STATISTICAL ANALYSIS OF THE ICE LOADING EVENTS ON THE CONFEDERATION BRIDGE

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ABSTRACT

We have examined the ice loading forces on two piers of the Confederation Bridge during the 2012-13 ice season using the updated NRC ice load monitoring system. The new system allows better time synchronization of the tiltmeter and video data from each pier as well as the anemometer. The new system has allowed for the analysis of two large ice loading events simultaneously occurring at two adjacent Confederation Bridge piers and discussion of the relation between the forces on each pier during the events. The maximum load on a single pier was 3640 kN, when a large flow with embedded ridges stalled against two adjacent piers on April 6th, 2013. The maximum total load on the two adjacent piers was 5130 kN, fifty-six minutes after the single pier maximum.

General statistics on the ice loads during a subset of the ice season were performed. Average ice loads during our observation period were 150 – 200 kN. Further refinement of the ice load and wind coefficients used at the NRC monitored bridge piers may be suggested from this work.

INTRODUCTION

The Confederation Bridge is a 13 km long structure that spans the Northumberland Strait connecting the provinces of New Brunswick and Prince Edward Island on Canada's East coast. The bridge opened in 1997 and since that time the University of Calgary (Brown et al., 2010) and the National Research Council of Canada (NRC) (Frederking et al., 2007) have each monitored the ice loading forces on two of the bridge piers. The bridge rests on 44 main piers which each have a cone at their waterline to reduce crushing and increase flexural failure of ice interacting with the bridge. Piers are instrumented to measure tilt in response to ice and wind loading. In the winter of 2012 the NRC's ice load monitoring equipment at the Confederation Bridge was connected to the bridge's network allowing for real-time monitoring of the ice conditions at the bridge. In this paper we present the first full season of ice load data acquired with the updated monitoring system.

The main benefit of connecting the instrumentation to the bridge network has been the improved time synchronization. For previous seasons time was only synchronized once per season and clock drift between data acquisition systems and the camera systems made certain events difficult to isolate. The clocks for all of the instrumentation at the bridge are now regularly synchronized removing a great deal of uncertainty. Signal drift in the tiltmeters requires the regular identification and synchronization of ice free conditions with video records to determine the baseline tilts from which ice induced tilt values are calculated. This has been greatly improved with the updated system. The synchronized measurement system and video records on two adjacent structures provides some unique data that may be applied to assessing loading on multi-leg structures. The availability of such data is limited for multi-leg structures (Wessels and Jochmann, 1990, Timco et al. 1999, and Johnston et al., 2000). We will include results from two such events will be provided in this paper.

2013 General Ice Conditions

According to the Canadian Ice Service (CIS) Gulf of St. Lawrence daily ice charts the first appearance of ice at the Confederation Bridge for the 2012-13 season was on December 31st and the last ice was noted on April 15th. Figure 1 shows that the ice conditions in the Gulf of St. Lawrence for the 2012-13 season were comparable to the previous 3 years but much less than the 2008-09 season and the 30 year median ice conditions. This CIS IceGraph representation, while averaging over the whole Gulf of St. Lawrence Region, is a good means of comparing one ice season to another. On the other hand, local ice conditions in Northumberland Strait may be substantially different at times.

