength	 **3.12.2.1 Effective ice strength** Unless more precise data is available, the following values for the effective crushing strength of ice, *p*, shall be used: (a) the ice breaks up at melting temperature and is substantially disintegrated: 400 kPa; (b) the ice breaks up at melting temperature and is somewhat disintegrated: 700 kPa; (c) the ice breaks up or ice movement occurs at melting temperature and is internally sound and moving in large pieces: 1100 kPa; and (d) the ice breaks up or ice movement occurs at temperatures considerably below the melting point or the ice: 1500 kPa.
Governing ice load, F	• Ice crushing load <= ice bending force: $F = F_c$ • Ice crushing load > ice bending force: ○ if $F_{bc} >= F_c$, $F = F_c$ ○ if $F_{bc} <= F_b$, $F = F_b$ ○ if $F_c > F_{bc} > F_b$, $F = F_{bc}$

The reader should refer to the Code for detailed evaluations. The algorithms in CSA S6-19 are based on the assumption that the environmental conditions (e.g., the kinetic energy of drifting ice floes) are sufficient to allow the ice load to reach the force to fail the ice (termed "limit-stress").

Firstly, the engineer is required to calculate the ice force resulting from: (a) ice bending failure, F_b; (b) ice crushing failure, F_c, and; (c) the transition between the bending and crushing force, F_{bc}. The ice force, F, is determined based on the fact that ice loads will be governed by the failure process leading to the lowest loads. The logic for determining the governing ice load case is also shown in Table 5.3.

It must be recognized though that CSA S6 was developed for application to highway bridges; and not all of it is believed to be applicable to docks in the lower Thames River. The following ice-related parts of it are considered to be inapplicable here:

(a) Design Cases 1 and 2 - To conform to CSA S6, the engineer is required to determine the longitudinal and transverse forces for two cases applicable when the longitudinal axis of the bridge pier is closely aligned with the flow. These are included in CSA S6 to account for the tendencies seen in the field data supporting CSA S6 for ice to fail non-symmetrically around a bridge pier as the ice moves past the pier in an open river. These are not considered to be relevant to ice loads on docks in the lower Thames River as the docks are close to the shoreline so the ice is more confined.

(b) Non-aligned piers – CSA S6-19 provides guidance for the case where the bridge piers are skewed to the flow. This is considered to be inapplicable as the docks are close to the shoreline so the ice is more confined. However, for docks in the lower Thames River, ice loads must be determined for all possible loading directions, as discussed subsequently.

(c) Small streams - CSA S6 provides guidance for the case where the river flow may be insufficient to allow the limit-stress ice force to be developed. This is inapplicable as during an ice run, the flow in the lower Thames River is high.

5.4.2 Recommended Ice Design Criteria for Calculating Ice Impact Loads

The following key ice properties must be defined to use the algorithms in CSA S6:

(a) The ice thickness, t: It is recommended that this be taken as 0.6m, which is the 100-year ice thickness for breakup for the lower Thames River (Section 3).

(b) The effective ice crushing strength, σ: It is recommended that this be taken as 1100 kPa, as discussed in Section 3.

5.4.3 Sample Calculations of Ice Impact Loads

Sample calculations were done for: (a) a single pile; (b) a single crib; (c) the deck of a dock, and; (d) an abutment. The calculations were done for a range of sizes considered to be realistic for each case (Table 5.4).

As expected, the load was controlled by the crushing force, F_c, as all structures were vertical. The highest line loads occurred for the pile and the lowest line loads occurred for the abutment as these structures have the smallest and largest loaded widths respectively. Note that the line load reduces with the loaded width as defined through the aspect ratio coefficient, C_a in equation 5.2 (Table 5.3).

In all cases, the line loads due to sheet ice impacts were much larger than thermal ice loads and ice jamming loads. (Compare the line loads in Table 5.4 with those in Sections 5.2 and 5.3 respectively). This shows that sheet ice impacts will likely be the governing load case.

Table 5.4: Sample Calculations of Ice Impact Loads

General Case	Ice Thick m	Ice Strength kPa	Loaded Width m	Vertical Angle of Structure, °	Ice Force, F kN	Ice Line Load kN/m
Single Pile	0.6	1100	0.15	90	453.7	3024.5
Single Pile	0.6	1100	0.3	90	656.7	2189.0
Single Crib	0.6	1100	0.9	90	1236.5	1373.9
Single Crib	0.6	1100	1.2	90	1481.7	1234.7
Deck of Dock	0.6	1100	3	90	2800.1	933.4
Deck of Dock	0.6	1100	4	90	3492.4	873.1
Deck of Dock	0.6	1100	5	90	4174.2	834.8
Abutment	0.6	1100	10	90	7525.2	752.5
Abutment	0.6	1100	20	90	14155.4	707.8
Abutment	0.6	1100	30	90	20766.4	692.2
Abutment	0.6	1100	40	90	27372.1	684.3

5.5 Corners

The deck protrudes from the river shoreline, which causes it to have offshore “corners” exposed to the ice. Also, the geometry of the dock may include exposed corners, such as at the joint between a walkway and deck. The ice action at these corners will be more severe than that along the “straight” wall portions of the dock.

More severe ice action will occur over deck lengths that are 0.6m or less away from the corner points for any exposed corners, or abrupt changes in geometry.

The line load for the corner sections affected by stress concentrations should be presumed to be three times the line load calculated using equations 5.1 to 5.3.

5.6 Summary of Overall Design Basis and Application Notes

5.6.1 Summary of the Process for Calculating Unfactored Horizontal Ice Loads

The analyses must start by assessing the elevation of the dock with respect to water level, as this affects which dock components will be exposed to ice. This will vary as the water level is typically elevated at the time of an ice run. Three cases are possible as follows:

(a) The water level is low enough that the ice only contacts the piles or supports beneath the deck.
(b) The water level is high enough that the ice only contacts the deck.
(c) The water level is in an intermediate range where the ice contacts both the deck and piles.

Ice loads must be considered for all three cases. Horizontal and vertical ice forces will be exerted by various loading scenarios (Table 5.5) on the dock components in contact with ice.

Table 5.5: Ice Loading Scenarios

Dock Component	Loading Type	Ice Loading Scenario		
		Impact by Sheet Ice	Water Level Change	Ice Jamming
Pile or Crib	Horizontal	Relevant load case	Not relevant	Relevant load case
	Vertical	Not relevant	Relevant load case	Not relevant
Deck or Walkway	Horizontal	Relevant load case	Not relevant	Relevant load case
	Vertical	Not relevant	Relevant load case	Relevant load case
Abutment	Horizontal	Relevant load case	Not relevant	Relevant load case
	Vertical	Not relevant	Relevant load case	Relevant load case

Next, the horizontal loads acting on the various individual dock components in contact with the ice must be calculated using the recommended approaches (Table 5.6). For some cases (e.g., horizontal ice loads on a pile or crib – Table 5.5), ice loads may get generated by more than one scenario. Ice loads must be calculated for all relevant ice loading scenarios; and the governing one must be taken as the one that produces the highest ice loads. Note that, for some but not all, of the cases listed in Table 5.5, the different ice loading scenarios would not occur at the same time. This is discussed further in the next section.

The individual horizontal ice loads should then be summed as appropriate taking into account the specific dock geometry and the water surface elevation.

