An Overview of Ice Load Measurements on Bridge Piers

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Large ice floes often move down a river during the spring break-up. These floes can impact bridge piers causing high attendant loads. A number of separate experimental investigations have been made over the years to measure the loads caused by these impacts. This paper presents a detailed examination of the loads measured on the Hondo, Pembridge, Rideau River and St. Regis River bridge piers during spring break-up. The data show increasing load levels with increasing ice thickness over the range 0.2 - 1.1 m. The thickest ice resulted in the ice failing by splitting or no ice failure was evident during the ice load occurrence: both resulted in the highest loads measured, 2300 kN. Splitting was noted to occur over the full range of ice thickness examined, crushing was noted in ice of thickness 0.2 - 0.8 m and bending primarily occurred at an ice thickness between 0.8 - 1.0 m. In general, crushing occurred for an ice velocity less than about 1.3 m/s, bending was noted to occur between 1 - 2 m/s and splitting occurred between 1 - 3 m/s. The highest measured line loads, normalized with respect to the maximum loaded width, of up to 2000 kN/m occurred at ice velocities from 1.3 - 1.9 m/s, and were characterized by splitting or no evident ice failure.

1. Introduction

The measured ice loads on numerous instrumented bridge piers are examined, providing an idea of the magnitude of load that can be experienced during spring break-up. This paper summarizes field measurements and provides an overview of the best ice loading events. The relationship between the measured load and maximum loaded width of the pier is explored. The floe size and the impact force were correlated, taking into account floe speed and the type of failure mode of the ice. The results of this analysis are useful for understanding the forces exerted on bridge piers by ice floes during the spring break-up of river ice.

2. Background

Over the last thirty years a number of bridge piers in Canada and the United States have been instrumented for ice load measurements. Hondo bridge in the Athabasca River was instrumented during construction in 1966 and gave the first ice force measurements in the spring of 1967. Two bridges over smaller streams in Alberta, Kneehills Creek and the Pembina River, were later constructed and instrumented to record ice forces. However, the Kneehills Creek instrumentation was dismantled due to insignificant ice runs. During two winters in the late 1960s, Schwarz (1970) instrumented a test pile on the Eider Estuary. More recently, the National Research Council of Canada has instrumented a bridge pier in the Rideau River, Ontario. Also the US Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) have instrumented a number of piers in different rivers, including St. Regis, Ottauquechee and White Rivers.

This paper compiles ice load data from, primarily, four of the above mentioned bridge piers, Hondo, Pembridge, Rideau River and St. Regis bridge piers. These four bridge piers were selected for a detailed examination, based upon the availability (and quality) of information about the load-time records and ice conditions that precipitated those load occurrences, as discussed in Timco et al., 1999. Table 1 presents some of the particulars of the four piers, including the shape, inclination and diameter of the structure, the type of instrumentation (and distance from the pinned base to the reaction support), the percent coverage of instrumentation (expressed in terms of the structural waterline width), the number of events considered and the data source.

Table 1 Structures Examined

Structure Name	*Structure shape and inclination from vertical*	*Structure diameter (m)*	*Instrumentation, distance from base to load cell*	*Percent coverage*	*Number of events*	*Data source*
Hondo	Semicircular, 23°	2.32	Hinged frame with load cell, 5.55 m	100	22	Strip chart recordings 1 - 25 mm/s in Lipsett and Gerard 1980
Pembridge	Circular cylinder, 0°	0.86	Hinged beam with load cell, 9.79 m	100	4	Strip chart recordings 25 mm/s in Lipsett and Gerard 1980
St. Regis	Circular, 5.7°	1.22	Simply supported beam with load cell, 2.49 m	100	6	Time series traces in Haynes et al. 1991
Rideau River	"V" shaped, 0°	2.0	Fluid filled panel and hinged plate with load cell, 0.6-0.9 m	14 – 28	13	Data at 45 Hz, Frederking and Sayed 1992 and unpublished

The ice force measurement system for the examined bridge piers consisted of a hinged panel, equipped with a single load cell at the top, from which the reaction force associated with the impacting floe was calculated. The measurement programs occurred as increasing air temperatures and rising water levels initiated spring break-up. As a result, the loads are associated with ice that is usually at its maximum thickness: however, the strength of the ice may be quite low at times. The ice may be "candled", deteriorated along its columnar grain boundaries, which significantly weakens the ice cover. Although the impacts involve freshwater ice in all cases, the ice strength can be quite variable, a point that should be borne in mind when interpreting the structural loads. Table 2 summarizes the ice conditions, failure modes and measured loads during the spring break-up at the examined piers.