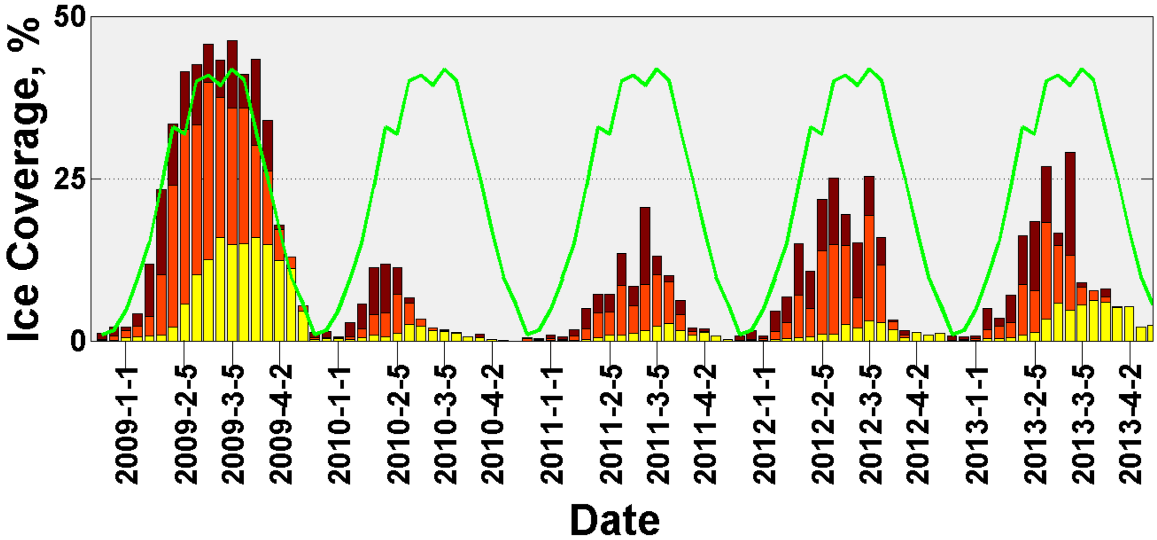

Figure 1. Multiple seasons ice concentration for the Gulf of St. Lawrence: weekly ice coverage by stage of development for the seasons 2009/10 to 2013/14, weeks Dec. 18 – Apr. 16. The columns represent concentrations of First-Year (yellow), Young (orange) and New (burgundy) ice. The green line represents the 30 year median concentration for 1980/81 to 2009/10. The figure was generated based on data from the Canadian Ice Services IceGraph 2.0 (http://iceweb1.cis.ec.gc.ca/IceGraph20/page1.xhtml).

ICE LOAD DATA

The National Research Council of Canada (NRC) has four (4) Applied Geomechanics 700 series tiltmeters and two digital cameras installed on the Confederation Bridge. The two tiltmeters and cameras are installed on piers 23 and 24 which are just to the SW of the navigation span, or centre of the bridge. Each pier has two (2) tiltmeters, one at the top and one at the waterline as well as a camera observing the pier at the waterline on a continual basis. Tiltmeter data is acquired at 5 Hz and the wind data is acquired at 1 Hz but both are averaged over three (3) seconds. Only the waterline tiltmeter is used to calculate ice loads on the bridge, the top tiltmeter is used only to help determine if loading is the result of ice which affects both tiltmeter similarly or wind which affects the top tiltmeter more than the bottom (Frederking et al., 2007).

For the entire ice season, 106 days from December 31st, 2012 to April 15th, 2013, the measured tilt from each pier and the wind speed component normal to the bridge span was examined. The approach for the systematic analysis of the data involved using the visual images from the video cameras to confirm the direction of ice movement and ice free periods when zero ice loading instances could be established. Movement intervals for analysis purposes were defined for the daylight portion of each day; typically two short intervals, at the beginning and end of each day, and one long mid-day interval where the ice travelled in the opposite direction. Ice movements were primarily in response to tidal currents, but high winds could superimpose shear on the ice so this regular pattern could be interrupted and in some cases movement intervals were shorter or movement could be in one direction for the entire daylight period. If ice loading did not exceed 500 kN during the movement interval, it was disregarded. The video cameras were used to identify ice free intervals at the pier during each ice movement to establish a base tilt reference for zero ice loading. Ice free intervals near the greatest ice loading event were identified when possible however; the ice free intervals were mostly obtained at reversals in the ice motion. On occasion ice free intervals from ice movements before or after the identified movement were used as reference when no ice free data was available during the movement. Wind corrections as described by Frederking et al. (2007) were applied to both the base reference and the measured tilt. The wind related tilt T_w is described in Eq. 1:

$$T_w = C_w V^2 \tag{1}$$

where C_w is the wind constant for the given pier (0.12 μrad/(m/s)^2 for pier 23 and 0.19 μrad/(m/s)^2 for pier 24) and V is the wind speed normal to the bridge span. Similar to Frederking et al. (2006) the ice load is calculated according to Eq. 2,

$$F = K_c(\theta - T_w) \tag{2}$$

where, K_c is the force constant for each pier (42 kN/μrad for pier 23 and 21 kN/μrad for pier 24) and θ is the measured tilt at that pier. In this work the ice load is calculated for each three (3) second interval during every ice movement with at least one ice loading event exceeding 500 kN. The first loading events exceeding 500 kN were observed on both piers on January 31st and the last loading events were recorded on April 12th after which no ice was observed at the NRC instrumented piers. The data examined was limited to dawn, dusk and daylight hours where ice presence at the site could be confirmed from the video and ice movements with at least one ice loading event exceeding 500 kN. This resulted in a total of 1 672 056 seconds (19.4 days) of data for pier 23 and 1 272 750 seconds (14.7 days) of data for pier 24 which respectively, represents 18 and 14 % of the total 106 day period where ice is present at the bridge.