Table 5.6: Recommended Approach for Horizontal Ice Loads on Individual Dock Components

Dock Component	Loading Type	Ice Loading Scenario and Recommended Calculation Approach		
		Impact by Sheet Ice	Water Level Change	Ice Jamming
Pile or Crib	Horizontal	As per Section 5.4 and 5.5	Not relevant	As per Section 5.3
Deck or Walkway	Horizontal	As per Section 5.4 and 5.5	Not relevant	As per Section 5.3
Abutment	Horizontal	As per Section 5.4 and 5.5	Not relevant	As per Section 5.3

Then, horizontal ice forces should be evaluated for the range of loading directions that is physically possible, as governed by the geometry of the river and the dock. The structure's structural integrity must be checked for all possible loading directions.

Finally, stress concentrations should be evaluated for corners and sharp changes in dock layout, such as at the joint between the walkway and deck of a dock. The dock must have adequate structural integrity to resist all possible stress concentrations.

5.6.2 Application Notes

The following notes are applicable to all cases related to horizontal ice loads.

(a) As discussed in section 6, vertical ice loads will also get exerted on the dock. The vertical and horizontal loads may or may not act at the same time as summarized below.
   a. Horizontal loads produced by ice impacts – these will not occur at the same time as the vertical loads produced by any of the mechanisms considered here. Hence, a combined case with both vertical and horizontal ice loads does not need to be included in the ice design criteria for this case.
   b. Horizontal and vertical loads produced by pack ice or ice jamming – these may occur at the same time. Hence, a combined case for these loads must be included in the ice design criteria.
   c. Horizontal loads produced by ice jamming and vertical loads produced by water level changes – these will not occur at the same time. Hence, a combined case for these loads need not be included in the ice design criteria for this case.

(b) The horizontal loads defined for all cases are unfactored. Load factors or safety factors must be applied to them within the context of the design basis being used.

(c) The dock's design should be in conformance with the National Building Code of Canada.

(d) Various components of the dock may be contacted by the ice (e.g., only the deck and a walkway if present; only the supports to the deck such as piles or cribs, and; a combination of the two). The dock must provide adequate structural integrity against horizontal ice loads for all possible cases. For the case where both the deck and the piles are contacted by the ice, the dock's structural integrity for horizontal ice loads must be checked for the case where the respective horizontal ice loads are exerted on each of the individual dock components (i.e., piles only and deck only).

(e) Horizontal ice forces shall be applied as a line load acting uniformly over the full width of contact between the ice and the pile or deck, or both, depending on the case being considered. Note that the ice load for the deck or walkway reduces with the loaded width (Section 5.4). Ice loads must be considered as follows:
   a. Deck or walkway – The deck's structural integrity must be checked for all possible loading widths. Furthermore, the location of the most severe ice load (corresponding to a low loaded width) may occur at any point along the length of the dock face or the walkway if present. The dock's structural integrity must be checked for all possible cases.
   b. Pile or cribs – The number of piles loaded during an ice impact may vary from only one, to all of those potentially in contact with the ice. The dock's structural integrity must be checked for all possible cases.
   c. Abutment - The abutment's structural integrity must be checked for all possible loading widths. Furthermore, the location of the most severe ice load (corresponding to a low loaded width) may occur at any point along the length of the abutment. Its structural integrity must be checked for all possible cases.

(f) For a dock with multiple components (e.g., a deck and a walkway), horizontal loads may act on either structure at the same time. The possible cases range from only one of the structures being loaded to all structures being loaded at the same time. The dock's structural integrity must be checked for all possible cases.

(g) Horizontal ice forces may be exerted from any direction that is physically possible, as governed by the geometry of the river and the dock. The structure's structural integrity must be checked for all possible loading directions. For an ice-dock contact oriented at an angle to the dock's longitudinal axis, horizontal ice loads should be resolved into components acting simultaneously that are normal to, and parallel to, the dock face. The deck's structural integrity must be checked for all possible loading directions.

(h) The ice line load should be presumed to act one third of the ice thickness below the water level. Because the water surface elevation can vary, all possible cases must be checked.

(i) Stress concentrations will occur at offshore corners of the dock, as well as at sharp changes in geometry such as at the joint between a deck and the walkway. The dock must have adequate structural integrity to resist all possible stress concentrations.

6.0 Vertical Ice Loads

6.1 Ice Loading Scenarios

6.1.1 Overview

Ice uplift forces may be produced by two mechanisms:

(a) Water level changes may occur, which would cause an ice sheet to move as well unless it is frozen to a structure. For sites where the water level may rise and fall, water level changes will exert vertical forces that act upwards and downwards respectively. For the lower Thames River, water level rises predominantly occur during breakup, due to increased river flow from snowmelt and rainfalls, although variable lake level conditions could also cause drops in water levels. Uplift forces (resulting from water level increases) are more likely to be of concern for a dock as they act to lift the dock off its supports, or to pull the dock supports (e.g., piles) out of their foundation; but both loading directions must be checked.

(b) During an ice run, ice may "pack in" underneath a structure such as the deck of a dock.

These mechanisms may affect various parts of a dock, as summarized in Table 6.1.

Table 6.1: Summary of Applicable Mechanisms for Creating Vertical Forces

Dock Component	Water Level Changes	Jamming of Pack Ice
Abutment	Vertical forces may be developed if ice is adhered to the abutment.	Not relevant
Supports (piles, cribs)	Vertical forces may be developed if the piles or cribs are frozen into the ice.	Not relevant
Deck	Vertical forces may be developed if the deck is frozen into the ice.	Vertical forces may be developed if ice "packs in" under the deck.

6.1.2 Ice Uplift Forces Produced by Water Level Changes

Ice uplift forces acting on a single pile are complex for many reasons:

(a) Progression of ice failure with time during the winter – Ice failure may occur steadily at the pile over the winter depending on the sequence of variations in water level fluctuations and air temperatures. This will create a complex ice failure pattern at the pile as the initial ice failure (in thin ice) will affect subsequent ice failure patterns. For further information, see Michel, 1978 and Zabilansky, 1986 among others.

(b) Ice failure locations: The ice may fail at either: (i) the ice-pile interface; or (ii) at some distance from it through radial and circumferential cracking. The latter mode will leave an ice cone adhered to the pile and possibly an open crack encircling the pile (Figure 6.1). Zabilansky, 1986 observed that, if the average air temperature has remained below 0°C and the ice is frozen to the pile, the ratio of the effective ice diameter to the pile diameter is about 1.5-2, 2, and 3 for wood, steel and concrete piles respectively.

Zabilansky, 1986 further commented that, if the average air temperature has fluctuated around 0°C, the ice failure location will be at the pile interface.

(c) Growth of an ice bustle: Ice may grow down the pile, creating thicker ice at the pile (Figure 6.2). This is especially true for hollow steel piles. The ice effective diameter will be much less if: (i) the pile has insulation inside it, or; (ii) it is jacketed, or; (iii) it is comprised of a material that retards heat flow such as wood.

(d) Variations in ice mechanical properties: Depending on the ice failure mode, the relevant ice properties may include its adhesive and shear strength at the pile, and the bending strength. These properties are dependent on many factors including the ice temperature, the ice grain size and type, and the loading rate, as load relief by ice creep will occur for slow loading rates.

(e) Variations in the ice adhesion strength at the pile: This is dependent on the properties of the ice and the substrate. The ice uplift force will be substantially reduced if the pile has a low-friction coating (e.g., CRREL, 2002; Zabilansky, 1989; Frederking, 1983).

(f) Scale effects: Ice failure processes may differ between small-diameter and large-diameter piles, leading to scale effects regarding the uplift forces.

Figure 1. Pile damaged by vertical forces.

Figure 2. Rubble pile surrounding a pile with sufficient anchoring.