Table 2 Ice Conditions at Structures during Load Occurrences

Structure name	*Ice description (floe diameter)*	*Ice thickness (m)*	*Coverage width (m)*	*Ice velocity (m/s)*	*Ice failure mode*	*Measured load (kN)*
Hondo	Isolated floes (50 m - 5 m)	0.40 - 1.07	2.33	0.40 - 2.87	Crushing, Bending, Splitting No failure	260 - 2270
Pembridge	Isolated floes (40 m - 20 m)	0.45	0.86	1.04	Crushing, Splitting	350 - 1060
St. Regis	Isolated floes (25 m)	0.15 - 0.20	1.22	--	Crushing, Splitting	93 - 355
Rideau River	Isolated floes (2 m – 15 m)	0.25 - 0.60	0.3 - 0.6	0.75 - 1.25	Crushing	12 - 160

3. Hondo Bridge Pier

The bridge over the Athabasca River near Hondo, Alberta, was constructed in 1966. During construction, a specially designed nose section was built into one of the center piers. The 2.32 m wide semicircular pier is fitted with a reinforced concrete, steel encased beam, (inclined at 23° to the vertical) pinned near the base and reacting against a load cell at the top. The centre of the load cell is 5.55 m above the pin. The reaction force measured by the load cell and the river elevation above the pin were used to determine ice forces exerted normal to the pier by summing moments about the pier. The river water level before, during and after the run was monitored and recorded by a float in a stilling well in the centre of the pier. In 1978-79 Hondo bridge pier was equipped with accelerometers (sensitivity of 2.5 volts/g) which measured the longitudinal and transverse acceleration of the pier. For a more detailed description of the ice runs at Hondo, see Sanden and Neill 1968; Neill 1970; Gerard 1978; Lipsett and Gerard 1980; Montgomery et al. 1980; Montgomery and Lipsett 1980; Alberta Cooperative Research Program [ACRP] 1967, 1969, 1971, 1973, 1979.

Ice Description

The ice run at the Hondo bridge pier was filmed using three movie cameras: one looking down on the ice and the pier from the instrument shed, one looking at the ice and impacted pier from an opposite pier on the right bank and the third looking upstream from the instrument shed. The nose beam had markings that were 0.91 m apart, to assist in determining the ice thickness and floe velocities from the movie coverage.

The ice runs at Hondo generally occur in three stages. The first stage involves the ice break-up in the vicinity of Hondo and generally proceeds in the upstream direction (about 2 km upstream). The second portion of the ice run involves the thicker ice found between Hondo Creek and Rourke Creek, about 4 km upstream of the bridge. The last stage of the ice run occurs when ice upstream of Rourke Creek passes the bridge. Initially, the ice sheets occupy the full width of the river and can be up to 1 km long. Gradually, the interaction between floes and the river banks reduces the sheets to approximately 50 m x 50 m. The thickest ice originates from the Rourke Creek area, where floes about 15 m x 15 m impact the pier and result in the most significant measured loads. By the time that the ice upstream of Rourke Creek releases and reaches the pier, the ice has usually deteriorated considerably, with typical floe sizes 5 m x 5 m. Figure 1 shows a general sketch of the ice-structure interaction at the Hondo Bridge Pier.

