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Laboratory Memorandum OCRE-LM-2017-007

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Assessing ice action on bridges in the context of climate change: Prospective approach

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Paul Barrette, Martin Richard, Louis Poirier, Hossein Babaei, Robert Frederking

1200 Montreal Rd, Ottawa, ON K1A 0R6

July 24, 2017

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National Research Council Canada
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[<u>*Photograph*</u>*: View from upstream of the two bridges in Quebec City crossing the St. Lawrence River. In front is the Pierre Laporte suspension bridge, built in the late 1960's. The distance between the piers is approximately 600 m. Right behind it (about 150 m), darker colored, is the old Quebec cantilever bridge, built early in the 20th century. This picture was taken in March 2008 by Brian Morse, Ed Stander and Martin Richard, from an ice canoe on the river.]*

Executive Summary

There are a large number of bridges in Canada which cross water expanses that freeze in the winter. Ice loads on bridge piers, which depend on floe size as well as ice strength, thickness and temperature, have to be factored in the design of these structures. Climate change is affecting ice growth patterns, in response to changes both in the water (floating ice) and in the atmosphere (precipitation). For instance, the extent of these changes, with positive or negative impact, needs to be addressed in order to guide codes and standards on bridge designs and construction.

These goals can be achieved via the following 4-step scheme:

1. Survey existing knowledge and background information and the prospective resources that could be mobilized – this report addresses that first step.
2. Analysis of today's loading regime on a representative sample of Canadian bridges, along with all required information on ice regime.
3. Derivation of ice regime based on climatic model recommended to us by CRBCPI, and estimation of loads in the next 50 and 100 years.
4. Recommendations for updates to relevant codes.

In Canada, the mandate for establishing design and construction requirements for highways, including highway bridges, lies with the provincial and territorial governments. All provinces and territories, with the exception of Manitoba, have mandated CSA S6-14 for use within their jurisdictions. Manitoba partners with the US Federal Highways Administration (FHWA) and uses AASHTO LFRD. In the US, the American Association of State Highway and Transportation Officials (AASHTO) develops and revises new editions of their bridge code nominally every two years. The International Organization for Standardization (ISO) has an offshore code – CSA/ISO 19906 Arctic offshore structures. For countries within the European Union a series of European standards known as Eurocodes (EN) related to construction have come into force.

During these investigations, a preliminary count of about 22,000 bridges managed by the public sector crossing water, has been obtained. Several provincial transportation departments have agreed to compile information on their bridge infrastructure and send that information to NRC – these procedures are pending. When designing a bridge, most jurisdictions have specific requirements related to ice, so as to complement those specified in the design code they use. For most of them, a major concern is the required vertical clearance under high water levels induced from an ice jam. Bridge piers instigate ice jams, which in turn allow the ice to rise and reach the superstructure. Important parameters such as discharge, ice thickness, and ice jam frequency and locations, depend on climatic conditions. Included in this report is a preliminary listing of the key contacts that were reached so far by the authors, for information on their jurisdiction's bridge infrastructure.

The Confederation Bridge is well instrumented and presents an opportunity to gather insightful information on ice-induced load regimes over time. That bridge connects New

Brunswick and Prince Edward Island. It is 11 km long and has 44 piers, some of which are instrumented to monitor loads. Twenty years of data were analyzed in an attempt to perceive some indication of climate pattern changes. In all cases, consistent trends were observed, but are minor compared to data scatter. Air temperature shows a 0.66^{o}C increase, concurrent with an overall decrease in ice thickness of 12 cm and an increase of 96 cm/s in wind speed.

Depending on several factors, dynamic loading of bridge piers by ice may lead to structural failure. A preliminary overview of cyclic ice-pier interaction (intermittent ice crushing, continuous brittle crushing and frequency lock-in) is presented. Fatigue and resonance are two parameters that have to be addressed in design. Physical modeling is a small-scale simulation designed to better understand the behavior of a significantly larger event. NRC has extensive experience in the matter. This is a tool that could be put to good use later on, if required.

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1. Introduction

There is a significant number of bridges in Canada that cross water expanses which freeze in the winter. That ice exerts horizontal loads on the piers of bridges, the effect of which has to be factored in the design of these structures. Also the river stage at break-up potentially brings the bridge superstructure into contact with ice. How are these loads likely to change over time, due to climate change?

Global warming is affecting ice growth patterns in response to changes both in the water and in the atmosphere. Air temperature evolution over time is a prime parameter when evaluating these loads. There are two main reasons. Firstly, that parameter has a direct bearing on ice growth and therefore on the thickness ultimately achieved by the ice. Secondly, temperature also affects the mechanical strength of the ice – warm ice is weaker than cold ice. The extent of these temperature changes needs to be addressed in order to guide codes and standards on bridge designs and construction. Other parameters should also be considered even though they only indirectly affect ice-structure interaction. For instance, snow act as an insulating material, slowing down growth. Winds and hydrological regimes control displacement rate, which in turns influences ice strength.

The purpose of this report is two-fold. Firstly, it is to present a preliminary statement of the work the authors feel would be required in order to evaluate ice action against bridges and the impact climate change may have in the long term on this infrastructure. Secondly, the report includes the outcome of initial findings to guide the proposed follow up investigations. The work summarized in this report will lead to follow up investigations whose ultimate objective is to produce design recommendations that can be fed into relevant codes and standards.

2. Preliminary statement of work

If we are to advance current knowledge on bridge pier loads due to ice, present and future, several aspects will have to be approached in a sequential manner (Figure 1).

2.1 Identify the parameters

The first step is to compile a review of all current codes/standards related with ice effects on bridges, to obtain an idea of what is covered and what is not (knowledge gaps). This will also provide guidance in assessing the factors that need to be addressed. A comprehensive listing of these factors as well as any others should be compiled. This includes both the nature of the ice action (vertical, horizontal loads, friction) as well as the following parameters:

- Air temperature (number of 'freezing degree-days')
- Upstream ice formation (thickness/strength)
- Hydrological effects (particularly with reference to spring break-up and river stage)
- Current velocity

2.2 Assessment of today's loads

A representative sample will be collected of the bridges that span water bodies in the country. This will provide an understanding of the types of structures, their design to withstand ice action and their usage. On that basis, we will select a specific number of target structures – the number has yet to be determined – from various geographical areas (Pan-Canadian representation). Good candidates will be those for which there is a load record. For instance, the current CSA bridge code CSA-S6-06 is based on ice load measurements from only two bridges in the West (northern Alberta). These will be augmented by existing NRC in-house data.

The Confederation Bridge has been recording loads for about 20 years. These loads are currently being used to validate CSA/ISO 19906. Load data will be analyzed as part of the proposed project for extrapolation purposes.

The *ultimate purpose* of the exercise is to establish a link between the ice loads sustained at the selected locations, the nature of the ice at these locations and the recommendations in the existing codes. This will give us the opportunity to improve the *current* guidelines, and also allow us to establish a baseline against which future scenarios can be compared.

2.3 Assessment of future loads

In order to assess what loads can be expected at any given target location, we will need to estimate the ice conditions upstream of the bridge, namely thickness, size of drifting fragments and ice type and temperature (for strength determination). A critical parameter will be the number of freezing degree-days, which will be derived from the climatic model recommended to us by CRBCPI. This procedure will be calibrated against data from the previous step, where loads, ice conditions and temperature data were analyzed. For each selected structure, a parametric analysis will be conducted, where ice thickness and strength as well as temperature will be varied, thereby providing a range in expected ice actions. The *ultimate purpose* of the exercise is the production of an updated load of structures due to climate change (extremes, recurrence, exposure, ...).

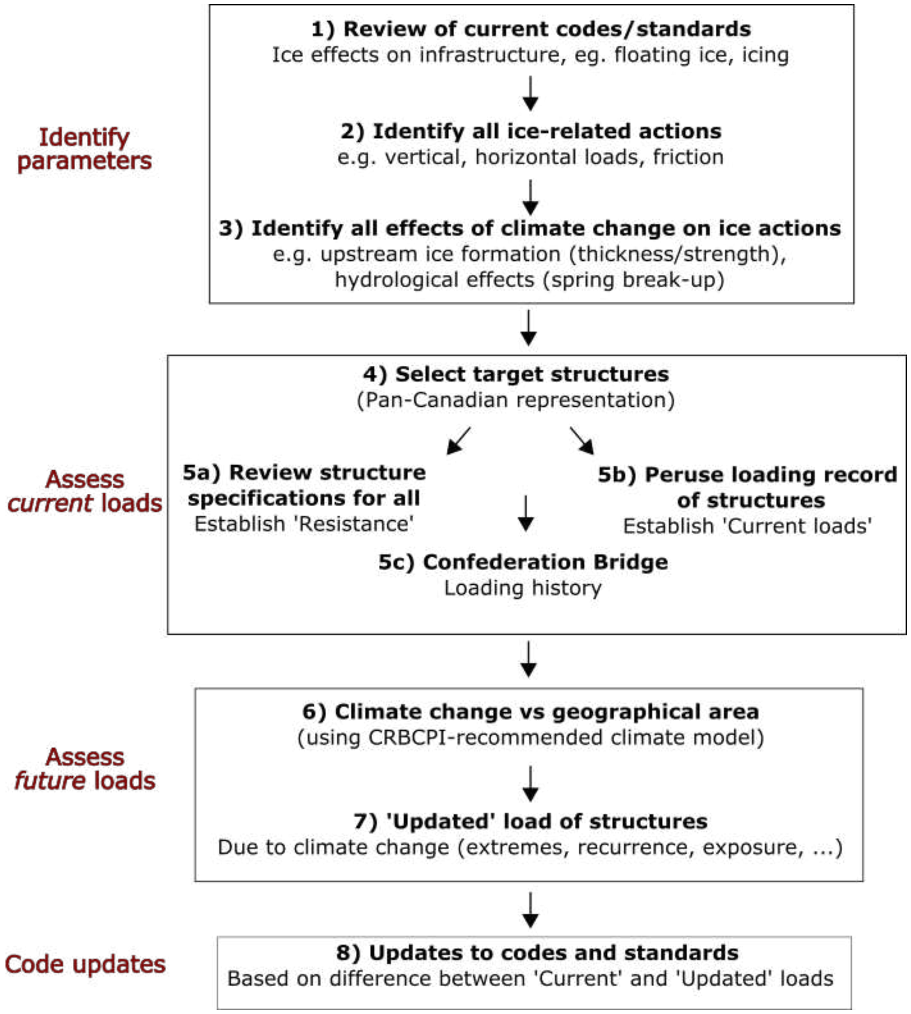

Figure 1: Approach to updating codes and standards in relation with bridge pier loading by ice.

2.4 Update to codes

The difference in loading between what the bridges see today with what they are expected to see in the next 50 and 100 years will be derived from the preceding exercises. Adaptation strategies, along with a baseline for prioritization, will be discussed at that stage.

3. Preliminary findings

In March 2017, OCRE was approached by CRBCPI to compile some information on the work plan shown in Figure 1. This preliminary work was divided into five parts:

- Survey of standards that guide bridge design
- Comprehensive listing of bridges in Canada that crosses water expanses (river, lakes, sea water), and related structural/hydrological parameters
- Preliminary analysis of ice and climate data at the Confederation Bridge (PEI)
- Dynamic loading of bridge piers due to ice
- Previous NRC experience with the physical modeling of ice-pier interaction

This section summarizes the outcome of this preliminary work.

3.1 Survey of standards that guide bridge design

3.1.1 General

Standards are prepared by standards development organizations (SDO). The actual writing is done by a committee of technical experts and interested parties, and generally uses a consensus approach in deciding on content. Standards or codes usually comprise two parts, a normative or mandatory part that sets out requirements that must be met in order to conform to the standard and an informative (non-mandatory) commentary part providing guidance on how to meet the normative provisions.