Figure 6.1: Ice Failure Processes over the Winter (Zabilansky, 1986)

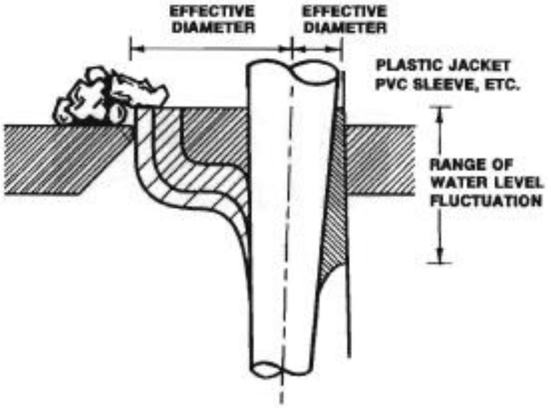


Figure 5. Left side is a cross section of a typical ice pile interface. Right side is a cross section of a jacketed pile.

Figure 6.2: Ice Effective Diameter (Zabilansky, 1986)

As a result, a theoretical, rationally-based method for evaluating ice uplift forces on a single pile is lacking; and the available approaches are empirical.

The ice forces on <u>an abutment</u> resulting from water level changes are produced by the same mechanisms as those for a single pile except that scale effects occur owing to the fact that the abutment is typically relatively long.

The ice forces on <u>a deck</u> also result from water level changes but they are produced by the different mechanisms as those for a single pile as scale effects occur owing to the fact that the deck is typically relatively large.

6.2 Vertical Uplift Forces on a Single Pile

6.2.1 Basic Information Regarding the Uplift Forces on a Single Pile

The vertical uplift force will be limited by the minimum of the force to:

(a) create a failure surface at the pile itself – this might occur through breakage of the ice-pile bond for example, or alternatively through shear in the ice at the pile.

(b) or to fail the ice around the pile – in this case, the ice sheet will fail in bending around the pile, through radial and circumferential cracking, leaving a ring of ice frozen to the pile itself. This failure mode will create an open crack in the ice around the pile.

Both failure modes have been observed in practice and the processes controlling which one occurs seem to be related to the ice temperature at the time when the ice movements take place (Zabilansky, 1986). Ice failure at the pile itself seems to mainly predominate when the ice is at near-melting temperatures (Zabilansky, 1986). For the docks in the lower Thames River, ice movements are most likely to occur during breakup which implies that the ice would probably fail at the pile through breakage of the ice-pile bond.

Consequently, methods were investigated in this report for predicting ice forces in relation to the force to create a failure surface at the ice-pile interface. Note that methods are also available for predicting ice failure around the pile (e.g., Wortley, 1984), but these are considered to be less relevant to the docks in the lower Thames River. Furthermore, this errs conservatively as upper-bound values will be determined if the ice loads are based on only one possible failure mode.

Methods for predicting ice uplift forces are generally based on laboratory tests done primarily with ice about 0.15m or less in thickness. The largest-scale tests were done by Vershinin, 1983, who carried out a small number of tests (i.e., 5) in the field in 1.15m thick ice with 1m diameter piles. The data show that the ice failure stress (for cases where the ice failed at the ice-pile interface) is related to the aspect ratio (i.e., pile diameter/ice thickness). See Figure 6.3.

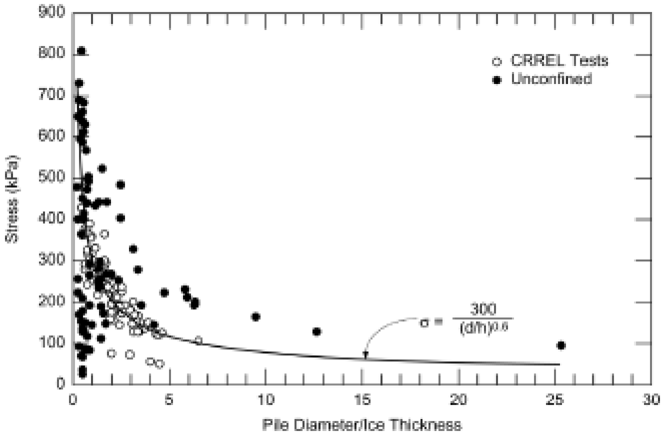


Figure 6-8. Failure shear stress vs. ratio of pile diameter to ice thickness. (1 kPa × 0.145 = 1 psi.)

Figure 6.3: Failure Shear Stress for Vertical Ice Forces on a Single Pile (CRREL, 2002)

Equation [6.1] was developed by Zabilansky, 1989 to predict ice uplift forces.

τ, kPa = $300/(d/h)^{0.6}$ [6.1]

where:

τ, kPa = the ice failure stress, defined as:
Pile uplift force, in kN/(π * d * h)
d = pile diameter, in m
h = the ice thickness, in m

Zabilansky, 1989 stated that equation [6.1] is applicable to wooden piles and that modifications would be required for other types of piles (e.g., steel or concrete). Subsequently, equation

[6.1] was included in the U.S. Army's Cold Regions Research and Engineering Laboratory's (CRREL) Ice Engineering Manual (CRREL, 2002) without restrictions regarding the pile type. This issue is considered further in a subsequent section.

The Russian SN 76-66 code (Belkov, 1973) also provides an approach for evaluating ice uplift loads.

$$P_c\text{, tonnes} = k_c\, h^2/\ln(50h/d) \qquad [6.2]$$

where:

P_c, = the ice uplift force in tonnes

k_c = 300 tonnes/m^2

SN 76-66 contains important notes regarding the application of equation [6.2] to a rectangular pile and to a group of piles as follows:

(a) Rectangular pile – "d" is defined as the diameter of the piles or piles cluster in meters; with a rectangular cluster with sides x and y, the value of "d" is taken to be $\sqrt{xy}$.
(b) General note – equation [6.2] is applicable when there is a continuous ice cover.
(c) Pile cluster - equation [6.2] is applicable to individual piles and pile clusters surrounded by a continuous ice cover extending over a radius of not less than 20 times the ice thickness.
(d) Pile cluster – equation [6.2] may be applied for a pile cluster in which the distance between individual piles is not more than 1m.

The results from both formulae are in good agreement (Figure 6.4). The following trends and observations are of interest:

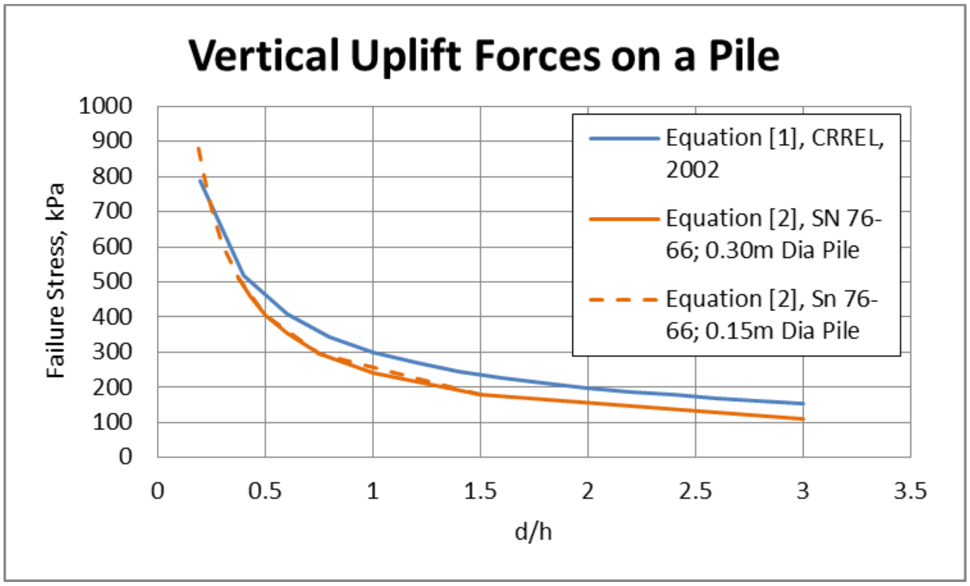


Figure 6.4: Failure Shear Stress for Vertical Ice Forces on a Single Pile

(a) Effect of the aspect ratio (i.e., d/h): The aspect ratio is a very significant parameter. The data from all of the tests (including the large-scale ones done by Vershinin, 1983) generally follow the same trend, which is re-assuring. The ice failure stress is quite large for low aspect ratios; and it decreases exponentially with increasing aspect ratio, to an asymptote at aspect ratios greater than about 3.