SPECIFIC ICE LOADING EVENTS

April 6th, 2013 Ice Loading Event on Piers 23 and 24

Examination of CIS Daily Ice Charts showed that substantial amounts of ice were present in Northumberland Strait in early April. A portion of the chart for April 6th, 2013 is presented in Figure 2. Ice regime D in the Strait was 9+ tenths total coverage, 2 tenths brash, 5 tenths medium first-year (> 0.7 m) medium floes (100 to 500 m) and 3 tenths thin first-year (0.3 to 0.7 m) big floes (500 to 2000 m). This infers that there were floes of substantial thickness, greater than 0.7 m, and greater than 100 m wide.

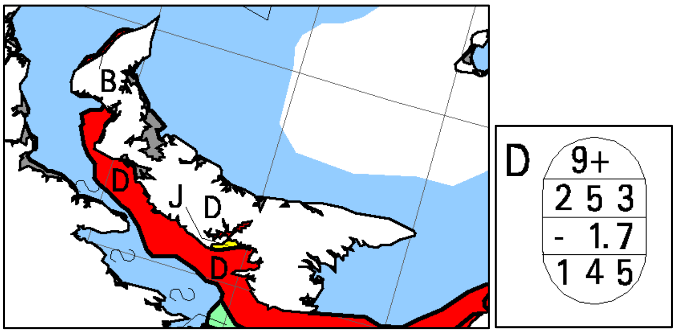

Figure 2. Extract from the Canadian Ice Service Daily Ice Chart for the Gulf of St. Lawrence for April 6th, 2013

The largest ice loads recorded in our data interval were obtained on April 6th and the same ice loading event was recorded on both piers. The event began at 7:13 when a large rough floe impacted pier 24. The ice failure was primarily in flexure and at 7:26 the movement stalled on the leading edge of a large consolidated ridge. The pile up on pier 24 was about 4 m high at the time of the stall. The large floe approached pier 23 but slowed dramatically at 7:26 under the influence of the interaction at pier 24, the floe comes into contact with pier 23 very slowly between 7:30 and 7:50. The ice load, shown in Figure 3, increases on both piers during the stall to a peak of 2334 kN on pier 24 at 8:24 shortly before the ice began a rapid movement at both piers. The rapid ice movement resulted in a sharp reduction in ice load on pier 24 but the load continued to increase on pier 23. The movement resulted in mostly crushing failure on both piers and led to a pile up of approximately 8 m in height on pier 23 and 4 m on pier 24 when the floe stalled again at 8:37.