The Standard Council of Canada is the national body that accredits SDOs. To be accredited requires that certain procedures be followed in the development and support of a standard. Some authority, usually a governmental one, mandates the use of a standard for particular applications.

3.1.2 Bridge codes in Canada

In Canada, the Canadian Standards Association (CSA) is one of several SDOs. CSA has a history of developing, supporting, and periodically revising a bridge design code. CSA has developed and continues to support the Canadian Highway Bridge Design Code, commonly referred to as the CHBDC. The most recent edition, the 11th, was published in 2014. It comprises two documents:

- CSA S6-14 - Canadian Highway Bridge Design Code. Mandatory requirements of the code which is based on limit states design principles, defined design loadings, load combinations and load factors, criteria for earthquake resistant design, and detailed design criteria for the various structural materials used in bridges. This Code has been written to be applicable in all provinces and territories of Canada. It provides requirements for determining ice loads on bridge piers.
- CSA S6.1-14, Commentary on CSA S6-14, Canadian Highway Bridge Design Code. This provides rationale and explanatory material for many of the clauses of this code. It contains background on ice load requirements.

In Canada, the mandate for establishing design and construction requirements for highways, including highway bridges, lies with the provincial and territorial governments. All provinces and territories, with the exception of Manitoba, have mandated CSA S6-14 for use within their jurisdictions. Most provinces and territories also publish supplements or exceptions to the bridge code to deal with situations specific to their local requirements. Examples of exceptions include:

- Level of extreme river stage: 50-year, 100-year, 200-year
- Load restrictions on infrequently used bridges, etc.

Supplementary documents have been located by web searches for Alberta, British Columbia, Manitoba, Ontario, Quebec and Saskatchewan. A more exhaustive search was conducted (section 3.2) and additional documents were located and reported upon therein.

Manitoba partners with the US Federal Highways Administration (FHWA) use AASHTO LFRD[1] Bridge Design Specification for the following reasons:

- Better support for the LRFD code than what is available for CHBDC
- More software applications for applying the provisions of the code
- More research and reference material available (typically due to the availability of funding in the US for this)
- Code updates and changes in the AASHTO LRFD code appear to be better reviewed.

The Canadian and US codes note that they are exclusively for use in freshwater bodies (rivers and lakes), and are not applicable for sea ice loads. The likely reason is that the experience base for the codes is bridges across rivers. CSA S6 does include some guidance on wave loading.

3.1.3 Bridge codes in the US

In the US, the American Association of State Highway and Transportation Officials (AASHTO) develops and revises new editions of their bridge code nominally every two years, most recent AASHTO LFRD Bridge Design Specification, 2014, 7th edition Different format to deal with code requirements and commentary; it uses two columns, left one the code requirements, the right one commentary. The provisions for ice loading are identical to and refer to the CHBDC.

3.1.4 Other codes

The International Organization for Standardization (ISO) has an offshore code ISO 19906 Arctic offshore structures, which addresses a range of offshore structures in sea ice and marine environments. In terms of environmental loading from waves and ice it would be an applicable code for bridges in a marine (sea ice) environment such as the Confederation Bridge. ISO 19906 is part of a suite of nine ISO standards that deal with environmental, structural design, materials and operational factors in a marine offshore environment.

---

[1] LFRD stands for 'Load and Resistance Factor Design'

For countries within the European Union a series of European standards known as Eurocodes (EN) related to construction have come into force. The objective is to have a set of harmonized technical rules for the design of construction works throughout the EU.

- The structure codes start with EN1900: Basis of structural design covering safety, serviceability, durability and structural reliability.
- Additional codes in the series EN 1991 to EN 1999 cover definition of loading, structural design with different materials and foundations.
- They apply to structural design of buildings and civil engineering works, including highway bridges.
- There is no separate standard for highway bridges; bridge related aspects for different construction materials are addressed within each individual standard.
- As a separate initiative, Handbook 4 Design of Bridges (2005) provides a unified approach and refers to relevant parts of the Eurocodes.
- Provision is made for national annexes wherein certain parameters noted in the main standard are specifically left open to national choice (Nationally Determined Parameters). These primarily are for issues related to climate and/or safety.

Norway has recently (2015) published a code for highway bridges and ferry piers in Norway. It has used ISO 19096 for guidance on ice forces on bridge piers and port structures. It is applied to structures in rivers, lakes and in coastal waters.

3.1.5 How ice forces in bridge codes may be affected by climate change

At this stage, it is worthwhile to briefly explore how climate change could affect the factors in codes that are used to determine ice loads. The CSA code is used here as an example but other codes will be similarly affected.

3.1.5.1 Load determination

CAN/CSA-S6-14 Canadian Highway Bridge Design Code is intended for calculating ice impact forces on highway bridge piers in rivers and lakes. Ice can fail in bending or crushing against a bridge pier and equations are provide for calculating ice load in either case. The equations contain environmental factors that are dependent upon climate and design factors for bridge piers that are optimized for the pier to serve its function.

The equation for ice failing <u>in bending</u> against a bridge pier is

$$F_b = C_n\, p\, t^2$$

where

$C_n = 0.5 \tan(\alpha + 15°)$, with α the slope from the horizontal of the pier's leading edge slope

p is effective ice crushing strength

t is ice thickness at time of break-up

The equation for ice failing <u>in crushing</u> against a bridge pier is

$$F_c = C_a\, p\, tw$$

where

$C_a = \sqrt{(5t/w + 1)}$

w is pier width

and t and p are as defined previously.

The value of effective ice crushing strength, which is used in both equations, is not precisely defined. The code states (clause 3.12.2.1, p. 67):

> *"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."*

The values are rounded to whole numbers. A broad range of choices for ice crushing strength are available to the designer. The commentary adds the following (clause C3.12.2.1, p. 87):

> *"As a guide, the 400 kPa stress applies at localities in which ice effects are minimal, and the 1500 kPa stress is appropriate where ice loads are expected to be severe. The effective ice strength depends primarily on the temperature and coarseness of the ice texture. However, the tensile strength is not sensitive to temperature."*

On the matter of ice crushing strength, this still leaves a broad range with limited guidance.

3.1.5.2 Factors likely to be influenced by climate change

Thus there are two environmental input factors in the load calculation which will likely change in the future as the climate changes: ice thickness t and effective ice strength p. These factors in turn are dependent primarily upon air temperatures and precipitation (snow fall and snow depth). Temperature is a simple factor, but what is more important is its involvement in the more complex matter of climate patterns, as they will affect the thickness of the ice and its strength at the time of Spring breakup.

Future input needs include

- Seasonal air temperatures
- Seasonal precipitation
- River stage at breakup
- Climate patterns in winter and spring

Outputs for revised or new codes include:

- New distributions of ice conditions (thickness, strength and river stage) at breakup for input to existing equations,
- A different range of ice crushing strengths
- Possibly new formulas including other factors for determining ice forces

Other issues could be considered. For instance, provincial manuals or guides should be reviewed carefully in terms of how changes proposed would be applied in provincial jurisdictions. Also, a liaison could be established between the Climate-Resilient Core Public Infrastructure Project at NRC and the CSA Technical Committee on the Canadian Highway Bridge Design Code. NRC already participates in one of the subcommittees, durability, but our interest might be expanded.

3.2 Bridges in Canada that cross water expanses (river, lakes, sea water)

This section's main objective was to initiate a comprehensive listing of bridges crossing water expanses in each province and territory. Stakeholders throughout the country were approached, including officials from provincial/territorial government departments responsible for bridge design, construction and maintenance, as well as personnel responsible for hydraulics and hydrological analyses, and monitoring and forecasting of ice and floods. For each province and territory, we have:

1. Identified key stakeholders;
2. Collected (or are in the process of collecting) a list of all bridges crossing water expanses which could be exposed to ice during the winter season;
3. Identified key bridges that have (or have had) piers on which ice loads are (or were) measured, or from which ice conditions/interactions are (or were) monitored;
4. Identified some recently designed bridges for which ice conditions were analyzed in more details during the design process and collected related relevant data, including drawings, pictures and engineering technical memoranda;
5. Collected known and available information on historical ice-related events that resulted in bridge damage or failure; and
6. Identified exceptions (when applicable) to the design code published by the province/territory used to account for situations specific to ice-related local requirements. Note that, as mentioned in section 3.1.2, all provinces and territories use the Canadian Highway Bridge Design Code – CHBDC – with the exception of Manitoba which uses the AASHTO LFRD Bridge Design Specification.

A brief summary of the information collected for each province and territory is presented in this section.

Table 1 is a preliminary count of the bridge network in the country crossing water. These do not include bridges managed by municipalities and the private sector.

Table 1: Preliminary overview of the bridge infrastructure managed by each of the provincial and territorial jurisdiction in Canada. Some of these numbers are estimates. See text for more information.

Jurisdiction	Crossing water
Alberta	1,877
British Columbia	300
Manitoba	650
New Brunswick	2,600
Newfoundland and Labrador	3,600
Northwest Territories	618
Nova Scotia	113
Nunavut	5
Ontario	2,800
Prince Edward Island	1,300
Quebec	6,186
Saskatchewan	2,200
Yukon	129
Total	22,378

3.2.1 British Columbia (BC)

The Ministry of Transportation (MoT) of British Columbia manages an inventory comprising of 4,500 structures throughout the province. For many of these structures, mostly those located in the south and southwest portions of the province, ice is not an important factor because these bridges are not exposed to ice conditions regularly and consistently during the winter season. The MoT maintains a Bridge Management Information System, to which the authors required access – that request has not been accepted as of this writing. The MoT is also currently preparing, for NRC, a list of bridges that are exposed to ice conditions for the entire province.

BC uses a supplement (published in a few volumes) to CHBDC S6-14, which is meant to be used in conjunction with the latter. Only Section 1.9.7.1 of Volume 1 refers to ice-related design considerations; additional specifications are provided with respect to vertical clearance. There is no explicit mention of ice loads in these documents.

The province has had a few historical events during which ice accumulations were reported to have reached the superstructure of bridges after an ice jam had formed or had been released, or during which ice jams had formed between a bridge's piers (Figure 2). There were no recent bridge damage or failure identified resulting from ice actions in BC. There were no instrumented bridge piers for ice loads or bridges from which ice was specifically being monitored, identified within the province.

Figure 2. Top left and right) Ice reaching the superstructure of a bridge located in Golden, across the Kicking Horse River on Highway 95.[2] *Bottom) Ice jam in Prince George on the railway bridge at the confluence of the Fraser River and the Nechako River.*[3]

3.2.2 Alberta (AB)

The Alberta Ministry of Transportation (MoT), along with rural municipalities within the province, manage an inventory of over 23,600 structures (including bridges and bridge-sized culverts). The MoT provided the authors with a comprehensive list of structures in which information such as structure ID, geographical coordinates, type of structure, number and length of spans, age of structure, number of piers, materials, and much more, were listed. Within this list, bridges characterized as 'major bridges' with multiple spans are of the most interest with respect to ice. There are a total of 1,877 of these bridges in AB; they have a number of spans ranging between 2 and 28, and the length ranges from 6.1 m up to 1,494 m.