(b) Probable range of cases for piles in the lower Thames River: It is of interest to examine where the piles for the docks in the lower Thames River are likely to lie in relation to the aspect ratio. This was assessed by presuming that the pile diameter would range from 0.15m to 0.3m. The ice thickness was assumed to range from 0.5m to 0.6m, which covers return periods from about 10 years to 100 years respectively. This gives a range of values for the aspect ratio from 0.25 to 0.6. These aspect ratios are in the "steep" part of the curve where the ice failure stress increases rapidly with decreasing aspect ratio (Figure 6.4).

Exploratory calculations were done using the methods in CRREL, 2002 and SN 76-66 (Table 6.2) for:

(a) The 10-yr and 100-yr ice thicknesses of 0.47m and 0.60m respectively; and

(b) Pile diameters ranging from 0.15m to 0.4m.

Table 6.2: Ice Uplift Forces for a Single Pile

10-year Ice Thickness					100-year Ice Thickness			
Ice Thick.	Pile Dia.	Ice Uplift Force, kN			Ice Thick.	Pile Dia.	Ice Uplift Force, kN	
m	m	CRREL, 2002	SN 76-66		m	m	CRREL, 2002	SN 76-66
0.47	0.15	145.6	143.8		0.6	0.15	200.1	206.0
0.47	0.2	163.3	152.3		0.6	0.2	224.5	217.8
0.47	0.25	178.6	159.7		0.6	0.25	245.5	227.9
0.47	0.3	192.1	166.3		0.6	0.3	264.0	236.9
0.47	0.35	204.3	172.3		0.6	0.35	280.8	245.0
0.47	0.4	215.5	177.9		0.6	0.4	296.2	252.6

Of course, there are some variations in the loads given by the two approaches. For this work, it was decided to base the analyses and recommendations on those in CRREL, 2002 (i.e., equation [6.1]) as it is a more recent reference. Also, the loads calculated using CRREL, 2002 are larger than those from SN 76-66 for all cases in Table 6.2, which errs conservatively.

6.2.2 Effect of Pile Type on the Uplift Forces on a Single Pile

Equation [6.1] (in CRREL, 2002) is based on the pile being wooden (Zabilansky, 1989). Information was not provided by Zabilansky, 1989 for other pile materials, who noted that other pile types would likely have different thermal properties. Variations in thermal properties would probably lead to differences in the either the size of the ice bustle at the pile, or the strength of the ice-pile adhesive bond, which would result in differences in the ice uplift force.

This limitation was addressed here using judgement based on the expected size of the ice bustle at the pile for different materials and its subsequent effect on the calculated loads, as summarized in Table 6.3.

Table 6.3: Effect of Pile Type on Ice Uplift Forces for a Single Pile

Pile Type	Expected Effect	Justification
Wooden	No ice bustle – local ice thickness at pile equal to that in far-field.	Engineering judgement
Steel pipe – either open at top, or capped but filled with air	Larger ice bustle - local ice thickness at pile double that in far-field.	Engineering judgement
Steel pipe – capped and filled with insulation	Ice uplift force 30% less than that for an air-filled steel pipe	This is the variation measured by Muschell and Lawrence, 1980 (cited by Zabilansky, 1989) in laboratory tests using vermiculite insulation inside the steel pipe.
Concrete pile	No ice bustle – local ice thickness at pile equal to that in far-field.	Concrete has a thermal conductivity that is within the same range as wood (i.e., about 0.8 W/mK vs 0.1 W/mK respectively). Note that the thermal conductivity of steel is about 45 W/mK.
Pile costed with epoxy coating	Ice uplift forces reduced by a factor of about 2	1. Frederking, 1983 found that coating a steel pile with Inerta 160 (a polymer-coating typically used as a low friction coating for icebreaking ships) reduced the ice adhesive strength by a factor of two. 2. Muschell and Lawrence, 1980 (cited by Zabilansky, 1989) found that the ice uplift forces for an epoxy-coated steel pipe were 35% and 70% of those for an air-filled steel pipe and for a steel pipe with vermiculite insulation inside it respectively.
PVC or polyethylene pipe	Ice uplift forces reduced by a factor of about 5	Frederking, 1983 found that the ice adhesive strength of polyethylene and PVC piles was about one-fifth of that for wood, steel and concrete piles.

6.3 Recommended Approach for Calculating Vertical Uplift Forces on a Single Pile

6.3.1 Single Vertical Cylindrical Pile

For a vertical cylindrical pile, the unfactored uplift force on a single pile, P_{uplift}, shall be calculated as follows:

$$P_{uplift} = \tau * A_c \qquad [6.3]$$

where:

A_c = the area of the ice in contact with the pile, defined as: $K_{bustle}\,\pi\,dh$ [6.4]
τ = the ice failure stress, as defined in equation [6.5]
K_{bustle} = an empirical factor to account for the effect of an ice bustle at the pile (Table 6.4)
d = the pile diameter
h = the ice thickness. For docks in the lower Thames River, “h” shall be taken as 0.6m, which is the annual maximum ice thickness with a 100-year return period.
π = a numerical constant, to be taken as 3.1416

Table 6.4: Recommended Ice Bustle and Surface Factors

Pile Material	K_{bustle}	$K_{surface}$
Bare Solid Wood	1.0	1.0
Solid Wood with a low-friction surface coating (notes 2 and 3)	1.0	0.5
Bare Solid Concrete	1.0	1.0
Solid Concrete with a low-friction surface coating (notes 2 and 3)	1.0	0.5
Bare Steel Cylinder filled with air inside it	2.0	1.0
Bare Steel Cylinder filled with insulation inside it (note 1)	1.4	1.0
Bare Steel Cylinder filled with concrete	1.7	1.0
Hollow Steel Cylinder filled with air, and with a low-friction surface coating (notes 2 and 3)	1.0	0.5
PVC Cylinder filled with air inside it	2.0	0.2
Polyethylene Cylinder filled with air inside it	2.0	0.2

Notes:

1. The insulation inside the steel cylinder must have a thermal conductivity equal to or less than that for vermiculite.
2. The adhesion strength between the coating and the ice must be equivalent to or less than that for Inerta 160.
3. The low-friction coating must remain on the pile over the design life of the pile.