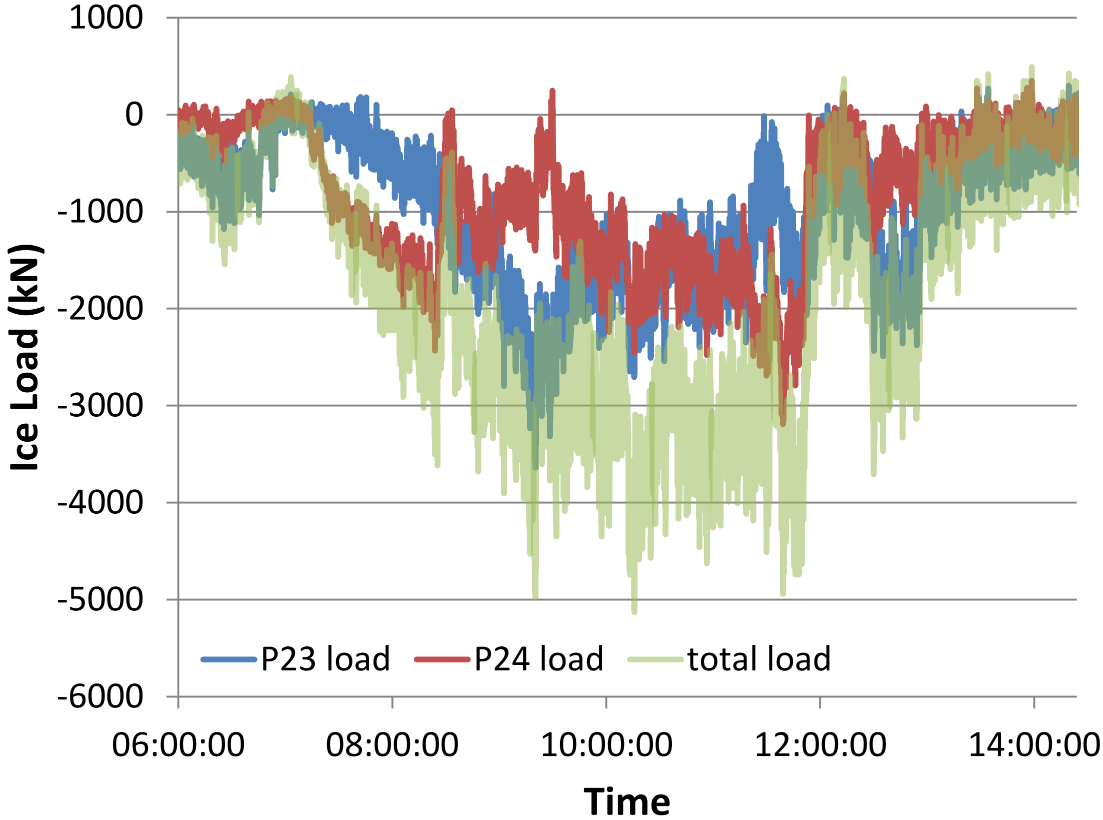

Figure 3. Ice loads during the April 6th, 2013 ice loading event at the Confederation Bridge.

The second stall occurred with a very large ridge ahead of pier 24, the ice load on the pier ranged from 500 – 1600 kN but it remained mostly around 1000 kN. The ice load on pier 23 continued to increase during the stall to a maximum load of 3640 kN at 9:20. The ice conditions during the peak load are shown in Figure 4. The pile up reaches approximately 10 m high on pier 23 overtopping both cones to rest on the vertical face of the pier. From 9:20 to 9:30 while the ice load is maximal on pier 23 it is minimal on pier 24. Beginning at 9:30 very slow ice movement is observed at pier 23 and the ice load reduces sharply then varies around 1500 kN until 11:25 when the first large flexural failures occur resulting in ice loads approaching zero and continual movement at pier 23. As the ice load on pier 23 reduces it is increasing on pier 24 under the action of the stalled floe until 11:25 when the floe begins to rotate around the pier. From 11:32 to 11:34 the ice floe lurches approximately 1.5 pier diameters pushing the large ridge into pier 24 leading to a 10 m high pile up on the pier. The rotation continued after the movement resulting in the maximum load on pier 24 of 3190 kN at 11:39, finally at 11:42 a long radial crack forms which is followed by a second crack that releases the floe around the pier. The floe movement resumes and the event comes to an end at 11:54.

Figure 4. Ice conditions at pier 23 during the maximum loading event on April 6th, 2013

The maximum observed load on a single pier during the 2012 – 13 ice season was recorded on pier 23 at 9:20 on April 6th. The maximum observed load was 3640 kN much less than the 1 year design loads of 8140 kN and the 100 year design loads of 15250 kN reported by MacGregor et al. (1997).

The total observed ice load on the two Confederation Bridge piers monitored by NRC peaked at 5130 kN at 10:16 when nothing significant is occurring on the video of either pier. There is slow movement at pier 23 and the ice is stalled at pier 24 at this time. This combined ice load is 40 % greater than the maximum observed ice load on an individual pier. At the time of maximum total ice loading the load is well balanced between the two piers. There are two large secondary peaks in the total load at 9:20 (4980 kN) and 11:39 (4940 kN) that correspond with the maximum loads at each individual pier.

April 5th, 2013 Ice Loading Event on Piers 23 and 24

Another large ice loading event occurred at both piers on April 5th, 2013. The CIS Daily Ice Chart indicates that the ice conditions at the Confederation Bridge during this event are very similar to those during the April 6th ice loading event. At 14:47 a large rough floe impacted pier 24 resulting in primarily flexure and splitting failures and very low loads on the pier until 14:50 when the splitting stopped. Flexural failures continued until the motion stalled at 14:57 with a small peak in the load as shown in Figure 5. The same large floe impacted pier 24 at 14:48, a 7 m pile up on the cone and a preliminary peak load of 1150 kN were observed at 14:50, as shown in Figure 5 and Figure 6.