To complement CHBDC S6-14, for all projects involving bridge-sized structures, AB uses a series of guidelines that cover all aspects of bridge conceptual design, including

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[2] http://www.cbc.ca/news/canada/british-columbia/ice-jam-threatens-bridge-in-golden-b-c-1.2460456

[3] http://www.cbc.ca/news/canada/british-columbia/fire-chief-says-children-playing-on-frozen-river-the-most-irresponsible-thing-he-s-seen-in-29-years-1.3914841

bridge location, sizing, geometries, and river protection works. In these guidelines, the following ice-related considerations are mentioned:

- The potential impact of the pier locations should be assessed with respect to their impact on ice conditions (Sections 2.2.4 and 3.1);
- Vertical clearance with respect to high ice-flood or ice-jam levels (Section 3.2.2.2);
- To resist ice forces, the use of riprap is recommended as a river protection works design (Section 3.2.3); and
- Ice-related design considerations should include design forces on piers, vertical clearance for ice jams, and structure blockage due to icing/aufeis (Section 3.2.4.1).

A new version of these guidelines will be released in the near future. MoT's Structural Engineering Specialist, John Alexander, is the Chair of the CHBDC Technical Committee and the MoT's representative on the regulatory authority committee. The MoT also sits on several technical sub-committees.

Several of Alberta's bridges are crossing large rivers in the northern part of the province (e.g. the Peace River and the Athabasca River) and have a significant history of ice-related issues. Alberta Environment and Parks does annual monitoring of both these rivers during the break-up season. The bridges over the Athabasca River near Fort McMurray may be of particular interest for the present study.

There were no bridge failures due to ice events in recent history. However, there were some in the late 1800s and early 1900s; these were mostly due to vulnerable designs. The MoT has a tool, available for download, called the Hydrotechnical Information System (HIS) – it includes most flood observations at bridge sites managed by Alberta Transportation, including ice-related events.

Currently, there are no instrumented bridge piers in the province on which ice loads are measured or bridges from which ice conditions are monitored. However, the Alberta Research Council (ARC) collected a wealth of ice load data from instrumented bridge piers in the late 1960s through the late 1980s. The bridge crossing the Athabasca River on Highway 2 near Hondo was built with access and monitoring equipment to facilitate a study by the ARC (Figure 3). The instrumented bridge pier has a semicircular shape, is inclined 23° from the vertical, and has a diameter of 2.32 m. Accelerometers were also installed to measure the longitudinal and transverse acceleration of the pier. A total of 22 ice loading events were recorded from that pier (ice loads varied from 260 to 2,270 kN; ice thicknesses reported ranged from 0.4 to 1.1 m; ice floes were 5 to 50 m in diameter; and ice drift speeds between 0.4 and 2.9 m/s). During the same decades, another bridge crossing the Pembina River, in Pembridge, was also instrumented (Figure 3). This pier has a vertical face with a diameter of 0.86 m. A total of four ice loading events (all from the year 1974) were recorded (ice loads varied from 350 to 1,060 kN; ice thickness was reported to be 0.45 m; ice floes were 20 to 40 m in diameter; and ice drift speeds were estimated to be 1.04 m/s). The equipment has since been removed from both of these bridges. The ice load data collected from these bridges have been incorporated into the NRC Ice Load Catalogue (Timco et al., 1999).

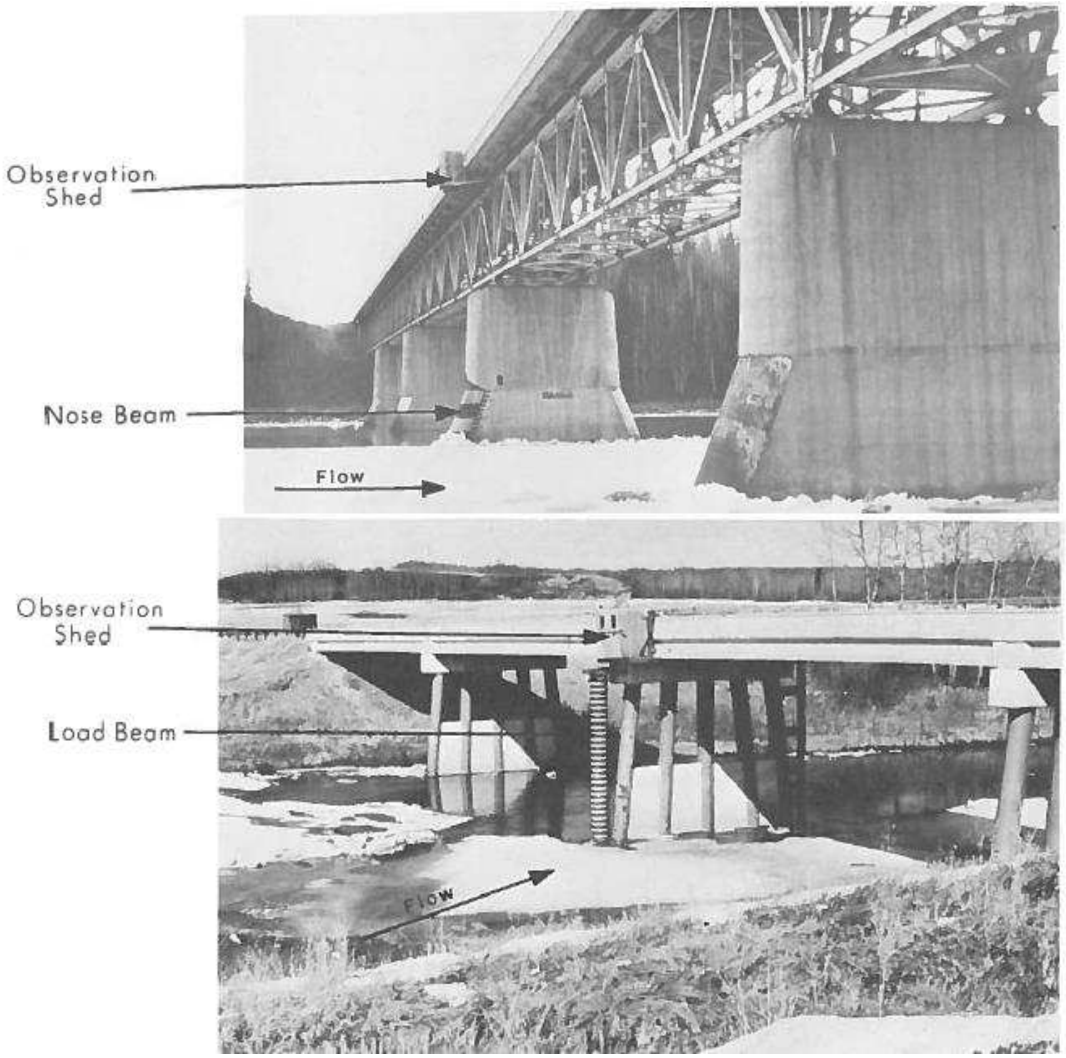

Figure 3. Top) Hondo bridge pier. Bottom) Pembridge bridge pier. From Lipsett and Gerard, 1980.

Bernard Trevor, the current manager of the River Forecast Team with Alberta Environment, was involved in the projects during which ice forces on the bridges in Hondo and Pembridge were measured by the ARC. Mr. Trevor graciously provided the authors with scanned copies of six separate reports pertaining to these projects from the late 1970s and the 1980s (Huiskamp, 1983; Lipsett and Gerard, 1980; Lipsett and Montgomery, 1979; Van Der Vinne, 1988a; 1988b; 1988c). The ARC had also instrumented a bridge pier in advance of the flooding of the Oldman River dam reservoir. However, with the disbandment of the ARC in the early 1990s; no measurements were taken.

Bernard Trevor mentioned one historical event (around 1940) on the Red Deer River during which a railway bridge failed from river ice actions. We have not been able to locate the exact photo of the event, but Figure 4 shows how severe ice jams were on the Red Deer River on that bridge.

The river ice forecast team at Alberta Environment monitors freeze-up and break-up of the Peace River near the Town of Peace River, and break-up of the Athabasca River near Fort McMurray due to the high ice jam flooding risks at these communities. Over the last few years, they have observed significant ice runs at Fort McMurray. There are a number of bridges in that area: triple bridge crossing within Fort McMurray, Suncor mine site bridge north of Fort McMurray, and the Highway #63 crossing of the Athabasca River near Fort MacKay.

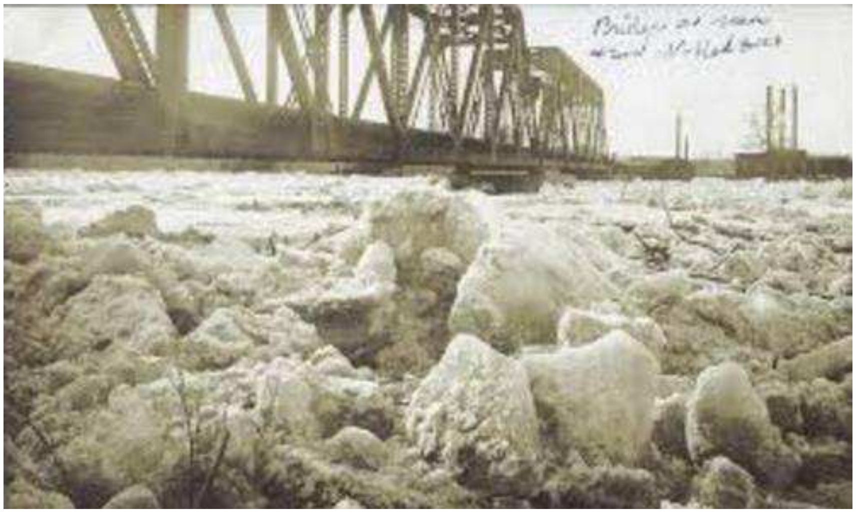

Figure 4. Ice jam acting on a railway bridge on the Red Deer River. Courtesy of Peel's Prairie Provinces, a digital initiative of the University of Alberta Libraries[4].

Flows on the Peace River are controlled by BC Hydro and ice events on that river have not been spectacular in recent years. There is a bridge on Highway #986 crossing of the Peace River a few miles north of the Town of Peace River. A second bridge at the Town of Peace River is planned to go to tender before the summer of 2017. There is another bridge on Highway #88 crossing at Fort Vermillion (Figure 5). This bridge's piers were specifically shaped to reduce ice loads. Pier vibration tests were also conducted over two winters – it has not yet been possible, as of this writing, to confirm if these tests were successful and if a report was issued.

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[4] http://peel.library.ualberta.ca/postcards/PC004724.html

Figure 5. Bridge crossing at Fort Vermillion.

3.2.3 Saskatchewan (SK)

Saskatchewan's Ministry of Highway & Infrastructure (MHI) manages approximately 700 bridges (75% of which are short span bridges with slender substructure elements of either timber or pipe piling), and the Saskatchewan Association of Rural Municipalities (SARM) manages a little over 1,500 bridges located on lower level roads (SARM do not have larger bridges as the main traffic is expected to utilize nearby provincial highway crossings). MHI and SARM are both currently preparing a list of bridges over watercourses at the authors' request – both organizations advised that this will take them some time. Major bridges that are exposed to ice and that might be of interest in the context of this study are bridges over the Saskatchewan River system, Battle River, and bridges located in the North of the province.

SK doesn't have or use any general exceptions to the CHBDC S6-14. If they do require something specific for a given bridge construction, it would be listed in the Contractors and Consultants Bridge Design Criteria. This would however be on a project by project basis, only when and if required.

MHI does not keep a database of historical ice-related events or issues on their bridges. According to them, only a small number of bridges have had ice damage over the years, and these bridges had either timber piers or unfilled pipe piles bent. There were no recent bridge damage or failure identified resulting from ice actions in SK.

There were no instrumented bridge piers for ice loads or bridges from which ice was specifically being monitored, identified within the province.

3.2.4 Manitoba (MB)

Manitoba Infrastructure and Transportation (MIT) is responsible for an asset inventory of over 3,000 structures on the highway and water control networks, of which 1,150 are bridges and overpasses, and 650 are bridges crossing watercourses. MIT is currently preparing a list of all the bridges for the entire province of MB for NRC; they are advising that this will require some time.