The ice failure stress, τ, shall be calculated as follows:
τ, kPa = $K_{surface} * 300/(d/h)^{0.6}$ [6.5]
where:
τ = the ice failure stress, in kPa
$K_{surface}$ = an empirical factor to account for a surface coating on the pile, as defined in Table 6.4

6.3.2 Single Non-Cylindrical Pile

For a <u>non-cylindrical vertical pile</u>, the unfactored uplift force on a single pile, P_{uplift}, shall be calculated using equations [6.3] to [6.5] with the following changes:

“d” “d” shall be defined as the equivalent diameter $[xy/0.25\pi]^{0.5}$ where x and y are the length and width of the pile’s cross-section at the waterline respectively.
“A_c” “A_c” shall be determined as: $2*(x+y) * K_{bustle} * h$

6.3.3 Single Rectangular Crib

The unfactored uplift force on a single vertical rectangular crib, P_{uplift}, shall be calculated using equations [6.3] to [6.5] with the following changes:

“d”	“d” shall be defined as the equivalent diameter $[xy/0.25\pi]^{0.5}$ where x and y are the length and width of the crib’s cross-section at the waterline respectively.
“A_c”	“A_c” shall be determined as: $2*(x+y) * K_{bustle} * h$

6.3.4 Group of Vertical Piles or Cribs

The unfactored uplift force on individual piles or cribs within a group shall be taken to be equal to the uplift force determined using equations [6.3] to [6.5] for single isolated piles or cribs.

The maximum total uplift force, $Uplift_{total}$, shall be determined as follows.

$$Uplift_{total} = \text{\# of piles or cribs} * P_{uplift} \qquad [6.6]$$

where:

# of piles or cribs = the number of individual piles or cribs in the group

P_{uplift} = the uplift force for a single pile or crib determined using equations [6.3] to [6.5]

It should be noted though that, for groups of piles, vertical loads may act on a number of the piles at the same time. The possible cases range from only one of the piles being loaded to all piles being loaded at the same time. The dock’s structural integrity must be checked for all possible cases.

6.3.5 Sample Results: Vertical Forces on a Single Pile

To illustrate the recommended calculation process, Table 6.5 shows sample results for a 0.15m diameter pile in 0.6m ice thickness. The uplift forces vary depending on the pile material and the surface coating.

Table 6.5: Sample Results: Ice Uplift Forces for a Single Pile

Pile Material	K_{bustle}	$K_{surface}$	Pile d,m	ice h, m	A_c, m^2	τ, kPa	Uplift, kN
Bare Solid Wood	1	1	0.15	0.6	0.28	689.2	194.9
Solid Wood with a low-friction surface coating (notes 2 and 3)	1	0.5	0.15	0.6	0.28	344.6	97.4
Bare Solid Concrete	1	1	0.15	0.6	0.28	689.2	194.9
Solid Concrete with a low-friction surface coating (notes 2 and 3)	1	0.5	0.15	0.6	0.28	344.6	97.4
Bare Steel Cylinder filled with air inside it	2	1	0.15	0.6	0.57	689.2	389.7
Bare Steel Cylinder filled with insulation inside it (note 1)	1.4	1	0.15	0.6	0.40	689.2	272.8
Bare Steel Cylinder filled with concrete	1.7	1	0.15	0.6	0.48	689.2	331.3
Hollow Steel Cylinder filled with air, and with a low-friction surface coating (notes 2 and 3)	1	0.5	0.15	0.6	0.28	344.6	97.4
PVC Cylinder filled with air inside it	2	0.2	0.15	0.6	0.57	137.8	77.9
Polyethylene Cylinder filled with air inside it	2	0.2	0.15	0.6	0.57	137.8	77.9

6.3.6 Application Notes

The following notes are applicable to all cases in section 6.3.

(a) The loads and stresses defined for all cases above are unfactored. Load factors or safety factors must be applied to them within the context of the design basis being used.
(b) Uplift forces shall be applied as a line load, defined as the total uplift force divided by the circumference or perimeter of the pile or crib respectively.
(c) Uplift forces may act vertically in a direction that is either upwards or downwards. The pile's structural integrity must be checked for both loading directions.
(d) For groups of piles or cribs, vertical loads may act on a number of the piles or cribs at the same time. The possible cases range from only one of the structures being loaded to all of them being loaded at the same time. The dock's structural integrity must be checked for all possible cases.
(e) For cases in which treatments are done to the pile or crib to lower the ice uplift forces, as illustrated by the examples below, the dock proponent must demonstrate that the treatment will be effective over the design life of the pile or crib.
    a. Filling the pile's interior with insulation.
    b. Applying a low-friction coating to the surface of the pile or crib.

6.4 Uplift Forces Exerted by Water Level Changes on a Deck or an Abutment

6.4.1 Ice Uplift Forces on a Deck, Walkway or Abutment due to a Rise in Water Level

Similar to the uplift forces on a pile or crib, this loading originates from water level changes, with the structure being solidly frozen into the ice. However, because a deck or abutment is a much larger structure compared to a pile, the ice loading process is different in that radial and circumferential cracking are the dominant mechanisms.

This case is analogous to the vertical loads exerted on a bridge pier due to ice adhesion (as the size of a bridge pier is in the same range as that for a dock's deck). This is covered in CSA S6-19 which states that the vertical force due to water level fluctuations, F_v, on a pier frozen to an ice formation shall be calculated as follows:

(a) For circular piers:

$$F_v \text{ (in kN)} = 1250t^2 * (1.05 + 0.13R/t^{0.75}) \quad [6.7]$$

(b) For oblong piers:

$$F_v \text{ (in kN)} = 15L_p\, t^{1.25} + 1250t^2 * (1.05 + 0.13R/t^{0.75}) \quad [6.8]$$

where:

t = the ice thickness

R = radius of a circular pier, m; radius of half-circles at the ends of an oblong pier, m; radius of a circle that circumscribes each end of an oblong pier whose ends are not circular in plan at water level, m.
L_p = perimeter of an oblong pier, excluding half-circles at the ends, m

6.4.2 Sample Calculation of Ice Uplift Forces on the Deck

Analyses were done for a rectangular 3m x 3m deck, as this is a typical size for the lower Thames River. The following parameter values were used for the calculation:

(a) Ice thickness: 0.6m – this is the 100-year ice thickness for the lower Thames River.
(b) R: 2.12m – this is the radius of a circle that circumscribes the deck.
(c) L_p: 12m – this is the perimeter of the deck.

The vertical force was calculated using equation 6.8 as this is an oblong geometry. This gives 803 kN as the overall uplift force, and an average line load on the full perimeter of 67 kN/m.

6.4.2 Application Notes

The following notes are applicable to all cases in section 6.4.

(a) The loads and stresses defined for all cases above are unfactored. Load factors or safety factors must be applied to them within the context of the design basis being used.
(b) Uplift forces shall be applied as a line load acting uniformly over the full length of contact between the ice and the abutment or deck. The uplift line load shall be calculated as the total uplift force (i.e., Fv) divided by the total dock perimeter that is in contact with the ice.
(c) Uplift forces may act vertically in a direction that is either upwards or downwards. The structure's structural integrity must be checked for both loading directions.
(d) For a dock with multiple structures, such as a deck and a walkway, vertical loads may act on either structure at the same time. The possible cases range from only one of the structures being loaded to all structures being loaded at the same time. The dock's structural integrity must be checked for all possible cases.

6.5 Uplift Forces Produced by Ice Packing in Under the Deck

6.5.1 Brief Description of the Processes

During an ice run, ice may "pack in" under the deck of a dock, thereby creating uplift forces. These forces will be controlled by:

(a) The driving forces from the ice pack acting to push ice under the deck - although these are not infinite, they are typically large enough that this will not control the ultimate force that can be reached.
(b) The strength of the ice rubble under the deck – this will likely be the mechanism by which uplift forces are limited as horizontal forces from the ice pack would likely result

in ice rubble being extruded upwards and outwards. The force will be controlled by the strength of the rubble and the loading mechanism.

6.5.2 The Loading Processes and Calculation Approaches

First, the ice loading scenario must be defined, and the one below was used here. It was selected because it can result in high ice uplift loads, controlled by the shear failure of the pack ice, that are concentrated on the upstream face of the deck. These would probably be the most severe ones as they could lead to the upstream face of the deck being either lifted off its frontal supports or rotated off them. This Guideline is based on the scenario below.

