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Effects of Ice Loads on the Confederation Bridge

Donald Campbell
Memorial University
St. John's, NL A1C 5S7, Canada
donald.campbell@mun.ca

ABSTRACT

As the longest bridge in Canada and the longest bridge over ice-covered water in the world, the design and construction of the Confederation Bridge presented a unique engineering challenge. There was no precedent for designing for the ice loads experienced by the bridge piers. As such, extensive studies were conducted by the National Research Council (NRC) and various independent groups to ensure the Confederation Bridge design was adequate for ice loads in the Northumberland Strait, but also that the design was not overly robust.

Since the completion of the Confederation Bridge studies have continued on the ice loads experienced by the bridge piers. These could prove very useful in determining the accuracy of original calculated expected loads and methods that could be used to calculate ice loads in the future. Also, engineers will be able to learn more about the effects of ice on fixed structures as the Confederation Bridge ages.

1 INTRODUCTION

The Confederation Bridge (hereinafter referred to a the Bridge) is a 12.9 km-long bridge connecting the Canadian Maritime provinces of Prince Edward Island and New Brunswick. Construction on the Bridge began on October 7, 1993 and it was opened to traffic on May 31 1997. The 65 piers (44 main piers and 21 approach piers) are designed as double-cantilever post-tensioned concrete box girders with drop-in sections connecting them. The main piers are spaced 250 meters apart and reach 40 to 60 meters above average sea level.

Most elements for the Bridge were built in a fabrication yard on the Prince Edward Island side of the Strait and placed in sections by a large floating crane (one example of a completed pier base before placement can be seen in Figure 1 below). Due to the shallowness of water near shore, the approach piers had to be shored and constructed in-place. The construction of the Bridge involved the use of

478,000 m^3 of concrete, 58,500 tonnes of reinforcement and approximately 12,690 km of post-tensioning cable.

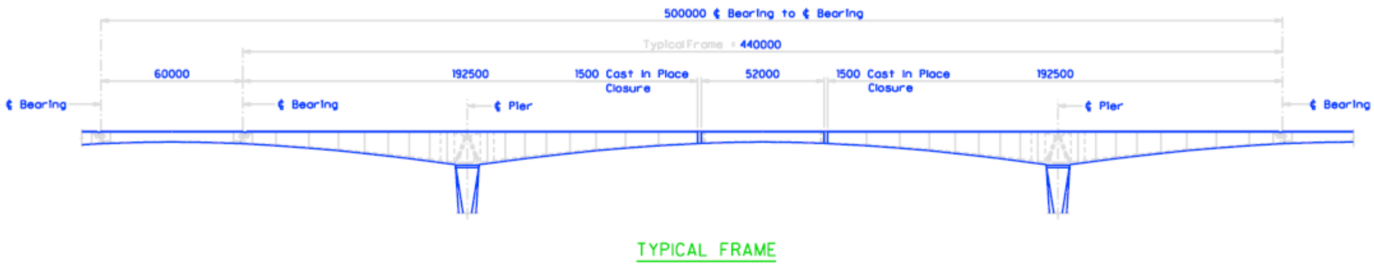

Figure 1: Typical Frame Dimensions for the Bridge (Source: Donald McGinn, P.Eng.)

2 ICE CONDITIONS

The Bridge was designed for a 100-year lifetime with a target safety factor of 4.0. As previously mentioned, there was no precedent for the ice loading conditions on a structure such as the Bridge and thus extensive studies had to be undertaken to accurately predict the expected loads on the piers. The Northumberland Strait is ice-covered for four months in an average year, forming what are known as first-year ice floes. In general, first-year ice is thinner and weaker than old ice that has lasted through at least one summer thaw.

2.1 Ice Elements

As ice floes collide with each other in the strait, two common elements of ice deformation that can occur are rafting and ridging. Rafting involves one floe sliding on top of another, doubling the thickness where the two overlap. It usually occurs early in the season when the floes are relatively thin and the amount of vertical movement required is minimal.

Ridging occurs when two (or more) ice floes collide and the resulting pressure causes the edges of the floes to crumble. Ridges usually occur later in the season as the ice becomes too thick for the floes to raft. They can also occur where an ice floe separates and open water is exposed (e.g. when a floe fails around a bridge pier). The rubble above-water is called the sail and below-water is called the keel. Initially this rubble does not have a high level of strength and poses a hazard only due to its thickness, which is often significantly greater than the floe thickness. Over time a layer of consolidated ice (up to 3 meters) forms as the water between the ice blocks freezes. Ridges with a thick consolidated layer often cause the greatest hazard to structures in ice-covered water due to their strength, thickness and frequency of occurrence.