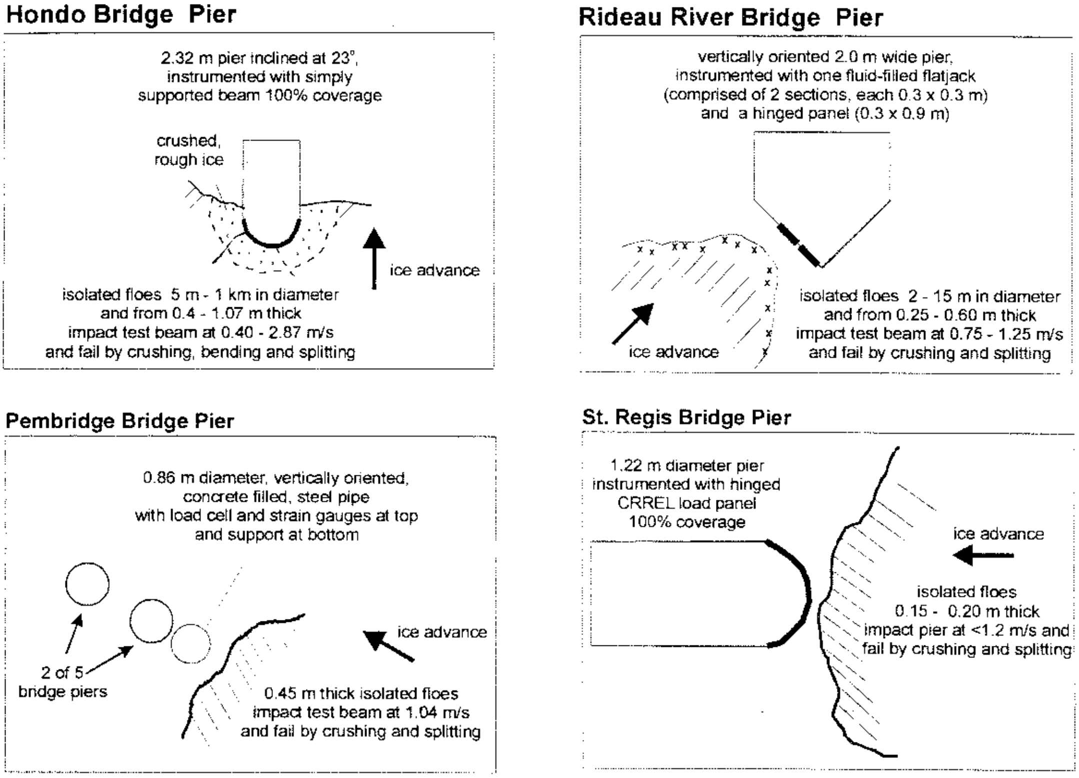

Figure 1 Loading scenario for the examined bridge piers

4. Pembridge

The Pembridge bridge crosses the sinuous Pembina River, in northern Alberta. Ice forces upon the Pembridge pier were determined from the bending strains measured by strain gauges placed inside a vertical, hollow, steel pipe (wall thickness of 10.3 mm) that was simply supported in front of the centre pier as shown in Figure 1. In 1969, the break-up caused local buckling of the pipe (ACRP, 1969). As a result, the original measurement system was replaced by a concrete-filled 0.86 m diameter steel pipe, supported by a moment-free connection at the bottom and a load cell at the top.

Horizontal bands were painted on the 0.86 m diameter steel pipe at 0.15 m intervals. The shed above the pipe housed the instruments for monitoring the ice run. The river water level was monitored from the stilling well just behind the rear bridge pier. The loads that were exerted normal to the pier were determined from the load cell at the top of the pipe, 9.79 m from the base of the pipe. The ice force normal to the pier was calculated by summing moments about the base of the instrumented pipe. The yoke that restrained laterally the top of the load beam was equipped with two pairs of strain gauges, from which the transverse ice loads were also calculated. When one pair of gauges, for example those on the north arm of the yoke, was activated, this implied that ice was advancing from the south side of the beam. The other pair of strain gauges was then inactive and served as temperature compensating gauges. The converse applies when the ice advanced from the north side of the beam. To deduce the transverse force, it was assumed that each arm of the yoke acts as an independent cantilever.