(a) Ice rubble is pushed under and packed under the deck to the point where it becomes heavily grounded, such that it presents an immovable front to incoming pack ice.
(b) Ice movements continue, causing ice rubble to build up in front of the deck.
(c) The ice rubble does not clear. This causes the forces to build up to the point where a slip plane is created in the ruble in front of the deck, which exerts a vertical component on the deck. To quantify this scenario, two key components must be defined:
    a. The horizontal force exerted by the pack ice, and then;
    b. The component of the horizontal force that is exerted vertically.

<u>The load to fail the rubble</u> may be determined using recommendations in the Canadian Highway Bridge Design code (i.e., CSA S6 - 19). CSA S6-19 specifies a pressure due to ice jams of 10 kPa for openings of 30m or less. The horizontal rubble line load can be calculated as follows:

$$H_{\text{Rubble Line Load}} = q * d \qquad [6.9]$$

where:

$H_{\text{Rubble Line Load}}$ = the rubble line load, in kN/m
q = the rubble ice pressure, to be taken as 10 kPa
d = the water depth, in m

<u>The vertical load exerted on a deck</u> may be determined presuming that a planar failure surface is produced in the rubble. Algorithms in ISO 19906 (ISO, 2010; 2018) are available to resolve the vertical line load, $V_{\text{Rubble Line Load}}$, for this case as follows:

$$V_{\text{Rubble Line Load}} = H_{\text{Rubble Line Load}} / \xi \qquad [6.10]$$

$$\xi = (\sin\alpha + \mu\cos\alpha)/(\cos\alpha - \mu\sin\alpha) \qquad [6.11]$$

where:

α = the angle of the failure plane, recommended as 45° here
μ = the friction factor along the failure plane, recommended as 0.2 here

6.5.3 Summary: The Strength of the Rubble and Other Key Ice Properties

The following recommendations are made:

(a) Failure of the ice rubble through the creation a slip plane: the rubble load should be calculated using the recommendations in CSA S6-19, with a horizontal pressure of 10 kPa being applied over all exposed surfaces.
(b) Shape of the failure plane: it should be considered to be planar with an angle of 45°
(c) Friction along the failure plane, for resolving vertical and horizontal forces: the friction factor should be taken as 0.2.

6.5.4 Sample Calculation of Ice Uplift Forces on the Deck

To facilitate comparisons, this was calculated for the same case as for loads due to water level changes (Section 6.4). The key inputs were taken as:

(a) Water depth, 3m: this is considered to be a reasonable value for the sample dock in the lower Thames River.
(b) Angle of failure plane, 45°: this is a reasonable value.
(c) Friction factor along the ice rubble failure plane, 0.2: this is a reasonable value.

The force to create a failure plane in the rubble was calculated using equation 6.9, which gave 30 kN/m. The vertical force on the upstream face of the deck was calculated using equations 6.10 and 6.11. The uplift line load acting on the front face of the deck was determined to be 20 kN/m.

It is of interest to compare the vertical forces exerted by ice jamming with those produced by water level changes (i.e., 67 kN/m - Section 6.4). Although water level changes produced larger vertical line loads, both loading cases must be checked as the load application differs between them. Water level changes will induce uniform vertical loads around the perimeter of the deck or walkway while ice jamming will create forces that are concentrated on the upstream face, which may lead to overturning of the deck or walkway. This is discussed further subsequently.

6.6 Overall Design Basis and Application Notes

6.6.1 Summary of the Process for Calculating Unfactored Vertical Loads

The process must be started by assessing the elevation of the dock above water level, as this affects which dock components will be in contact with the ice. Of course, this will vary as usually, the water level is elevated at the time of an ice run. Three cases are possible as follows:

(a) The water level is low enough that the ice only contacts the piles or supports beneath the deck.
(b) The water level is high enough that the ice only contacts the deck.
(c) The water level is in an intermediate range where the ice contacts both the deck and piles.

Ice loads must be considered for all three cases. Horizontal and vertical ice forces will be exerted on the components of the dock in contact with the ice, by various loading scenarios as summarized in Table 6.6.

Table 6.6: Ice Loading Scenarios

Dock	Loading	Ice Loading Scenario		
Component	Type	Impact by Sheet Ice	Water Level Change	Ice Jamming
Pile or Crib	Horizontal	Relevant load case	Not relevant	Relevant load case
	Vertical	Not relevant	Relevant load case	Not relevant
Deck or Walkway	Horizontal	Relevant load case	Not relevant	Relevant load case
	Vertical	Not relevant	Relevant load case	Relevant load case
Abutment	Horizontal	Relevant load case	Not relevant	Relevant load case
	Vertical	Not relevant	Relevant load case	Relevant load case

Next, the vertical loads acting on the various individual dock components in contact with the ice must be calculated (Table 6.7).

Table 6.7: Recommended Approaches for Vertical Ice Loads on Individual Dock Components

Dock	Loading	Ice Loading Scenario and Recommended Calculation Approach		
Component	Type	Impact by Sheet Ice	Water Level Change	Ice Jamming
Pile or Crib	Vertical	Not relevant	As per Section 6.3	Not relevant
Deck or Walkway	Vertical	Not relevant	As per Section 6.4	As per Section 6.5
Abutment	Vertical	Not relevant	As per Section 6.4	As per Section 6.5

For some cases, vertical ice loads may get produced by more than one scenario (e.g., vertical loads on the deck or walkway, or an abutment – Table 6.6). For these cases, the vertical loads produced by each ice loading scenario must be determined; and the governing load must be selected as follows.

The structural integrity of either a deck and walkway, or an abutment, must be checked for both ice loading scenarios as they exert different types of loadings. The vertical loads produced by water level changes are distributed uniformly around the perimeter of the structure that is in contact with the ice. However, the loads due to ice jamming are only exerted on the faces that are in contact with the moving ice in the river (e.g., the faces upstream or along the length of the river), which has the potential to cause the deck or walkway, or the abutment, to be rotated or lifted off its supports. As a result, the vertical loads due to ice jamming must only be applied to the faces that are upstream or along the length of the structure in contact with the ice.

Note that, for all the cases listed in Table 6.6, the different ice loading scenarios would not occur at the same time, so a loading case combining the ice loads from different scenarios need not be included in the ice design criteria.

The individual vertical ice loads should then be summed as appropriate taking into account the specific dock geometry and the water surface elevation.

Then, vertical ice forces should be evaluated for the range of loading directions that is physically possible, as governed by the geometry of the river and the dock. The structure's structural integrity must be checked for all possible loading directions.

6.6.2 Application Notes

The following notes are applicable to all cases related to vertical ice loads.

(a) As discussed in section 5, horizontal ice loads will also get exerted on the dock. The vertical and horizontal loads may or may not act at the same time as summarized below.
    a. Horizontal loads produced by ice impacts – these will not occur at the same time as the vertical loads produced by any of the mechanisms considered here. Hence, a combined case with both vertical and horizontal ice loads does not need to be included in the ice design criteria for this case.
    b. Horizontal and vertical loads produced by pack ice or ice jamming – these may occur at the same time. Hence, a combined case for these loads must be included in the ice design criteria.
    c. Horizontal loads produced by ice jamming and vertical loads produced by water level changes – these will not occur at the same time. Hence, a combined case for these loads need not be included in the ice design criteria for this case.

(b) The vertical loads defined for all cases are <u>unfactored</u>. Load factors or safety factors must be applied to them within the context of the design basis being used.

(c) The dock's design must be in conformance with the National Building Code of Canada.