Figure 2: Typical Ice Ridge Cross-Section (Source: www.ec.gc.ca)

2.2 Ice Loads on the Bridge

Due to the lack of similar structures, ice loads on the Bridge were calculated using probabilistic methods. Loads are governed by the lowest of either the driving force of the ice floe or the force required for the floe to fail. Parameters for both driving force and ice failure load were determined by researchers and it was determined that the ice failure load was lower. The load required for the failure of a floe is a function of both the thickness and the ice strength when it comes into contact with the pier. Due to the thickness and the added strength in the consolidated layer in ice ridges, the extreme loading case was determined to be most likely to occur in March and April when ridges are often partially consolidated.

The average number and standard deviation of freezing degree-days were taken (information for Summerside, approx. 20 kilometres from the Bridge, was used) and used to determine the distribution of the average thicknesses of ice flows. Field data and thermodynamic analysis were used to model the thickness of the consolidated ridge core, which can be highly variable over short distances. The thickness of each type of ice (sheet, consolidated layer, keel, etc.), along with the properties of the ice can be used to determine the force applied on a pier as an ice floe breaks on it.

Also, researchers observed the concentration (c), mean diameters ($\bar{L}$) and standard deviation (σ) of ice floes for the months of March and April along with the mean velocity ($\bar{V}$) of floe movement and the waterline diameter (d). Assuming the floes to be roughly circular and using the mean diameter and standard deviation to define the area ($\bar{A}$), the density (ρ) of floes can be found using Eq. (1).

$$\rho = \frac{c}{\bar{\mathrm{A}}} \tag{1}$$

The density is then used to find the probability of impact in Eq. (2)

$$\Pr(I) = \rho\bar{V}(\bar{L} + d) \tag{2}$$

By inputting the thicknesses of the ice floes and probability of impact into a simulation system, researchers were able to come to a conclusion for the design loads one the piers. Due to the conical shape of the piers at sea level the ice often fails in flexure as is slides up the cone, resulting in significantly lower loads than if the ice were to fail in shear. The resulting maximum load found for a 60° conical pier over a 100-year period was found to be 18.5 mega-newtons (MN) and 24.3 MN for a 10,000-year period. Analysis was also performed for a 55° conical pier and the 100-year and 10,000-year loads were found to be 13.5 MN and 18.0 MN respectively.

2.3 Bridge Design

The Bridge piers were structurally designed and constructed to resist an ice load of 30 MN. To mitigate shear loads and cause the ice to fail in flexure the piers were designed to be conical in shape for the area 4 m below and 2.6 m above the mean sea level (M.S.L.). They were designed with a slope of 52°, significantly lower than both the 60° and 55° piers indicating that the ice loads should be smaller than those previously mentioned.

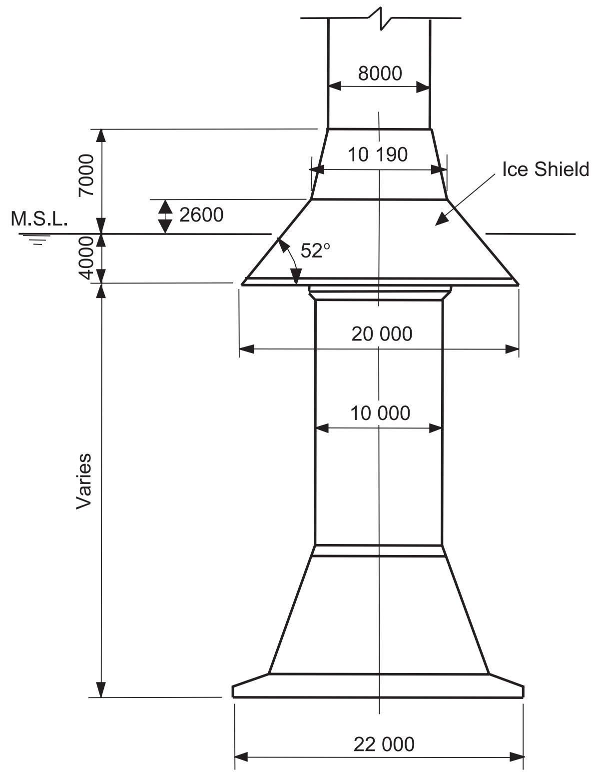

Figure 3: Typical Main Pier Design Details
(Source: A probabilistic approach to analysis of ice loads for the Confederation Bridge)

One factor that can significantly affect the rate of abrasion due to ice is the friction between the ice and pier surfaces. Concrete surfaces can be quite rough and can become even rougher as the cement paste wears away and the aggregate becomes exposed. In order to decrease friction and the slow the wear on the surface, it was recommended that the steel forms used when pouring concrete cones be left on as "ice shields". In general, steel is a much smoother surface than concrete and is less susceptible to abrasion, therefore reducing the friction and wear on the piers.

3 CURRENT CONDITIONS

Since its completion there has been regular monitoring of the Bridge and the effects of ice loads on the piers. Most notable are the effects seen on the piers with steel ice shields versus those without, and the magnitude of observed ice loads compared to the design loads.