As previously mentioned in this report, in Manitoba, the design and detail of all bridge structures and structural components have to conform to the requirements set forth in the latest edition, including the interim update(s), of the AASHTO Load and Resistance

Factor Design (LRFD) Bridge Design Specifications. MIT also publishes and uses a Structures Design Manual to modify and amend specific parts of AASHTO. In this manual, ice loading and vertical clearance requirements (Sections 2.2.4.1 and 2.2.4.2.3) are vaguely discussed. Although MIT do not design to the CHBDC, it is an alternate code that they also use and refer to internally.

There is no known damage or failures of “major” bridges caused by ice in MB. They have seen some failures due to ice loading, but these were typically timber bridges crossing provincial drains (these drains are typically man-made and ice floes typically come in larger pieces; the ice impact then bents the timber or steel bent). An example is the collapse, in April 2011, of a bridge located on Tobacco Creek on PR 332, approximately 5 km north of Lowe Farm Manitoba (Figure 6). The bridge was a typical four span timber bridge on timber piles. The ice destroyed the interior pile bent, causing collapse, with one span separating from the structure completely. There were likely other similar cases on similar types of bridges in the past few decades, but these are not catalogued or recorded in a specific database.

There were no instrumented bridge piers for ice loads or bridges from which ice was specifically being monitored, identified within the province.

3.2.5 Ontario (ON)

Ontario’s Ministry of Transportation (MoT) owns approximately 2,800 bridges on the provincial highway system (in addition to many culverts, retaining walls, sign supports and other highway infrastructure). Within the MoT, the Bridge Office contributes to the management of this infrastructure with the development, maintenance, and implementation of policies, procedures, guidelines, standards, manuals and specifications. The MoT’s Bridge Office is currently preparing a list of all bridges crossing water expanses for the province, which will be provided to the authors; they have to consult with all regional offices and have advised that it will take them some time.

According to Tony Merlo, Manager of the Bridge Office, bridge design with respect to ice is performed according to the CHBDC only. While there is a document that complement the CHBCD (“Exceptions to the CHBDC CSA S6-14 for Ontario”), the latter does not mention any specifications related to ice.

In the late 1980s and early 1990s, NRC instrumented a pier on the Minto Bridge, a heritage bridge crossing the Rideau River in Ottawa (Johnston et al., 1999). The pier is V-shaped in the horizontal plane, has a vertical face at the waterline, and a width perpendicular to the ice movement of 2 m. The ice load measurements were conducted as part of an experimental program during which controlled blasting of the river ice initiated an artificial break-up run. A total of 13 ice loading events were recorded from that pier (ice loads varied from 12 to 160 kN, ice thicknesses reported ranged from 0.3 to 0.6 m; ice floes were 2 to 15 m in diameter, and ice drift speeds between 0.75 and 1.25 m/s). These data have been incorporated into the NRC Ice Load Catalogue. There are currently no instrumented bridge piers in the province on which ice loads are measured or bridges from which ice conditions are monitored. There were no recent bridge damage or failure identified resulting from ice actions in ON.

Figure 6. Collapse, due to ice loading, of a bridge located on Tobacco Creek on PR 332 (MB). Courtesy of Manitoba Infrastructure and Transportation.

3.2.6 Québec (QC)

In the province of Quebec, the Ministère des Transports, de la Mobilité durable et de l'Électrification des transports (MTMDET) is responsible for a total of 6,185 bridge crossing watercourses. The MTMDET has provided the authors with a full list of these bridges, which includes the following information: structure ID, road, name of obstacle, municipality and geographical coordinates.

QC published and uses guidelines (in a few volumes) to the CHBDC S6-14, the "Manuel de conception des structures". Section 3.4 of Volume 1 vaguely mentions ice loading; the Hydraulic Design Manual (Volume 3) has requirements with respect to the vertical clearance and ice levels.

It was difficult to obtain information from the MTMDET on historical events for which ice actions on bridges resulted in either damage or failure of the structure. No major event was found through a superficial search on the internet, although there surely exist historical events during which high water levels resulting from ice-related flooding would have impacted or endangered the superstructure of some bridges in the province.

There were no instrumented bridge piers for ice loads or bridge from which ice was specifically being monitored, identified within the province. However, a few lighthouses in the St. Lawrence Seaway have been instrumented in the past (e.g., Frederking et al., 1992). Also, the Pierre Laporte Bridge (in Quebec City) and the Laviolette Bridge (in Trois-Rivière) have cameras overlooking the St. Lawrence River (which can be accessed in near real-time).

3.2.7 New Brunswick (NB)

The New Brunswick Department of Transportation and Infrastructure (NBDTI) is responsible for over 2,600 bridges and culverts within the province. Most of the bridges in NB are solely exposed to freshwater ice, but some of them located in coastal areas are exposed (at least partially, depending on the tidal regime) to saline ice. The authors requested a more detailed listing of bridge structures within the province; the NBDTI has yet to confirm whether or not they will be able to provide such a list.

Because the province has historically been extremely vulnerable to floods, and because 70% of the floods in NB are ice-related, the province has adopted a proactive approach in how they deal with these issues by sponsoring a fair amount of river ice research on their rivers. A NB Subcommittee on River Ice was established under the Flood Forecasting Technical Committee within the Canada-New Brunswick Flood Damage Reduction Program (FDRP). The Subcommittee is composed of the following agencies: New Brunswick Department of Environment (NB ENV), the New Brunswick Electric Power Commission (NBEPC), the University of New Brunswick (UNB), and Environment Canada, as represented by the National Water Research Institute (NWRI), the National Hydrology Research Institute (NHRI), the Atmospheric Environment Service (AES), the Water Resources Branch (WRB) and the Water Planning and Management Branch (WPM). This Subcommittee has published a ‘NB River Ice Manual’, which provides details of general river ice processes and specific characteristics of the river ice regime in New Brunswick’s rivers. Many of the researchers involved in this Subcommittee also have published a significant amount of literature over the past few decades.

Several ice-related floods and ice-related bridge damage events have occurred in NB (e.g., Figure 7), notably on structures crossing the Saint John River. Beltaos et al. (2003; 2006) reported several ice-related flood events (in the late 1800s, early 1900s and one in 1970) that resulted in five or more bridges being damaged or destroyed, with the 1970 ice-induced flood resulting in 32 bridges destroyed and over 75 bridge structures damaged. Spyros Beltaos, a pioneer in the river ice research, has conducted a lot of his research on the Saint John River in NB. The focus of the river ice research in NB has been with respect to ice jams and ice-induced flooding. Other ice-induced flood-prone rivers in the province include the Nashwaak River, the Canaan River, and the Kennebecasis River.

In 1986, a bridge in Bathurst failed due to moving ice floes during a spring freshet, forcing the closure of the road for over one month. In 1987, the Perth-Andover Bridge over the Saint John River sustained superstructure damage due to ice impacts. In 2006, an ice jam on the Saint John River threatened the covered bridge in Hartland. A 2014 flood resulting from an ice jam on the Saint John River caused more than $16M in damage. Two bridges were washed away and one was pushed off its abutments by ice.

While there are no formal exceptions to the CBHDC published for NB, when designing a bridge, in addition to ice loading, the province also considers the impact of bridge piers on the potential for ice jamming, and the potential high water levels during ice-induced floods. As part of the engineering design of a new bridge at Clair in the early 2000s (as reported in Beltaos et al., 2003), the NBDTI optimized the number of piers and their relative location within the channel. This was done to minimize the impact that the new bridge would have on the ice regime, and to minimize the potential for ice jamming and, therefore, for ice-induced flooding. They changed an initial design of four piers to a final design with two, more robust piers.

Figure 7. Top) Ice jam at a railway bridges in New Brunswick. Bottom) Collapsed bridge under ice forces. Images from the NB River Ice Manual.

3.2.8 Prince Edward Island (PEI)

The Department of Transportation, Infrastructure and Energy (TIE) of Prince Edward Island has an overall network of over 1,500 structures, of which 219 are bridges (five overpasses, and the remaining being structures over water). The Highway Design and Bridges section of the Department is responsible for providing design services for the highway and bridge network within PEI, as well as maintaining inspection and maintenance programs. The Department has provided the authors with a comprehensive list of structures in which information such as structure ID, location, type of structure, number and length of spans, age of structure, number of piers, materials, and much more, were listed. Most bridges in PEI are single span bridges (67%); 96% of all bridges have four spans or less. Bridge lengths in PEI vary from 3 to 248 m and averages 22 m. The Department has also identified a sub-list of bridges that they consider would be of interest in the context of this study (i.e., bridges with multiple spans and which are impacted by ice during the winter).

While some of the bridges in PEI are solely exposed to freshwater ice, many of them are located in estuaries and/or close to bays and are exposed to saline ice. Notwithstanding the Confederation Bridge (which is not managed by the province), the bridge with the most spans (17) on the island is in Grand River on Highway 12 (crosses the Grand River which flows into Malpeque Bay). The longest bridge is located in Charlottetown as part of the Trans-Canada Highway and crosses the Hillsborough River.

PEI does not publish or use exceptions to CHBDC S6-14 when designing bridges.

There were no bridge failures or significant damages incurred on a bridge from ice in recent history in the province. It was pointed out by the maintenance people that the most common form of damage caused by ice on their bridges was in the form of abrasion on the sub-structure elements.

Apart from the Confederation Bridge, there are no instrumented bridges in the province. Note that the Confederation Bridge is not discussed here, as an entire section of the present report is dedicated to it.

3.2.9 Nova Scotia (NS)

The Nova Scotia Department of Transportation and Infrastructure Renewal (NSTIR) is responsible for 4,100 bridges (except those under the Halifax Dartmouth Bridge Commission), including 200 steel truss bridges and a large quantity of smaller bridges, with a lot of them built out of timber. NSTIR provided the authors with a list of over 3,600 structures (bridges and culverts) and all available related information (structure ID, location, type of structure, number and length of spans, age of structure, number of piers, materials, etc.), along with a suite of Google Earth KMZ files (which includes these bridges and many more, like overpasses). The NS government also has an ‘open data’ project (https://data.novascotia.ca/) which contains all of the roads, structures (including bridges), and water features within the province.

The NSTIR designs bridges to the CHBDC and do not publish any exceptions to the code with respect to ice (they have a ‘Standard Specification’ document, but it has no mention of ice). All new structures have a hydraulic study completed as part of the pre-engineering work so that high water flows are considered, with and without ice, both in terms of vertical clearance requirements and whether high levels could contribute to additional ice loading.

Figure 8. Top left) The East River Bridge, in Sheet Harbour NS - courtesy of NSDTIR. Top right) Schematic of the piers geometry (from a technical memo provided by the NSDTIR). Bottom) The new Sydney River Bridge - courtesy of Transportation and Infrastructure Renewal.

On one new structure built recently by the NSTIR (the East River Bridge located in Sheet Harbour) and for which ice was specifically considered in the design, 'ice skirts' (also referred to as 'ice shields' in their documentation) were included on the piers (see Figure 8). Analyses have shown that ice forces generated from crushing on a vertical pier would induce deflections well beyond the Service Limit State (SLS) allowable value. For this reason, in order to promote ice failure in bending and reduce the ice loads, the final design included a sloped surface (the ice skirts) on the piers, with a slope of 38° from the vertical. A similar design was considered for the new Sydney River Bridge. The latter is located in Sydney Harbour and is exposed to tidal conditions; it is therefore exposed to both saline and freshwater ice originating from both the Gulf of St. Lawrence and the river. For both these new bridges, and on all new bridges, the NSTIR allows for an increased vertical clearance based upon the 1:100 flood event (open-water and ice-covered) and an additional amount for sea level rise (when applicable). For the existing infrastructure, the NSTIR typically do not proactively retrofit for water levels or ice flows, unless there is a major rehab of the bridge.