Ice Description

1974 was the only year between 1973 and 1979 during which significant loads were recorded on the Pembridge pier. For the other years, the ice moving past the bridge lasted only a few minutes and consisted of small, weak floes that produced low measured loads. One contributing factor to the poorer ice runs between 1973 and 1979 was the relatively small amount of snow in the Pembina River basin upstream of Pembridge, which was not sufficient to elevate the water levels and initiate an ice run while the ice was still competent. Rather, the low water levels resulted in the *in-situ* deterioration of the ice before the ice was discharged by the river. In contrast, in 1974, significant and rapid snowmelt produced water levels (about 3 m higher than the other years) that were sufficient to lift the ice and initiate the run while the ice was still competent and strong. Due to the sinuous nature of the Pembina River, advancing ice floes undergo a rapid reduction in size as the run progresses. The maximum floe size observed is about 40 m x 40 m, with floes 20 m x 20 m being more typical.

5. St. Regis Bridge Pier

The New York State Department of Transportation (NYS DOT) and the Cold Regions Research and Engineering Laboratory (CRREL) instrumented a bridge pier in the St. Regis River at Hogansburg in upper New York State. The work is conducted under the Federal Highway Administration project "Measuring ice forces on the St. Regis River, Hogansburg, NY" with pooled funding from five states. Only results from 1990 were available during the preparation of this paper. However, an agreement has been made between the National Research Council of Canada (NRCC) and CRREL to supply data from subsequent years. These data will be analyzed and reported in due course.

Ice forces on the upstream side of the St. Regis pier were measured with a load panel designed by CRREL, that consisted of a simply supported beam, pinned at the bottom and equipped with a load cell for the reaction support at the top. The panel presents a rounded face to the advancing ice, is flush with the pier at an angle of 5.7°, has a water plane diameter of 1.22 m and has a moment arm of 2.49 m between the pin connection and the reaction support. The ice force on the panel was calculated by summing the moments about the pin location. A pressure transducer was placed inside the panel at the bottom to record the water depth above the transducer.

Ice Description

The winter of 1990 was unusual in that air temperature for the month of December was about 9°C below normal. The cold air temperatures enabled an ice sheet of measured thickness 0.36 m - 0.66 m to grow before 16 January. However, above-normal January air temperatures caused the ice to break up prematurely and move later that month. During the first week of February there was no ice at the bridge. By 28 February a new cover of ice had grown near the pier, measuring 0.08 m to 0.20 m in thickness. On March 16 - 17, 1990 a major run took place which resulted in six load-time series events, obtained from Haynes et al. (1991) and shown in Table 1.

6. Rideau River Bridge Pier

The Rideau River bridge pier has a "V"-shaped nose, presents a vertical face to incident floes and has a waterline width of 2.12 m (along the exposed face). The pier is part of the Minto Bridge, a heritage bridge that spans the Rideau River in Ottawa, Ontario, Canada. The National Research Council of Canada (NRCC) measured the ice impact forces on the bridge pier during artificially-induced break-up (controlled blasting of the river ice) in an experimental program that was conducted from 1986 – 1991.

Good quality data were obtained from the 1988 and 1991 programs, as summarized in Table 1. During the 1988 break-up season, a fluid-filled flatjack (subdivided into an upper and lower section, each 0.3 m x 0.3 m) was used to measure the ice forces. In 1991, ice forces on the pier were measured with this two-section flatjack and a steel plate (0.3 m x 0.91 m) hinged at the bottom and supported by a load cell at the top (see Figure 1). The percent coverage of instrumentation was 14% for 1988 and 28% for 1991, see Table 1.

Ice Description

Ice conditions at the Rideau River bridge pier in 1988 and 1991 were recorded from personal observation, photographs and/or video cameras (one located on the nearby shore and the second looking down on the pier from the bridge). Since the break-up of the ice was artificially induced, competent ice floes were produced that were 2 m to 15 m in diameter and had an ice thickness of 0.6 m or less. Current velocity near the Rideau River bridge pier varies substantially but can reach 2 m/s, with the ice run occurring, typically, over a 10-day period. During the 1991 spring break-up, two boats (operated by the City of Ottawa) were used to guide the ice floes towards the instrumented pier, enabling direct impact with the instrumentation and enhanced ice velocity.