(d) Vertical loads may act either downwards or upwards. The deck's structural integrity must be checked for both loading directions.

(e) Various components of the dock may be contacted by the ice (e.g., the deck or walkway only; the piles or cribs only; or a combination of the two). The dock must provide adequate structural integrity against vertical ice loads for all possible cases. For the case where both the deck and the piles are contacted by the ice, the dock's structural integrity for vertical ice loads must be checked for the case where the respective vertical loads are exerted on each of the individual dock components (i.e., piles only and deck only).

(f) Vertical ice forces for a <u>pile or crib</u> – Vertical ice forces shall be applied as a line load acting uniformly over the full circumference of the pile or crib. The number of piles or cribs loaded may vary from only one, to all of those potentially in contact with the ice. The dock's structural integrity must be checked for all possible cases.

(g) Vertical ice forces for a deck or walkway; or an abutment – the load application shall vary depending on the scenario producing vertical loads, as follows:
   a. Vertical loads produced by water level changes – Vertical ice forces shall be applied as a line load acting uniformly over the perimeter of contact between the ice and the deck or walkway. The deck's structural integrity must be checked for all possible loading widths, ranging from as low as 3m to the full perimeter of the dock face. Furthermore, the location for a low loaded width (such as 3m) may occur at any point along the perimeter of the dock face. The dock's structural integrity must be checked for all possible cases.
   b. Vertical loads produced by ice jamming – Vertical ice forces shall only be applied on the faces of the structure the faces that are in contact with the moving ice in the river (i.e., facing upstream or along the length of the river). Thus, they have the potential to cause lifting or rotation of the deck or walkway; or abutment. The following shall be done:
      i. Vertical loads shall be applied as a line load acting uniformly over various lengths up to the full length or width of the structure that is in contact with the moving ice in the river (e.g., the faces upstream or along the length of the river). The abutment's structural integrity must be checked for all possible loading widths, ranging from as low as 3m to the full length of the abutment face. Furthermore, the location for a low loaded width (such as 3m) may occur at any point along the length of the abutment. The abutment's structural integrity must be checked for all possible cases.
      ii. For a dock with multiple components (e.g., a deck and a walkway), the number of structures loaded may vary from only one, to all of those potentially in contact with the ice. The dock's structural integrity must be checked for all possible cases.

7.0 Criteria Related to Ice Jamming

7.1 Purpose and Background

The work was aimed at qualitatively assessing a dock's potential to affect ice jamming, based primarily on the LTVCA's experience. The work did not include hydraulic or ice modelling.

Discussions were held with the LTVCA, including Jack Robertson (LTVCA retired), which indicated that docks did not seem to noticeably affect ice jamming. However, in the past, docks were not very robust so they tended to get broken up if they became part of an ice jam. Also, in the past, relatively few docks were exposed to ice as people generally did not leave them in the river in winter. Furthermore, the LTVCA would only give approval for temporary docks. There appears to be more interest now in having permanent docks; and if docks were built to withstand ice forces, they would likely be more robust than the ones in the past. Thus, the LTVCA's experience to date must be interpreted with care.

7.2 The Existing Docks

The impact of a dock on the potential for ice jamming is related to the distance that it extends out from the river bank (termed the "offshore length"). This was investigated using information from the LTVCA for 82 docks in the lower Thames River. The offshore length averaged 5.5m with a range from 1 to 12.5m. Most offshore lengths ranged from about 3m to 9m (Figure 7.1).

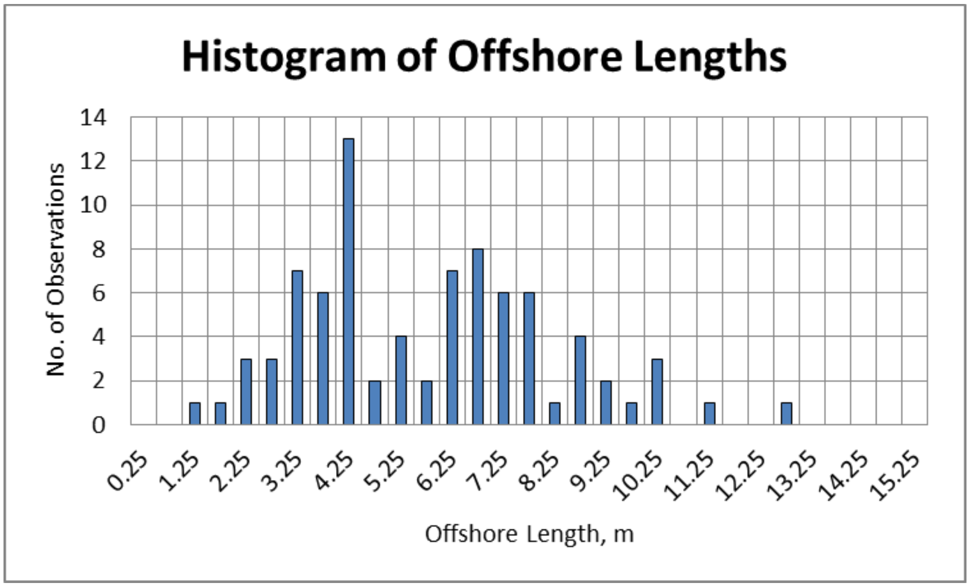


Figure 7.1: Histogram of Offshore Lengths for the Existing Docks

Probably not all of the size measurements apply to permanent docks, as the dataset likely included temporary or floating ones (J. Homewood, LTVCA, personal communication). Furthermore, there was never a location where two of the measured docks were directly across the river from each other, which would lead to the greatest potential for blockage of the river. Consequently, the data set must be interpreted with care.

7.3 Ice Jam Locations

The LTVCA has identified the usual locations for ice jams (Figure 7.2). None of the docks reported to be damaged by ice (Section 2) were at sites where ice jams typically occur. Two of the docks seen in the Swoop aerial surveys were near known ice jam locations (Figure 7.3). Both of these docks were only seen in the 2015 aerial survey, and not in the one in 2016.

Figure 7.2: Usual Ice Jam Locations Downstream of Chatham

5949 Tecumseh Line near Prairie Siding

5417-29 Tecumseh Line near St. Peters Church

Figure 7.3: Existing Docks near Ice Jam Locations (photos courtesy of the LTVCA)

7.4 Dock Offshore Lengths for Locations on Outside Bend of the River

Intuitively, it is expected that the most severe ice actions would occur for docks located: (a) on a bend in the river, and; (b) on an "outside" bend of the river. An outside bend is expected to produce the most severe ice actions as the flow velocities would likely be highest there. About 60% of the docks seen in the LTVCA's aerial surveys were located on a bend, while about 40% of them were located on an outside bend.

The offshore lengths for the docks on outside bends of the river averaged 5.8m, with a range from 1m to 11m. Most of the offshore lengths for these docks were in the range from about 3m to 9m (Figure 7.4). These data show qualitatively that the offshore lengths for the docks on an outside bend were not different from those for the overall population of docks.

However, this result must be treated with care for the same reasons given in Section 7.2.