The NSTIR does not keep an exhaustive list of historical ice-related issues/events for bridges in the province. One of the most infamous cases of ice-related bridge failure in the province is that of the Bridgewater Bridge (LUN003). This bridge is a 100+ year old deck truss bridge crossing over the LaHave River. In 2003, ice jams had reached very close to the underside of the bridge and the bridge was closed for engineering assessments. That same structure had one span washed down the river during a flood circa 1976. Similar situations may happen on a somewhat regular basis during spring thaws.

There were no instrumented bridge piers for ice loads or bridges from which ice was being monitored identified within the province.

3.2.10 Newfoundland and Labrador (NL)

In NL, the Highway Design and Construction Section of the Department of Transportation and Works (TW) is responsible for the design, management and maintenance of all bridges. Over 750 bridges were listed in the province, of which 618 are over watercourses. For each of these bridges, additional information was collected, including the structure ID, location, type of structure, number and length of spans, age of structure, number of piers, materials, photos, current state of the structure (with respect to the superstructure and the substructure), the hydrology (including the ice and a list of possible/known ice-related problems on the bridge), and other general observations.

TW-NL designs bridges to the CHBDC and do not publish any exceptions to the code.

There is no formal registry/database of historical ice-bridge events in NL. Some areas are well known for being prone to ice-induced flooding, such as the Exploits River at the Town of Badger. The Exploits River is the most important river on the Island of Newfoundland. The concrete piers of the Sir Robert Bond Bridge, which crosses the Exploits River at the town of Bishop’s Falls, show clear signs of abrasion resulting from the action of water and ice. Metal plates have been added on the upstream sides of the piers (Figure 9) to offer extra protection against ice abrasion.

No bridges are instrumented for ice loads or used to explicitly monitor ice conditions around bridges in the province.

Figure 9.The Sir Robert Bond Bridge, over the Exploits River, at the town of Bishop's Falls (two angles). Note the signs of abrasion on the concrete piers resulting from ice action. Photos by Krysta Colbourne/Transcontinental Media[5].

3.2.11 Yukon (YT)

Yukon's Department of Transportation (DoT) maintains 4,800 kilometres of road (from which only 250 kilometres are paved - the third smallest in the country ahead of only the Northwest Territories and Nunavut). Within this highway system, there are a total of 129 bridges. It has been difficult to get in touch with key personnel in the Highways and Public Works Section of the DoT and to obtain more details on their bridge network and design practices. More information will be added in the near future when it becomes available.

3.2.12 Northwest Territories (NWT)

The Highways and Marine Division of the Department of Transportation (DoT) of the NWT manages over 300 bridges and major structures (of which 113 bridges are crossing water expanses – these range from 10 m to 1,045 m in length) spread within 3,835 km of all-weather highway and winter roads. The NWT also has four ferry and ice crossings. The DoT has provided the authors with a detailed list of all bridges (which contains the structure ID, location, asset name, geographical coordinates, number of spans, length, year constructed, materials used, and superstructure and substructure type and shape). Of this list, a sub-list of 17 multi span bridges was created in which the main bridges for which ice is an important consideration are identified.

The only exception to the CHBDC used in the NWT relates to the required vertical clearance. The NWT requires 1.5 m freeboard (as opposed to 1.0 m as per the CHBDC). This is to accommodate ice build-up (aufeis) conditions and water back-up at break-up which may cause drifting ice to pile up, in the case of bridges on tributaries near the

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[5] http://www.gfwadvertiser.ca/news/local/2015/6/2/tender-awarded-for-latest-bond-bridge-ph-4167610.html

Mackenzie River, for example. During break-up, the Mackenzie water levels may rise when there is an ice jam or if it is still frozen further north. This would cause the water to backflow into tributary rivers, and the combination of the tributary flow with the Mackenzie backflow could cause both high water and drifting ice to ride higher up the piers and shores. The DoT uses hydrological studies, field evidence and the additional 0.5 m freeboard to determine the minimum bridge soffit elevation.

Drifting ice and ice loading has not caused problems with any of the bridges currently in place in the NWT. There are, however, some bridge openings that experience aufeis (winter overflow/icing); ice plugs create an issue at freshet when the restricted opening resists spring melt run-off.

There are no piers instrumented for ice loads or bridges used to explicitly monitor ice conditions in the NWT.

The largest bridge in the NWT is the relatively recent Deh Cho Bridge, on the Mackenzie River (Figure 10). The bridge was built to eliminate lengthy and uncertain ferry disruptions during winter freeze-up and spring break-up. The bridge is 1,045 m long and crosses a 1,600 m span of the Mackenzie River on the Yellowknife Highway (kilometer 23 of Highway 3) near Fort Providence. There are two lanes, nine spans and eight piers in water. The longest span is 190 m long (central) and the other spans are 90 m, 112.5 m and 112.5 m (identical on each side). The bridge is exposed to fairly significant ice conditions during the winter. The piers are sloped at the waterline, promoting flexural failure of the ice and lower ice loads relative to crushing loads. Each pier consists of a lower solid concrete cone (reinforced with an outer steel shell protecting the concrete against ice actions) and an upper steel head. The steel head has a base, two inclined legs, and a tie-beam connecting the legs.

Figure 10. Deh Cho Bridge, crossing the Mackenzie River, in the NWT. Top) Structure drawing (source: Wikimedia[6]*). Middle and bottom) Near and far range views of the bridge (source: The Deh Cho Bridge Project website by NWT Transportation*[7]*)*

3.2.13 Nunavut (NU)

The majority of bridges in Nunavut are within community boundaries and are considered municipal infrastructure. As a result, they are the responsibility of the Department of Community Government Services (CGS) (and not of the Department of Economic Development and Transportation). There are 26 communities in Nunavut (17 of which are above the Arctic Circle), and there is no road infrastructure connecting them. People rely on air transport for their essential needs.

There are only a handful of bridges in Nunavut and there is no official database for these bridges:

- Iqaluit (across Apex Creek, between Iqaluit and Apex)

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[6] https://en.wikipedia.org/wiki/Deh_Cho_Bridge#/media/File:Pont_de_Deh_Cho.png
[7] http://www.dehchobridge.info/photos.html

- Pangnirtung, just outside Arctic Bay
- in Rankin, just outside Cambridge Bay
- in Kugaaruk
- in Coral Harbour

There are also a small number of bridges on privately-built roads, such as the one connecting Baker Lake and the Meadowbank Gold Project. All of these bridges are exposed to ice actions for a fair amount of the year.

Nunavut does not have any standards/codes to design bridges. If a bridge requires replacement, the Department of CGS would ask a consultant to design to industry standards or to those set out by AASHTO.

There were two historical bridges failures known to the official at the Department of CGS with which the NRC had discussions: the bridge at Kugaaruk (age-related – the bridge was replaced), and the bridge in Pangnirtung, which had a sudden failure caused by erosion. It is unknown what role ice played in these failures.

3.2.14 Ice impact on the Canadian bridge infrastructure and climate change

More than 22,000 bridges crossing water expanses have been identified across Canada as part of this study. This is a preliminary estimate, based on a semi-complete dataset, as described in this section. For most provinces and territories, ice interaction with bridges is a major concern and is explicitly considered in the design of bridges. Throughout the country, examples of historical events of ice-induced damage on a bridge or, in the worst cases, failure of the bridge due to ice, were identified.

When designing a bridge, most jurisdictions have specific requirements related to ice, so as to complement those specified in the design code they use. For most of them, a major concern is the required vertical clearance under high water levels induced from an ice jam. While ice loading on a pier is always a consideration while designing a bridge (as a pier has to be able to sustain the ice load and maintain an acceptable deflection), it is the secondary effects of the ice presence in a river that has had the most impact on Canadian bridges historically: ice jams inducing flooding and high water levels resulting in ice impacting the superstructure, or bridges being pushed off their abutments and/or being washed out. Over saline waters, such as is the case for the Confederation Bridge, the ice regime is different than in rivers and therefore the main concerns are of a different nature. For those, ice loads and ice jamming across the piers are more of a concern.

Climate change is affecting the ice regimes in rivers and estuaries in many different ways and the processes governing ice interactions with bridges are directly impacted by these changes. Important parameters such as discharge, ice thickness, and ice jam frequency and locations, all depend on climatic conditions (Beltaos et al., 2007). In New Brunswick, for example, it has been reported that warmer and shorter winters are resulting in earlier spring breakup, reduced snow pack due to more precipitation falling as rain and, as a result, more frequent mid-winter thaws that can enhance the severity of midwinter breakup and ice jamming (Beltaos et al., 2007).

There are several ice-related considerations that have to be accounted for in the design of a bridge (some of which were described in Beltaos et al., 2003). They include:

- Static loads generated by the thermal expansion/contraction of an ice cover.
- Dynamic ice loads imparted from moving ice floes. This can be from a floating ice sheet, a collection of ice floes, or from an ice jam – it is not straightforward to evaluate the potential ice load from an ice jam (as a result of climate change, ice jams are becoming more common in several regions across Canada).
- The geometry, number and relative locations of the bridge piers will influence the ice loads (e.g. vertical vs. sloped face at the waterline) generated from an impact and could also instigate ice jams, i.e. too many piers could increase the likelihood of an ice jam forming upstream of the bridge.
- The maximum stage that occurs during open-water conditions is often exceeded by the stage of water and ice resulting from ice jams (Beltaos et al., 2003). Vertical clearance between the high water levels and the superstructure has to be sufficient to avoid the bridge being damaged or destroyed by moving or jammed ice. Further, the bridge abutments have to be able to sustain forces generated from an ice run during break-up.
- The frequency and severity of the spring freshet will have an impact on the ice break-up regime and on the frequency and severity of ice-induced floods.
- The elevation at which ice forces are applied determines the overturning moment. This elevation depends largely on the hydrology, which is tightly linked to climate change.
- The scour potential of a surge resulting from the release of an ice jam has to be evaluated, as this can result in significant scour depths which could exceed those generated from open-water floods.
- The timing of break-ups and ice runs is changing – the estimation of freshwater ice properties (used in ice loads calculations) with respect to the time of year is a challenge.
- The presence of aufeis (i.e. a culvert or opening that becomes blocked by solid ice) has been reported as being a concern in some parts of Canada.

3.3 Contacts and useful links

A significant component of the ground work that is required to conduct this R&D work is the establishment of strong stakeholder network. This section lists some of the key contacts that were reached so far by the authors, for information on their jurisdiction's bridge infrastructure.