7. Additional Bridge Piers

A number of other bridges have been instrumented to provide information on ice loads on piers. However, these measurements do not provide direct, detailed information on the load levels or ice conditions associated with particular interactions. These instrumented piers are discussed below, providing added insight to load levels on bridge piers.

Ottauquechee Bridge Pier

Sodhi et al. (1983) measured the general level of ice forces during the release of ice in the Ottauquechee River near Quechee, Vermont in 1982. Two load panels, each measuring both the normal and tangential component of load, were mounted in a V-shape on the front of the pier. Each panel was 0.56 m by 1.22 m high. Loads were measured during the break-up on March 26, 1982. The measured loads indicated a static load of 110 kN during the ice run, with a maximum measured ice force of 120 kN. Observations of the ice indicated that it was broken with floe sizes from 1 m to 10 m. The ice thickness was quite variable with a range of 0.15 m to 0.6 m. The uni-axial compressive strength of the ice (measured at CRREL) ranged from 1.5 MPa to 2.7 MPa for this ice.

Yukon River Bridge Pier

Zabilansky (1996) instrumented the Bridge Street pier (1.22 m width) at White River Junction in Vermont, USA during 1992-1993. Heavy rains initiated the break-up on March 9-10,1992. Maximum floe size was of the order of 4.6 m (with an average of about 2 m) and ice thickness varied from 0.25 m - 0.46 m. 8,056 impacts were identified during the 20-hour ice run, with a maximum load of 116 kN. In March 1993, a very heavy snowfall, combined with sunny days and warm nights, produced conditions that resulted in the ice sheet essentially deteriorating and melting in place. The measured loads were of the order of 27 kN, with a few distinct impacts of the order of 160 kN.

Eider River Bridge Pier

A test pile was instrumented on a bridge crossing the Eider estuary in Germany (Schwarz, 1970). The pile was 0.60 m in diameter. A total of thirty 0.15 m x 0.15 m load sensing plates were distributed around half of the pile in an array six high by five across. The instrumented side of the pile faced the sea. Total ice force on the pile was obtained by taking the vector sum of the loads on all the individual plates. The ice at the location could be either river ice or sea ice. Measurements were made for two winter seasons, 1967/68 and 1968/69. The maximum ice thickness encountered at the site was 0.14 m and the corresponding maximum reported ice pressure was 530 kPa or a total force of 45 kN.

Confederation Bridge

A two-lane vehicle bridge has recently been built across Northumberland Strait between Prince Edward Island and New Brunswick, in Eastern Canada. The bridge, which is approximately 13 km long, consists of 45 marine spans, each with a length of 250 m. Each span is supported by a pier with a 13.8 m waterline diameter. The pier is cylindrical below the waterline (with a 10 m diameter) and has a conical collar that extends from 4 m below the waterline (diameter 20 m) to 2.6 m above waterline.

There is a multi-year monitoring program in effect for the bridge, overseen by Public Works and Government Services Canada which monitors the loads and response of the bridge, as well as details the environmental conditions. Detailed measurements of the ice forces are made with very sensitive tilt meters and load panels (Brown et al., 1998). Results from ice load measurements on the PEI bridge are not yet in the public domain.

8. Discussion

The type of loads and failure modes that can be expected during spring break-up were quantified by examining four different bridge piers, for a total of 45 ice load occurrences. For each load occurrence, the peak ice loads and their coincident failure mode were determined. Figure 2 shows the measured load versus the maximum loaded width, according to structure type.