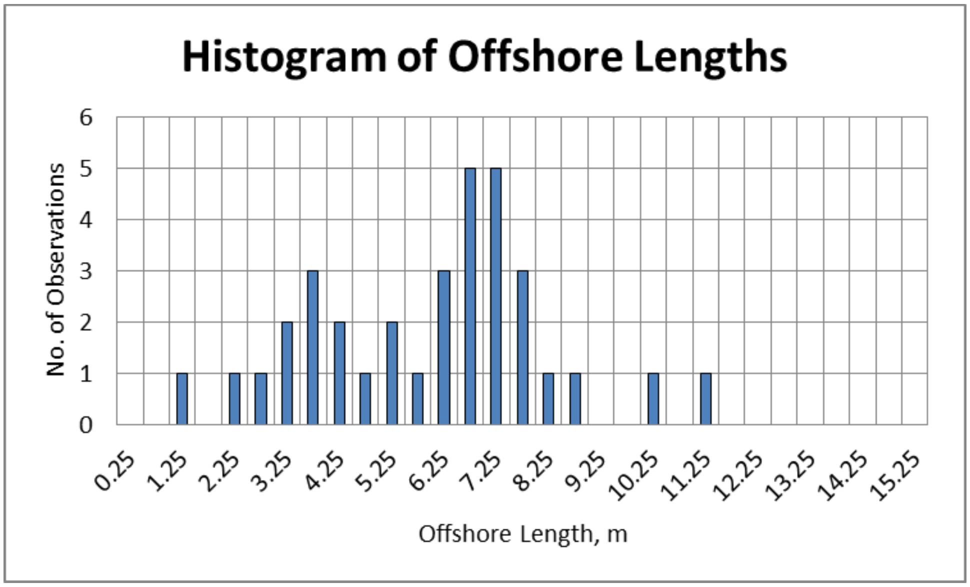


Figure 7.4: Histogram of Offshore Lengths for Existing Docks on an Outside Bend

7.5 Preliminary Recommendations

The LTVCA's experience to date must be interpreted with care, because the available information is inadequate to allow firm conclusions. Nevertheless, the LTVCA's experience does provide useful insights regarding the likely effect of a dock on ice jamming. However, the LTVCA is cautioned that this is a very complex issue; and that the state-of-the-art is subject to many uncertainties. As a result, it is not possible to establish firm reliable guidelines.

As an overall recommendation, the LTVCA should recognize that the recommendations below are tentative. It should continue to monitor docks in the river and update these recommendations as appropriate.

The following preliminary recommendations are made:

(a) The LTVCA should develop separate policy for docks that are:
   a. On a straight section of the river; or
   b. On an inside bend of the river; or
   c. On an outside bend of the river

(b) Docks on a straight section of the river:
   a. The offshore length of a dock should not exceed 3m.
   b. Docks should not be allowed that are across the river from each other unless the dock proponent can demonstrate that the proposed dock will not affect ice jamming.

(c) Docks on an inside bend of the river:
   a. The offshore length of a dock should not exceed 3m.

(d) Docks on an outside bend of the river;
   a. Permanent docks should not be allowed on the outside bend of the river.
   b. In the event that a dock is proposed for the outside bend of the river, it should be incumbent on the dock proponent to demonstrate that the proposed dock will not affect ice jamming.

8.0 Recommendations Regarding Ice Monitoring

The recommendations fall into two general categories:

(a) Observations and monitoring that would lead to an improvement in this Ice Guideline.
(b) The type of analyses that are required to ensure that a proposed dock meets the ice load criteria set out in this Guideline.

8.1 Field Monitoring to Optimize this Ice Guideline

Various assumptions had to be made in order to prepare this Guideline. The following field observations would help to optimize it.

(a) Dock damage record – a record should be kept of all damages suffered by docks, especially ones that are ice-related. The record should include: (i) the location and type of dock damage that occurred, and; (ii) the type of dock that was damaged. Recognizing that it may be difficult to obtain a dock damage record in practice, it is suggested, that drone surveys be done each year before and after the ice season as an alternative.
(b) Impact of docks on ice jamming – records and notes should be kept regarding any impact that docks may have had on ice jams that occurred.
(c) Ice interaction with docks – it is suggested that photos be taken during the normal course of monitoring operations (of which there is an extensive record of photos and videos so far), that are aimed at showing the fate and behaviour of docks during ice runs.

8.2 Structural Analyses for Docks

Ice loads are specified in this Guideline. To be effective, dock proponents must be required to demonstrate that their proposed dock is safe for the prescribed ice loadings.

Of course, this can be evaluated using various methods that vary in complexity.

For maximum flexibility, it is believed that the LTVCA should not specify the type of analysis that must be done, other than to require the following:

(a) The analyses must be in conformance with the Canadian National Building Code.
(b) The analyses must be stamped by a professional engineer licensed to practice in Ontario.

9.0 References and Bibliography

[1] Belkov, G. (translator), 1973, Instructions for Determining Ice Loads on River Structures, Russian Standard SN 76-66, available from the National Research Council of Canada.

[2] CAN/CSA-ISO, 2011, CAN/CSA-ISO 19906:11 Petroleum and Natural Gas Industries – Arctic Offshore Structures (Adopted ISO 19906:2010, first edition, 2010-12-15).

[3] Comfort, G., Gong, Y., and Liddiard, A., 2003, Static Ice Loads on Dams, proc ICOLD.

[4] Comfort, G., Cote, A., Taras, A., Wagner, J., and Abdelnour, E., 2012, Static Ice Loads on Dams – Measurements Over the Past Four Years, proc CDA Conference.

[5] Comfort, G., 2021, Engineering Ice Guideline for Docks in the Lower Thames River, report 173-1 submitted by G Comfort Ice Engineering Ltd. to the Lower Thames River Conservation Authority.

[6] CSA, 2019, Canadian Highway Bridge Design Code S6-19, Canadian Standards Association, Rexdale, ON.

[7] CRREL, 2002, Engineering and Design - Ice Engineering, Manual EM-1110-2-1612, published by the US Army Cold Regions Research and Engineering Laboratory (CRREL).

[8] Frederking, R., and Karri, J., 1983, Effects of Pile Material and Loading State on the Adhesive Strength of Piles in Ice, Canadian Geotechnical Journal, Vol. 20, 1983

[9] IEC, 2008, IEC 61400-3, International Standard, Wind Turbines- Part 3: Design Requirements for Offshore Turbines. International Electro-Technical Commission.

[10] ISO, 2010, Petroleum and Natural Gas Industries – Arctic Offshore Structures, International Standards Organization ISO/DIS 19906.

[11] ISO, 2018, Petroleum and Natural Gas Industries – Arctic Offshore Structures, International Standards Organization ISO/DIS 19906, update at FDIS stage.

[12] Michel, 1978, Ice Mechanics, Laval University press, Quebec City, Quebec.

[13] Muschell, J., and Lawrence, R., 1980, Ice Uplift on Piles: Progress Report of Water Temperature and Ice Pile Adhesion Investigations on the Upper Great Lakes, Michigan Sea Grant Program MICHU-SG-80-506.

[14] OGP, 2010, Calibration of Action Factors for ISO 19906 Arctic Offshore Structures, report no. 422, December, 2010, International Association of Oil and Gas Producers.

[15] Vershinin, 1983, Effect of an Ice Cover Frozen to the Cylindrical Supports of Offshore Oil Well Platforms Subjected to Water Level Fluctuations, available from the National Research Council of Canada.

[16] Wintermute, J., 2015, Ice Jam Flooding Risk – Spring 2015, presentation on behalf of the LTVCA, March 2, 2015.

[17] Wortley, C., 1984, Great Lakes Small Craft Harbour and Structure Design for Ice Conditions: An Engineering Manual, University of Wisconsin Sea Grant Institute WIS-SG-84-426.

[18] Zabilansky, Z., 1986, Model Study of Ice Forces on a Single Pile, proc IAHR, Iowa City, Iowa.

[19] Zabilansky, Z., 1989, Vertical Ice Forces and Aspect Ratio of Pile Diameter versus Ice Thickness, Ice in Surface Waters, Shen (ed.), Rotterdam, ISBN 90 54109718.