3.3.1 British Columbia

Kevin Weicker | Provincial Design Manager
Bridge Engineering | BC Ministry of Transportation and Infrastructure
Government of British Columbia
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Useful link(s):

- Policies, specifications, standards and guidelines to be followed in the development of bridges and related structures on the highway system in British Columbia for the Ministry of Transportation and Infrastructure: http://www2.gov.bc.ca/gov/content/transportation/transportation-infrastructure/engineering-standards-guidelines/structural
- Supplement to CHBDC S6-14 – Volume 1: http://www2.gov.bc.ca/assets/gov/driving-and-transportation/transportation-infrastructure/engineering-standards-and-guidelines/bridge/volume-1/2016/volume-1.pdf
- Supplement to CHBDC S6-14 – Volume 2: http://www2.gov.bc.ca/assets/gov/driving-and-transportation/transportation-infrastructure/engineering-standards-and-guidelines/bridge/volume-2/bsm_vol_2_procedures.pdf
- Supplement to CHBDC S6-14 – Volume 6 (Hydrotechnical Engineering): http://www2.gov.bc.ca/gov/content/transportation/transportation-infrastructure/engineering-standards-guidelines/structural/standards-procedures/volume-6
- Bridge Management Information System (BMIS): http://www.th.gov.bc.ca/bmis

3.3.2 Alberta

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Technical Standards Branch | Alberta Transportation
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Bernard Trevor, M.Eng., P.Eng. | Manager River Forecast Team
River Engineering and Technical Services | Watershed Resilience and Mitigation
Environment and Parks | Government of Alberta
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Email: Bernard.Trevor@gov.ab.ca
Useful link(s):

- Main page on bridges and structures: http://www.transportation.alberta.ca/565.htm
- Bridge Structures Export (contains a list of all bridges managed by Alberta Transportation and rural municipalities): http://www.transportation.alberta.ca/4827.htm
- Information on bridge design: http://www.transportation.alberta.ca/4865.htm and http://www.transportation.alberta.ca/4866.htm
- Alberta’s Bridge Structures Design Criteria document: http://www.transportation.alberta.ca/content/doctype30/production/bridgeconceptualdesignguidelines.pdf
- River forecast team: http://www.environment.alberta.ca/forecasting/RiverIce/index.html

3.3.3 Saskatchewan

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Useful link(s):

- Ministry of Highways and Infrastructure: http://www.highways.gov.sk.ca/

3.3.4 Manitoba

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Sunny Sidhu | Bridge Design Engineer
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Useful link(s):

- Water control and structures – design manual: https://www.gov.mb.ca/mit/wms/structures/pdf/manuals/structures_design_manual_version1.pdf
- Manitoba Infrastructure's asset inventory: http://gov.mb.ca/mit/wms/structures/index.html

3.3.5 Ontario

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Useful link(s):

- Hydrotechnical design process: http://www.mto.gov.on.ca/english/publications/drainage/hydrology/
- Section on ice forces: http://www.mto.gov.on.ca/english/publications/drainage/hydrology/section10.shtml#ice

3.3.6 Québec

Christian Poirier, ing. M.Sc. | Chef du module hydraulique
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Gérard Desgagné, ing., M.Sc. | Chef du Service de la Conception des structures
Direction des structures | Ministère des Transports, de la Mobilité durable et de l'Électrification des transports
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Courriel: Gerard.Desgagne@transports.gouv.qc.ca

Useful link(s):

- Québec's "Manuel de conception des structures":
- Older, archived, versions of the manual:
    - Volume 1: http://collections.banq.qc.ca/ark:/52327/bs1946809
    - Volume 2: http://collections.banq.qc.ca/ark:/52327/bs1867901
    - Volume 3: http://collections.banq.qc.ca/ark:/52327/bs58736

3.3.7 New Brunswick

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Tracy MacDonald | Engineer
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Government of New Brunswick
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Useful link(s):

- Flood history database: http://www.elgegl.gnb.ca/0001/en/Flood/Search
- Bridge Condition Index: http://www2.gnb.ca/content/dam/gnb/Departments/trans/pdf/en/Bridges/Districts-EN.pdf

3.3.8 Prince Edward Island

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Neil G. Lawless| Bridge Engineer
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3.3.9 Nova Scotia

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Structural Engineering | Nova Scotia Transportation & Infrastructure Renewal
Government of Nova Scotia
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Useful link(s):

- Government of Nova Scotia Open Data project: https://data.novascotia.ca/

- List of road structures (bridges, culverts): https://data.novascotia.ca/Roads-Driving-and-Transport/Structures-Database/gs26-c3fm
- Water features: https://data.novascotia.ca/Lands-Forests-and-Wildlife/Nova-Scotia-Topographic-Database-Water-Features/fpca-jrmt

3.3.10 Newfoundland and Labrador

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Amir Ali Khan, Ph.D., P.Eng. | Manager, Hydraulic Modelling Section
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Useful link(s):

- List of bridges, details on each and available inspection reports: http://www.tw.gov.nl.ca/BridgeInspections/index.asp
- Flood risk mapping studies: http://www.ecc.gov.nl.ca/waterres/flooding/frm.html

3.3.11 Yukon

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3.3.12 Northwest Territories

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3.3.13 Nunavut

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4. Possible climate change effects on the Confederation Bridge

There are anecdotal accounts of the effects of climate change on the Confederation Bridge. These need to be quantified in an effort to determine if a variation in the ice loads on the bridge can be related to the effects of climate change. The preliminary work presented in this section points out to possible short-term climate-related effects on ice thickness and wind regime. Ultimately, it should lead to follow-up work whose final purpose would be recommendations for design guidelines, to be fed into CSA/ISO 19906.

4.1 Bridge description

The Confederation Bridge (CB) connects New Brunswick and Prince Edward Island (Figure 11). For context, following is some information on that structure[8]:

- Construction took place between October 1993 and May 1997, at a cost of $1B.
- It was designed to last 100 years.
- It is the longest bridge in the world over freezing waters.
- It has a length of 12.9 km - the main section of the bridge is 11 km long and contains 44 piers 250 m apart (Figure 12).
- It has some curves and a 1.1 m wall, to mitigate driver distraction and minimize risks of accident.
- Because of its considerable length, multi-span concrete box girder structure.

Each pier has a cone at the waterline to promote ice failure in flexure. This is common waterline pier configuration in icy waters. The reason is the ice would otherwise fail in ‘crushing mode’ against the piers, thereby inducing much higher loads than in flexure. For the CB, the cone design incorporated some innovative features. Crushing also has the potential to excite vibrations near the natural frequency of the piers and resonance (see section 5).

The 44 piers are numbered from the PEI side, as shown in a cross section view of the bridge in Figure 12. Located in the middle of the bridge, a navigation span between the 21st and 22nd piers (P21/P22) provides a channel with a 60 m clearance above the water line for ship traffic.

In Figure 12, the water line (GML) is defined as the baseline on the vertical axis. The green line is the height of pier shaft above the water line, and the purple line is the bridge deck height, which is the sum of the pier’s height and girder’s depth. The red line is the foundation depth below the water line, and the blue line represents the water depth. Beside the navigation channel the 23rd and 24th piers (P23/P24), which are indicated as two orange lines in Figure 12, were selected by NRC as the research object for this project to examine the response of the Confederation Bridge to ice while piers 31 and 32 were chosen by the University of Calgary for their studies (Brown, 1997). These projects are both studying the behavior of the ice interaction with the bridge.

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[8] http://www.confederationbridge.com

4.2 Bridge relevance to design – Accounting for climate change

During the construction of the Confederation Bridge, the bridges effect on the local ice conditions and the ice loads on the structure were seen as a source of uncertainty prior to construction. Because the bridge was such a large and innovative engineering project a joint monitoring and research team was developed as a partnership between Public Works and Government Services Canada (PWGSC), Strait Crossing Development Inc. and Canadian Universities (Cheung et al., 1997).

Figure 11: Top) The Confederation Bridge sustaining ice action – drift is toward the right (S. Prinsenberg, April 2003). Note the linear wake behind the piers. Bottom) View of the bridge from the New Brunswick shoreline – taken by one of the authors (LP), January 2007.

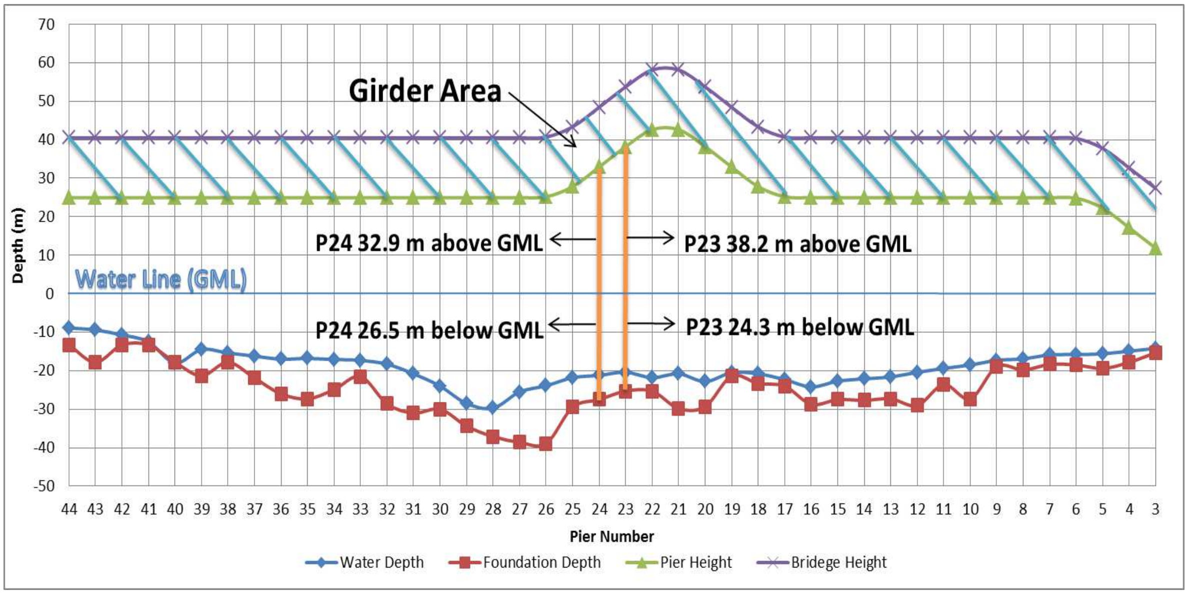


Figure 12: Profile of the Confederation Bridge.

This long term monitoring of the Confederation Bridge over the past 20 years makes it an ideal structure to examine the effects of climate change. While 20 years is a relatively short period of time over which to observe the effects of climate change some telltale signatures of climate change can be observed at or near the site from the climatic record since the construction of the bridge in 1997.

4.2.1 Air temperature

By examining the average daily temperature measurements in Summerside (Figure 13), the nearest weather station with a complete record since the summer of 1999, we note an increase of 0.03°C/year in average temperature during the season when ice can be present (December 1 – May 15). Over a 20 year period, the increase is 0.66°C. The average temperature over the period is -2.1°C and the standard deviation in the data in 6.8°C. While the temperature variation is statistically insignificant, it can still be real – this is the assumption we make at this stage for the purpose of this exercise.

4.2.2 Ice thickness

As mentioned previously, ice thickness is an important parameter, as it directly affects the amount of load the ice will exert on the bridge piers – the thicker the ice, the higher the loads, and vice versa. The variation in ice thickness, as reported in the Canadian Ice Service East Coast Regional Charts, is shown in Figure 15. Over a 15-year period, a small reduction in the ice thickness is observed.