Figure 2 classifies ice impacts with Hondo Bridge Pier at two contact widths. Floes that impacted Hondo Bridge Pier and failed in crushing or bending were assumed to contact the full width of the pier (2.32 m). Floes that impacted the pier and failed by splitting or if no ice failure was evident, were assumed to contact half the pier width (1.2 m). Comparison of the load levels for each of the examined bridge piers indicate that the highest load levels occurred at Hondo Bridge Pier: loads up to 2300 kN resulted for the reduced contact width of 1.2 m and up to 2100 kN for the full contact width. Pembridge Bridge Pier showed the second highest loads, up to 1100 kN. The St. Regis Bridge Pier was typified by loads up to 400 kN and a maximum load of 160 kN was recorded at the Rideau River Bridge Pier. In Figure 2 a force of about 120 kN was used to represent the maximum measured load on the Ottauquechee River Bridge pier. The Eider River Bridge Pier has a similar contact width to the Ottauquechee River pier, but significantly lower loads, 45 kN, were documented. A single point was used to indicate the maximum measured load at the Yukon River Bridge Pier, 160 kN.

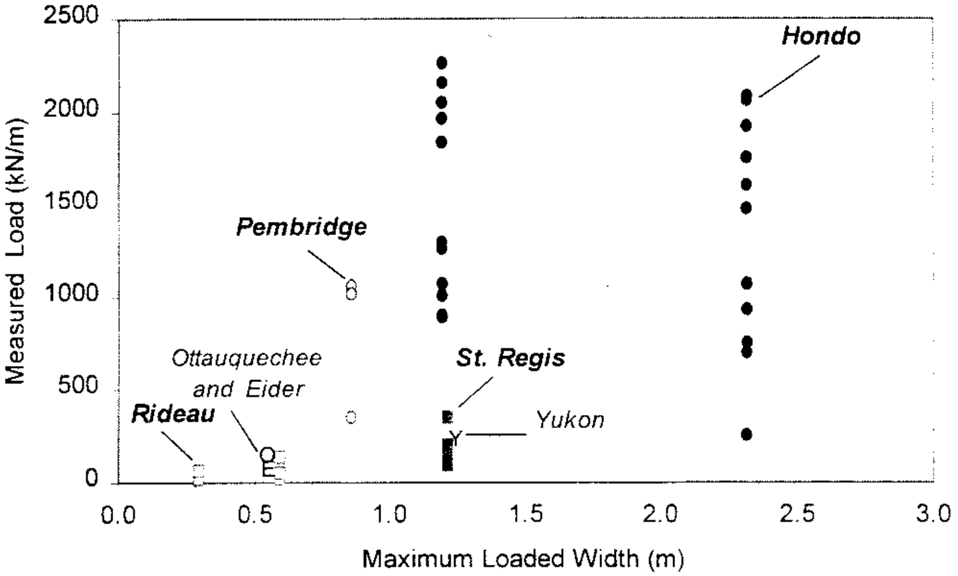

Figure 2 Measured load versus maximum loaded width

The severity of the ice run. as indicated by the measured ice forces. mainly depends upon the meteorological conditions preceding spring breakup, which in turn govern the amount of deterioration of the ice from its mid-winter values. For example. Hondo in 1976 was characterized by a rapid warming trend in early April that caused breakup to occur quite suddenly. At breakup the ice had deteriorated little and consequently, ice forces up to 2270 kN were recorded. In contrast, a long extended warm spell before breakup at Hondo in 1978 resulted in considerable deterioration of the ice before its release, resulting in ice-structure interactions with peak ice loads as low as 260 kN.

Figure 3 presents the measured line load (measured load normalized to the maximum loaded waterline width) as a function of ice thickness. Note that Figures 2 and 3 use the same symbols to distinguish the different piers. Figure 3 shows that ice from 0.18 m to 1.07 m thick can produce loads from 27 kN/m to 1900 kN/m, illustrating clearly that the measured load increases with ice thickness. Considering the specifics of spring break-up at individual sites. ambient air/ice temperatures. the ice characteristics and the particulars of the similar. but unique. instrumentation systems. the trend of increasing load with ice thickness is encouraging.