3.1 Ice Shields

When construction crews began using the steel ice shields simply for formwork instead of keeping them permanently attached to the conical surface of the pier shaft it was believed by some to be an error. Steel is significantly less coarse than average concrete, which generally becomes even rougher over time as the cement paste has been known to erode and leave a very uneven surface as the aggregate is exposed. The decision to discontinue the use of steel shields was made base on the finish of the high-strength concrete used in construction.

In recent years significant damage has been noticed to the steel shields on some of the piers ranging from mild abrasion and corrosion to large tears. In instances where these damages could possibly prove hazardous to bridge maintenance workers and others who may need to work near the piers, it was decided that the ice shields must be removed. Currently ice shields remain on all of the approach bridge piers and on main piers P1, P2 and P10.

The ultimate failure of the ice shields was caused by two separate conditions. Firstly, as water that was trapped between the pier and shield froze it would expand; this expansion could have lead to local deformations in the steel. Secondly, the cathodic protection used to protect the steel from corrosion was ineffective in some areas leading to corrosion of both the internal and external faces of shields, significantly weakening the steel. It is likely that the shields on the approach bridge piers have remained in better condition than those on the main pier because the fast ice located close to shore does not put as much stress on the shields. Nevertheless, even the ice shields on the approach bridge piers have corroded significantly.

Figure 4: Corrosion of the Steel Ice Shields on the Approach Bridge Piers (Source: www.confederationbridge.com)

For those piers that were placed without the ice shields, the cement paste in the concrete has worn slightly over the years since the Bridge was completed, but studies have shown that the paste is sufficiently strong for the aggregates to control the abrasion process. This means that the surface texture has stabilized after slight wear and slowed the rate of abrasion. An abrasion rate of less than 35mm over 100 years was originally predicted and it has been confirmed that the current rate of abrasion is less than 0.40mm per year. The only areas in which the rate of abrasion has not yet stabilized to this rate are where the concrete was over-vibrated during placement, decreasing the quantity of aggregate near the surface. The concrete piers have proven durable thus far and there are currently no plans to replace the steel ice shields or otherwise mitigate loads on the piers other than those already in place.

3.2 Observed Ice Loads

The Bridge was designed to resist maximum ice loads on the piers of 30 MN. Two tiltmeters, located in each pier shaft, track any movement of the pier with an accuracy of 0.1 micro-radians (μrad). Due to the large side area of the girders at the pier shafts it is also necessary to measure the wind velocity so that the tilt caused by ice loads is accurate. When the tilt due to wind loads is subtracted from the measured tilt, the load on the pier can be calculated using a conversion factor (units: $\frac{MN}{\mu rad}$) that is unique for each individual pier. The largest measured ice load on the Bridge in the 16 years since completion has been 8MN, suggesting that the design load of 30 MN was quite conservative.

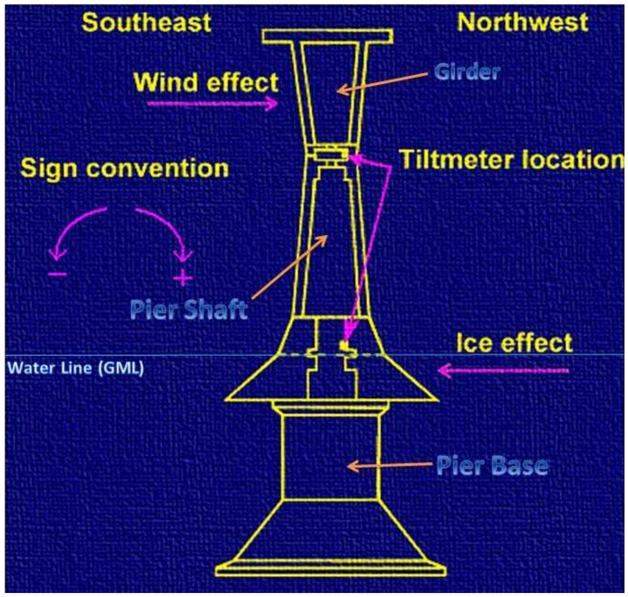

Figure 5: Location of Tiltmeters in the Pier Shafts
(Source: Response of Confederation Bridge to Ice Forces)

4 CONCLUSIONS

The ice loads on the Bridge were a critical consideration in the design and have potential to cause serious damage if they are larger than anticipated. Extensive research has occurred both before and after construction to ensure that the design is sufficient to withstand even extreme ice conditions for the area. Given the unique nature of the Bridge for both its size and environmental loads, it was necessary that many conservative assumptions and estimates had to be made when calculating loads. The design load of 30 MN is on par with the maximum anticipated load of 24.3 MN, and the maximum observed load of 8 MN indicates that this should indeed be sufficient for the expected life of the Bridge.

The successful design and construction of the Bridge, along with its performance since completion, is a major feat for Canadian Engineering. The methods used in calculating the ice loads and the continuing studies of ice effects on the piers set an important precedent for the design of structures in ice-infected water worldwide. Engineers will be able to take examples and lessons learned from the Bridge to improve designs and construction for many years to come.

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