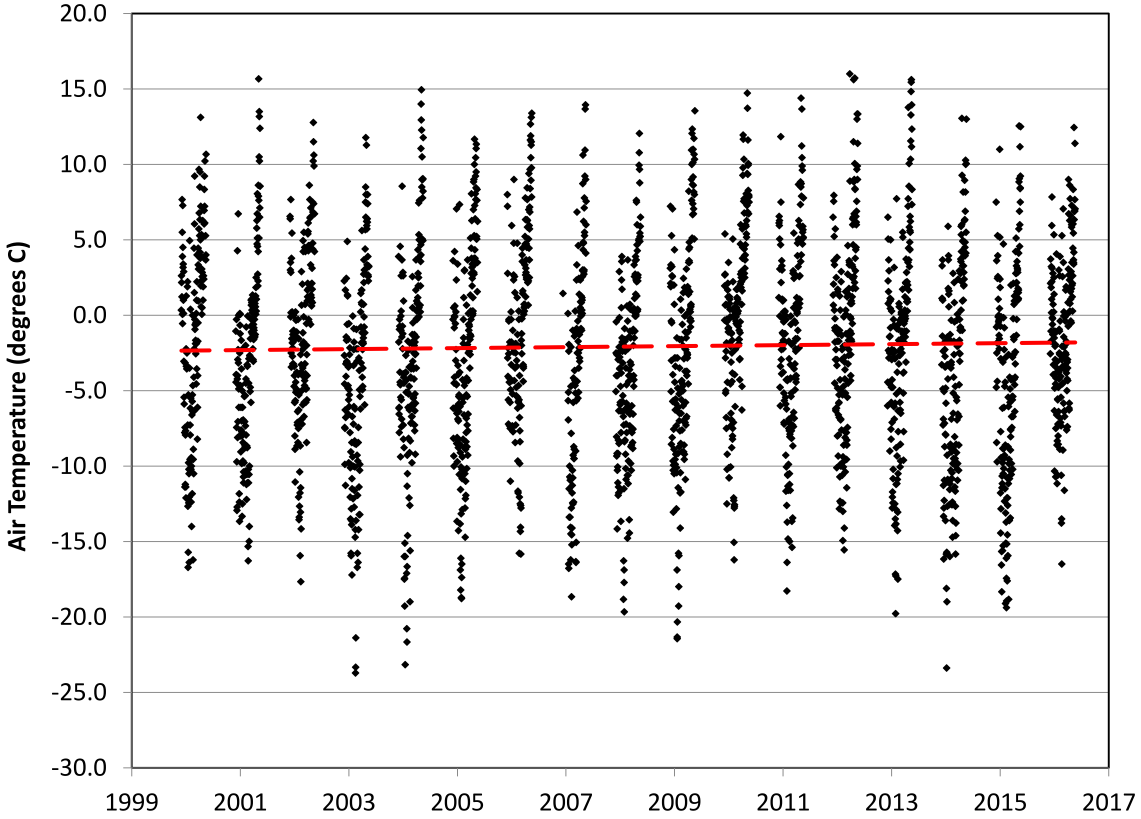


Figure 13: Daily average temperatures during the ice season in Summerside PEI. The dashed red line is a linear regression – it shows a very small increase in temperature over a 16 year time span.

Figure 14: Ice action at the water line (S. Prinsenberg, April 2003).

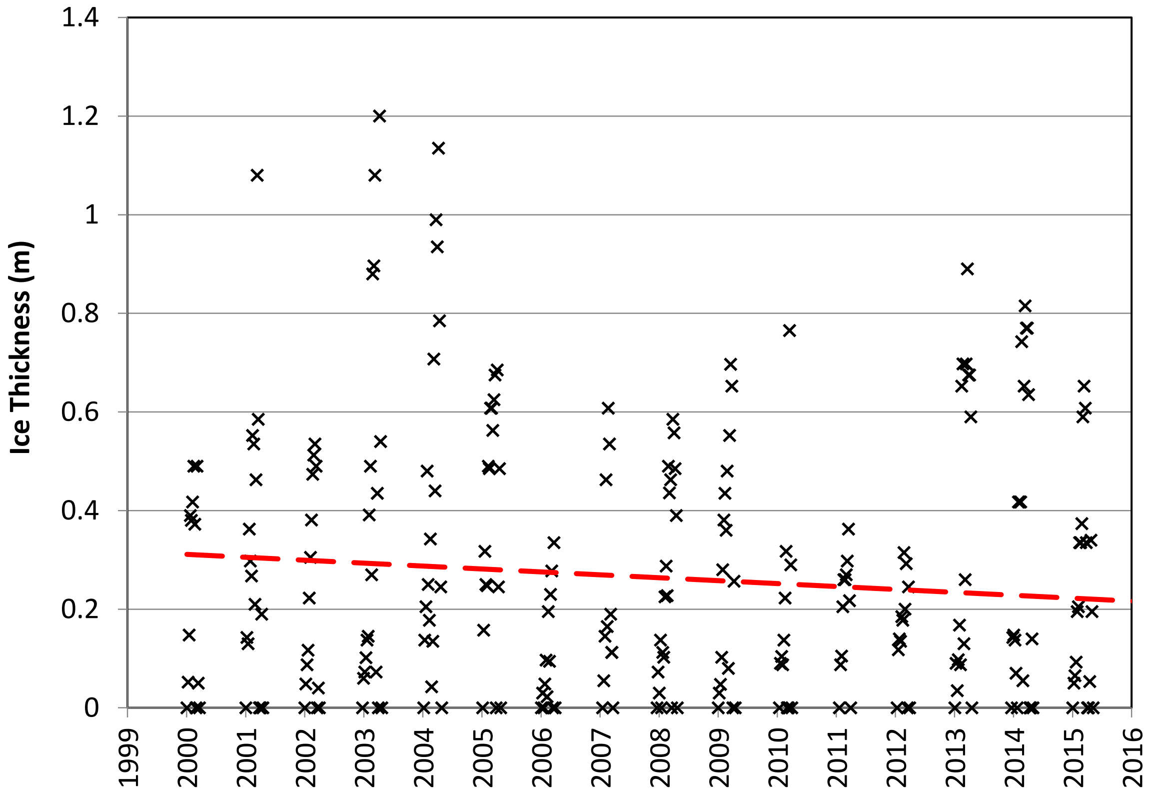


Figure 15: Average ice thickness at the Confederation Bridge from Canadian Ice Service Regional Charts. The dashed red line is a linear regression – it shows a very small decrease in thickness over a 15 year time span.

That reduction in ice thickness over this period of time is 0.6 cm/year, which would correspond to a total of 12 cm over a 20 year period. Again this change in ice thickness is not large in comparison with seasonal variations in ice thickness but it becomes appreciable over the life span of the monitoring program at the bridge. The data were compiled using the last chart before the ice formation and the first chart after the last melt of the season, additional ice free charts at the location at the start and end of the season were ignored so as to not drag down the average ice thicknesses. The average ice thickness during the period of time examined was 26 cm and the standard deviation in the data was 26 cm.

4.2.3 Wind speed

Wind speed may also play a role in the amount of load exerted on the piers due to ice. Data from the Summerside weather station were used to produce Figure 16. This plot indicates the winds may have increased at an average of 4.8 cm/s/year. This is once again a small increase when we consider the very large variation in wind speeds over that time. The average wind speed observed at the bridge over that time was 5.4 m/s and the standard deviation was 2.7 m/s. The cumulative change over a 20 year period would, however, be 96 cm/s.

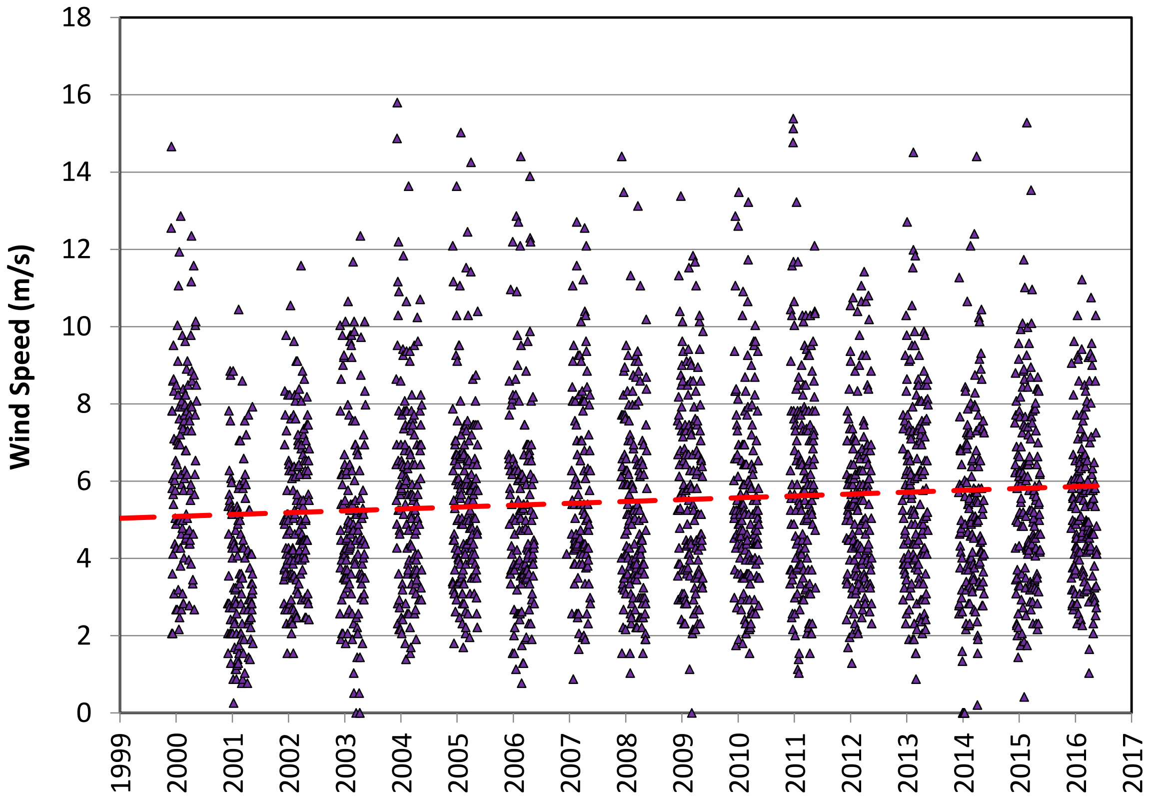


Figure 16: Daily average wind speeds during the ice season in Summerside PEI. The dashed red line is a linear regression – it shows a very small increase in speed over a 16 year time span.

4.3 Summary

In the preliminary work presented in this section, a few parameters expected to influence ice loading at the Confederation Bridge were examined. The ice thickness and air temperature trends are consistent with a warming climate. The wind speed records suggest a slight increase in trend. In the next phase of this project, we will review the published ice loading events (Figure 14) at the Confederation Bridge (Brown, 1997; Brown et al., 2010; Frederking et al., 2006; Frederking et al., 2007; Frederking et al., 2013; Tibbo et al., 2009) as well as unpublished ice loading data since 2013. We will aim to determine if there has been a measurable change in ice loading at the Confederation Bridge due to climate change since 1997.

5. Dynamic loading on bridge piers

Moving ice sheets covering rivers, large lakes and sea expanses impose dynamic loads on structures such as bridge piers, power transmission towers, wind turbines, lighthouses and offshore oil and gas platforms. Depending on several factors, discussed in this section, dynamic loading, which is usually cyclic in nature, could lead to structural failure, because of:

1. Resonance causing large structural deformations and stresses.
2. Structural fatigue and failure at stresses smaller than the stresses associated with static failure.

This section of the report summarizes the outcome of a short literature review. The material that was consulted included codes, standards, reports and other documents on design and ice load estimates for slender vertical structures subject to moving ice. This section also looks into resonance and fatigue phenomena – most of this information at this time is from ISO 19906 (CSA/ISO 19906, 2011). Effects of climate change are also addressed in this section.

5.1 Modes of cyclic ice-structure interaction

CSA/ISO 19906 on this topic is mainly based on full-scale measurements done on narrow structures. Measured ice loads reveal three main interaction modes depending on conditions of ice and the structure.

5.1.1 The first mode

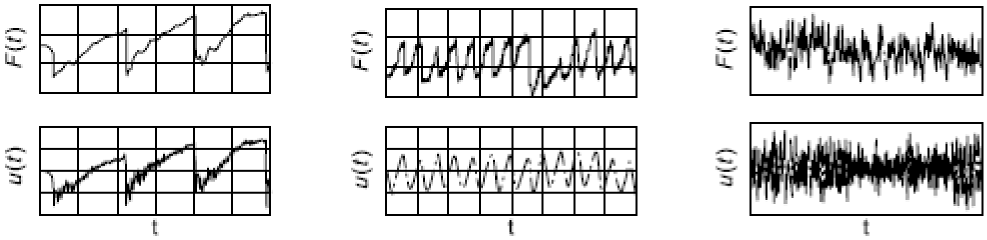
The first mode (Figure 17a) is known as intermittent crushing and consists of a distinct loading and unloading phase. The loading phase is associated with ductile local failure of ice edge and continuous increase in the imposed load until the sudden brittle failure of ice which is the onset of a relatively fast unloading phase before the loading phase starts again. This intermittent crushing mode is usually observed for slow ice conditions and the period of the force cycle is much larger than the largest natural time period of structures hence the structural resonance is not a concern, but structural fatigue needs to be considered for this loading mode.