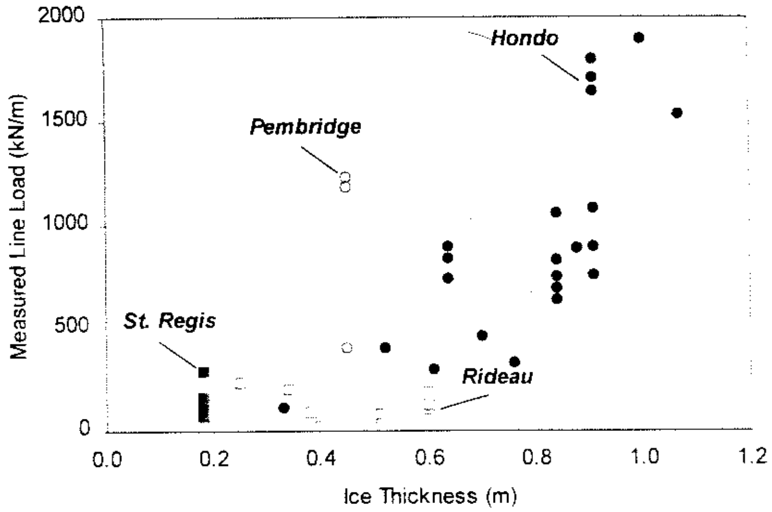

Figure 3 Measured line load versus ice thickness, grouped by structure

Figure 4 examines the relationship between ice thickness, load and ice failure mode by grouping the data according to ice failure mode. It is evident that the highest loads are produced by the thicker ice, which fails either by splitting or no observed failure mode during the interaction. In the latter case, the floe would impact the pier, rotate and bypass the pier, with no failure mode evident. It should also be noted that splitting of the floe was observed over the entire range of ice thickness. In general, the ice failed in bending at ice thickness of 0.8 - 1.0 with accompanying line loads of 600 - 900 kN/m. Crushing of the ice was observed for ice in the range of 0.2 - 0.8 m thick, which produced loads of 500 kN/m or less, with the exception of the 1300 kN/m ice crushing load observed at Pembridge.

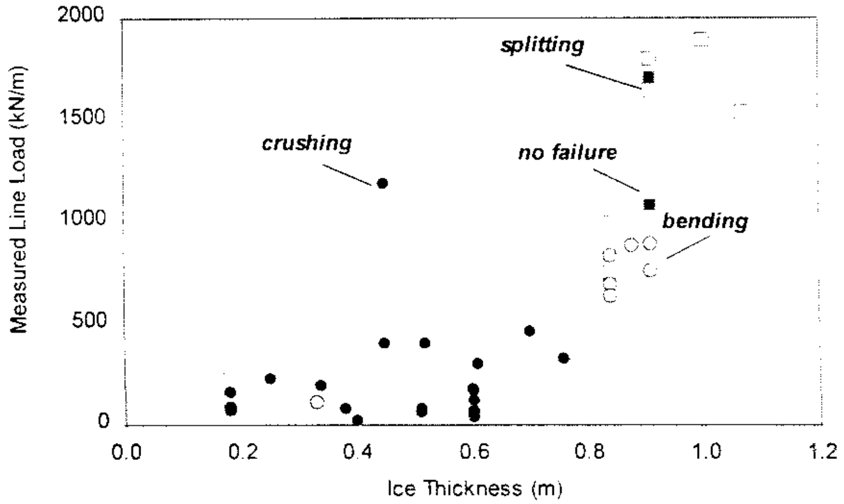

Figure 4 Measured line load versus ice thickness, grouped by ice failure mode

The description of the ice run at Hondo provides further insight to the failure modes observed during the different stages of break-up. Lipsett and Gerard (1980) state that during the initial stages of the run the largest, but deteriorated, floes impacted the pierand failed by crushing. The ice failure mode changed to bending when the thicker, competent ice floes (15 m x 15 m) from the Rourke Creek area impacted the pier, while the smaller floes either impacted the pier without failure or failed by splitting. Finally, the ice upstream of Rourke Creek passed the bridge, usually having deteriorated significantly en route, with typical floe sizes 5 m x 5 m. The small floes produced either impact events, in which the floe was either momentarily stopped by the pier and then rotated to the side, or splitting failure, where the floe was completely split upon contacting the pier.