5.1.2 The second mode

The second interaction mode (Figure 17c) is generally associated with ice which is moving fast. This mode is named continuous brittle crushing. The structure is exposed to high-frequency generally random loading and unloading phases and consequently random vibrations. It does not lead to structural resonance because of irregularity of imposed forces. However, the structural fatigue needs to be considered.

5.1.3 The third mode

The third mode of interaction (Figure 17b) is generally associated with ice moving at intermediate speeds. This mode is named frequency lock-in or self-excited vibration. It poses a threat to structures due to both structural resonance and fatigue and is the main focus of current research endeavor. Frequency lock-in involves regular cyclic loads with loading and unloading phases respectively caused by ductile and brittle failure of ice. The frequency of cyclic loads is similar to one of the smaller natural frequencies of the structure (ISO 199906, 2016; Wang and Poh, 2016) hence large structural deformations could occur.



a) Intermittent ice crushing b) Frequency lock-in c) Continuous brittle crushing

Key

t time

F ice action

u structure displacement

Figure 17: Three types of loading scenarios (CSA/ISO 19906, 2011, p. 199). See text for discussion.

5.2 Parameters involved, design considerations and ice load calculations

We divide this section into two parts: the first and the second parts are related to fatigue and resonance, respectively.

5.2.1 Fatigue

To design against fatigue failure, characteristics of the cyclic load, including minimum and maximum values of load, need to be known. Regardless of the interaction modes mentioned above, the maximum load (the upper limit of the force cycle) imposed on the structure happens just before brittle failure of the ice. These maximum loads are generally estimated by equations relating the load (F) to the width (w), thickness (h) and an average ice pressure (P_G) (CSA/ISO 19906, 2011; CSA-S6-06, 2011, Bureau Veritas, 2010) with equations of the type $F = P_G hw$. The average ice pressure is usually related to the width and thickness and some other empirical value related to stiffness of the structure and ice velocity and type. Literature on the estimation of the lower limit of the cyclic load is less developed than that of the upper limit mentioned here. This lower limit is also required for design against fatigue. CSA/ISO 19906 provides an equation for the calculation of the double amplitude of the lock-in force (maximum force minus minimum force). It is

$$\Delta F = qF$$

where

q: coefficient less than one.

That equation is found iteratively to satisfy the condition that the speed of the structure at the water line, which is in part a function of ice loads, is at least 1.4 times larger than the speed of ice associated with the self-exited mode. The double amplitude of the load is then a function of vibrational characteristics of the structure and the ice velocity. No similar information was found for intermittent crushing and continuous brittle crushing modes.

5.2.2 Resonance

As mentioned earlier, the frequency lock-in mode is when the frequency of the ice load is close to one of the smaller natural frequencies of the structure and consequently the structural deformations could be harmfully large. Observations of offshore structures subject to sea ice reveal that the self-exited mode could materialize for structural frequencies ranging from 0.4 Hz to 10 Hz and structural damping ratios lower than 3% of the critical damping (CSA/ISO 19906, 2010). The vibrational behavior of structures depends on the structure itself and characteristics of its foundation. Typical bridge piers have natural frequencies ranging between 1 Hz to 20 Hz and damping rations of up to 20% and the frequency lock-in mode has been observed for bridge piers subject to river ice (Montgomery et al., 1980). CSA/ISO 19906 recommends the structure-foundation to be designed to have damping characteristics which satisfy

$$\xi_n \geq \frac{\emptyset_{nC}^2}{4\pi M_n f_n} h\theta$$

where
h : ice thickness
θ : coefficient related to the structure with a recommended value for stiff slender structures
ξ_n : structural damping ratio
$\emptyset_{nC}$: amplitude of structural oscillation at ice level
M_n : modal mass
f_n : natural frequency

All parameters are generally associated with the smallest mode shapes of the structure. For wide and compliant structures, θ needs to be estimated. The satisfaction of this mathematical relation ensures enough structural damping to prevent resonance.

5.3 Climate change implications

As mentioned above, characteristics of the structure resisting ice motion and ice conditions govern the ice-structure interaction mode. The ice conditions include speed, thickness and mechanical properties which are frequently different and forecast to deviate from historic normals. This is because of changes in the climatic conditions including air and water temperatures, wind (Pryor and Barthelmie, 2010) and water current speeds (Beltaos and Prowse, 2001) and ocean salinities (Stark, 2012). To design safe and optimal structures subject to moving ice, it is critical to know how changes in climate will impact ice conditions.

6. Physical modeling of ice-pier interaction at NRC

Physical modeling of the interaction between ice and bridge piers have been done in the past by various organizations (Christensen and Klinting, 1992; Feng et al., 2004; Haynes et al., 1983). That includes the National Research Council. It is an expertise we have available in-house and which can be mobilized if required. For this reason, and for future reference, examples of this work are now presented.

6.1 General principles

Physical modeling is a small-scale simulation designed to better understand the behavior of a significantly larger event (Jordaan et al., 2005; Palmer, 2008; Randolph and House, 2001). It is a powerful and relatively inexpensive procedure used to simulate complex scenarios that cannot be modeled numerically. In many cases, the physical model is also used as a validation tool for the numerical exercise. Physical models also have limitations should be carefully considered. The scaling effect is a good example (Jensen et al., 2000; Jordaan et al., 2012). The physics being the same in the model and the real-scale event, size reduction needs to be factored in the model.

6.2 NRC experience

NRC has developed a high-level expertise in the production of model ice and ice-structure dynamics. The 'recipe' for the model ice currently used at NRC's ice tank facilities in Ottawa was designed by G.W. Timco (Timco, 1986) – it is used in other testing facilities in the world.

6.2.1 Basin studies in Ottawa

The physical modeling studies conducted on bridge piers and other similar structures can be summarized as follows.

Frederking and Timco (1987)
The prime purpose of this modeling endeavor was to investigate the flexibility of a structure and the dynamic behavior of its interaction with ice. The Yamachiche lightpier, in the St. Lawrence River downstream of Montreal, was the modeled structure.

Timco et al. (1992)
That study focused on a four-legged structure (that was known as JZ-20-2) in the Bohai Bay in China. That structure had experimented severe cyclic vibrations which led to failure. Scaling was 1:26.

Timco et al. (1995), Christensen et al. (1995)
The structure being simulated was a twin-legged pier (railway shaft and roadway shaft). The purpose of that study was to help design a fixed link in Denmark along a major strait crossing. The scale was 1:30 and the client was the Danish Hydraulic Institute and LIC Engineering.

Timco et al. (1996)
The purpose of this study was to test out the ship protection collar for the Northumberland Strait Bridge, i.e. the amount of additional ice forces could be induced on the piers with the collar. The scale was 1:30 and the client was Westmar Consultants Inc (Vancouver).

Barker and Timco (2002), Barker et al. (2005)
The purpose work, which was sponsored by SEAS, one of Denmark's power production companies, was to simulate ice loading on an offshore windmill. The scale was 1:26.

Figure 18: Left) Photograph showing as-built offshore wind turbines and ice-breaking cones (55j inverted cone), Nysted Offshore Wind Farm near Rødsand, Denmark (Barker et al., 2005). Right) Experimental apparatus used to simulate the interaction with ice – note the structure is upside down (Barker and Timco, 2002).

6.2.2 Centrifuge modeling

The interaction between floating ice and a model conical piers has also been investigated by one of the authors (Barrette et al., 2000; Barrette et al., 1999). These were done inside a test package on the arm of a centrifuge. This technique, well known in geotechnical engineering, had not been used extensively at the time. If need be, it could be resorted to in collaboration with C-CORE in St. John's, Newfoundland (Phillips et al., 1994).

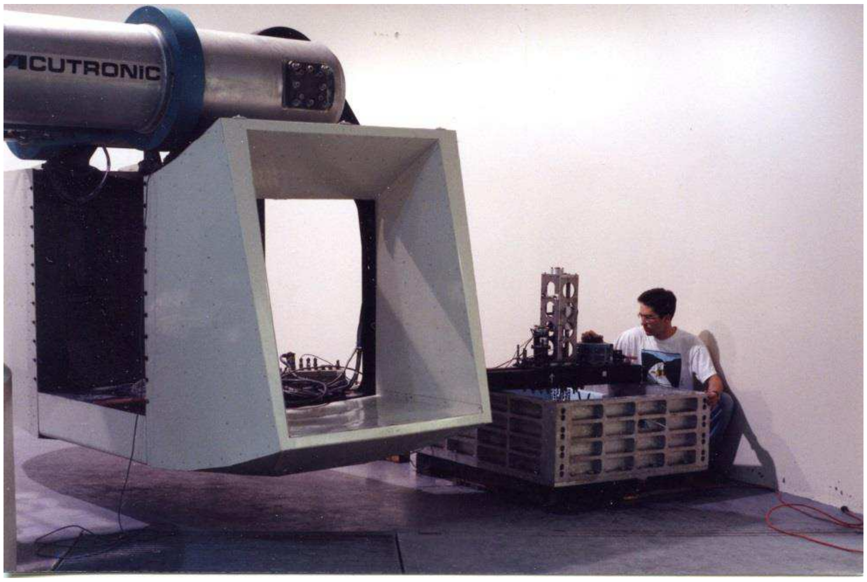


Figure 19: Ice test package next to the C-CORE centrifuge basket – that facility was used by one author to conduct ice-pier interaction (Barrette et al., 1999; Barrette et al., 2000).

7. Way forward

Follow up work would be divided into two tasks:

Task 1: To address and provide guidance to standards and codes about the prospective impact of climate change on ice loads sustained by bridge piers.

Task 2: Upgrade the Confederation Bridge instrumentation so as to be able to extend the data collection time span and *produce more significant trends*.

Because of time constraints (CSA plans to update its code by 2019 – which includes approval, etc.), Task 1 would include a component with an 18-month firm deliverable. This could be done, for instance, by targeting five bridges, as well as analyzing already existing NRC in-house data. That work would be divided into three sequential phases:

a) Assessment of ice action on bridges today
b) Prediction of ice loads in 50 years and 100 years
c) Guidance for updating the CSA code.

In the longer term (3 years), that work would be extended to include more structures.

The objective of Task 2 will be to assess the recorded ice loads at the Confederation bridge from 1997 to 2017 to determine if there is any evidence that the ice loads on the structure are being affected by climate change and if so, will the effect increase or decrease the life expectancy of this and other similar structures. Most of these data exist at the NRC and have been published. The last few years of data still must be analyzed and we will look to see if there are changing trends over the 20 years of the project. While ice conditions have overall decreased with time, other changing components such as wind could also impact ice loading on the structure. In this task, we will also complete a modernization of the ice load monitoring system currently underway to ensure the long term monitoring of ice loads because 20 years is a short period of time when examining climatologic effects.

Financial input from external stakeholders will be sought. This includes, but is not limited to, NRC's CRBCPI, all provincial and territorial jurisdictions, Transport Canada, Hydro-Quebec, Hydro-One as well as other electricity transmission and distribution utilities in the country, the Canadian National Railway Company and the Canadian Pacific Railway. Collaboration with the Arctic Program will be envisaged.

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