Data from the bridge piers were next examined in terms of the influence of floe velocity upon the measured line load. Figure 5 shows the line load plotted as a function of ice velocity. The data originate primarily from the Hondo Bridge pier and secondly, from the Rideau River bridge pier. Floe velocities were not indicated for the Pembridge and St. Regis bridge pier data.

Figure 5 indicates that crushing is the predominant failure mode for floe velocities less than 1 m/s, where the magnitude of load is less than about 500 kN/m. Between 1 - 2 m/s the ice failed by splitting, bending or no ice failure was noted, with accompanying load levels of about 500 - 2000 kN/m. For floe velocities greater than 2.5 m/s, the ice failed by either crushing or splitting and the loads range from 500 kN/m for crushing and up to 1100 kN/m for splitting.

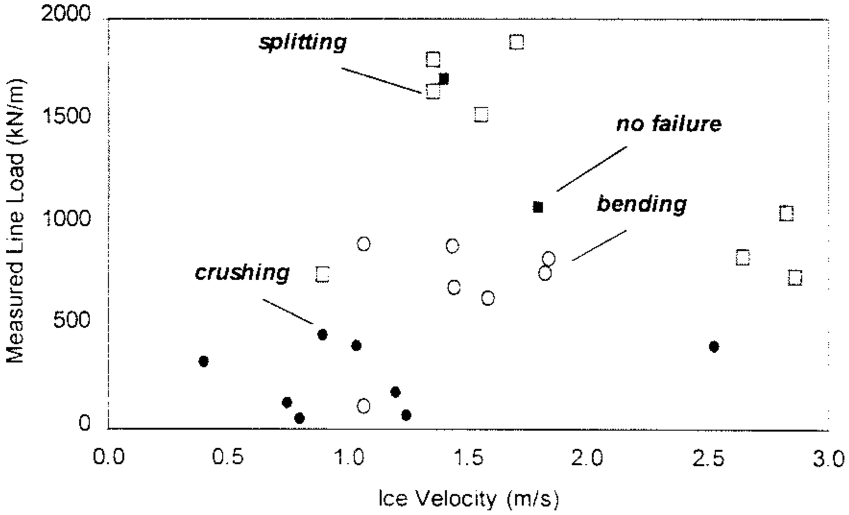

Figure 5 Measured line load versus floe velocity, grouped by ice failure mode

9. Summary

The load levels associated with floes that impact bridge piers during spring break-up were quantified from a detailed examination of four bridge piers. The data show that load levels increase with increasing ice thickness, over the range 0.2 - 1.1 m. Given the wide range of ice conditions and unique instrumentation systems used to monitor the ice forces, the increase in measured load with increasing ice thickness is an encouraging confirmation of expectations. The data were also examined to determine the relationship between the measured load levels and ice thickness for various ice failure modes. The thickest ice resulted in the ice failing by splitting or no ice failure was evident during the ice load occurrence; both cases resulted in the highest loads measured. Splitting was noted to occur over the full range of ice thickness, 0.2 - 1.1 m, crushing was noted for ice thickness of 0.2 - 0.8 m, and bending primarily occurred at an ice thickness between 0.8 - 1.0 m. In general, crushing occurred for an ice velocity less than about 1.3 m/s, bending was noted to occur between 1 - 2 m/s and splitting occurred between 1 - 3 m/s. The highest line loads, up to 2000 kN/m, occurred at ice velocities from 1.3 - 1.9 m/s, and were characterized by splitting and no evident ice failure.

The author is not aware of any previous report that examines, as a whole, the measurements of ice loads on instrumented bridge piers. In presenting a coherent picture of the ice-structure interactions that involve bridge piers, this paper indicates the load levels (and the failure modes) that can be anticipated during spring break-up. This type of synopsis will assist future revisions to design codes for bridges in ice covered waters.

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