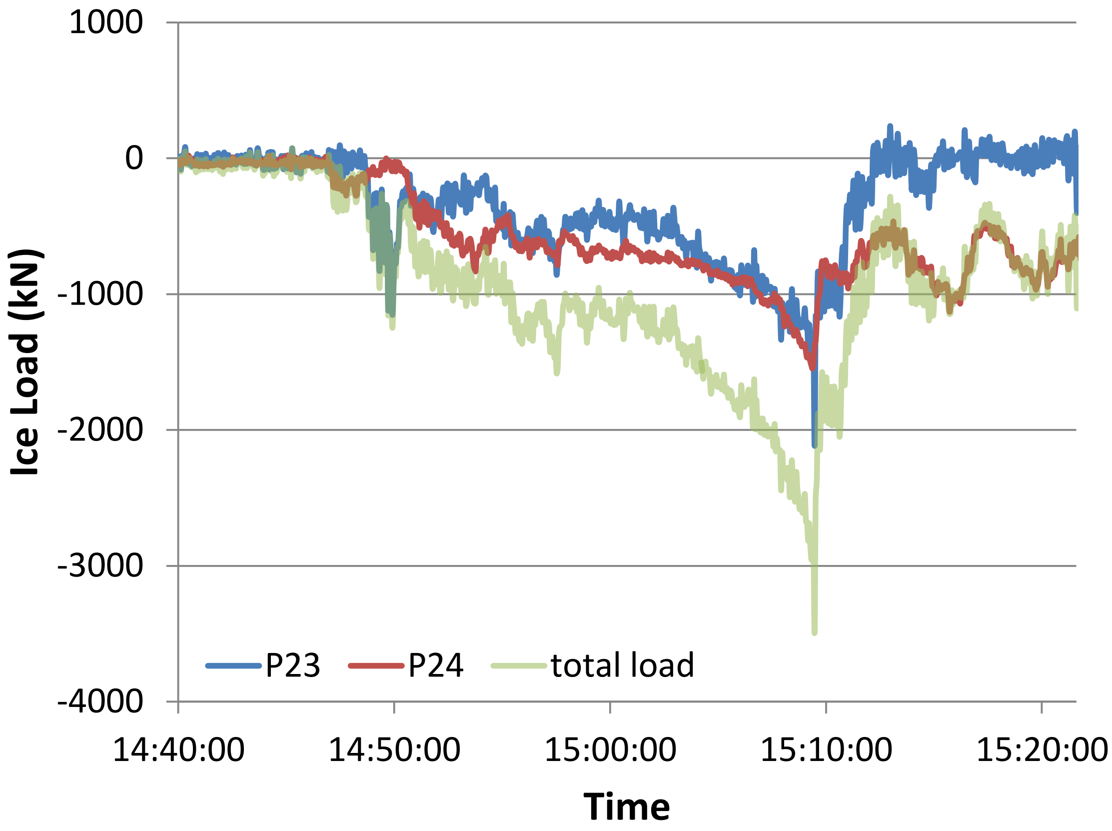

Figure 5. Ice loads during the April 5th, 2013 ice loading event on pier 23 of the Confederation Bridge

At 14:57 the motion at both piers was stalled after which the ice load at both piers began to increase slowly until 15:09 when the maximum loads of 2120 kN for pier 23 and 1550 kN for pier 24 occurred. At pier 23 the ice movement resumed resulting in two large radial cracks at 15:10 which released the floe around the pier. The ice conditions at pier 23 during the April 5th, 2013 ice loading event are shown in Figure 6. The ice pile up reaches 6 m high in front of the pier. At pier 24 the ice motion resumed with continuous flexural and crushing failures.

The maximum total load on the two NRC monitored bridge piers of 3490 kN occurred at 13:09 and coincided with the peak load of each of the individual piers. The maximum load is 65 % greater than the highest ice load recorded on an individual pier during the event.

Two ice loading events were described in this paper that simultaneously affected two piers on the single structure. The two events were different in that for the April 6th event the peak forces were generally shared between the two legs. There were several instances of the load increasing on one pier while simultaneously decreasing on the other and the peak loads for the two piers were separated by over 2 hours. For the April 5th event both piers experienced a similar load profile and the peak load was experienced only seconds apart at the two piers.

Figure 6. Ice conditions at pier 23 during the maximum loading event on April 5th, 2013

GLOBAL ICE LOAD RESULTS

Basic statistics of the ice loads were performed for the complete record examined. Positive loads reflect ice drift to the NW and negative loads reflect ice drift to the SE. The average ice loads calculated on piers 23 and 24 were 20 and -30 kN respectively which approximately reflects the precision of the ice load measurements. The average of absolute values of the ice loads were 200 kN for pier 23 and 150 kN for pier 24 while the median values were 130 and 90 kN respectively. The exceedance values for the dataset which contain 19.4 days of data for pier 23 and 14.7 days of data for pier 24 are presented in Table 1.

Table 1. Exceedance values on the two dominant faces of the Confederation Bridge piers. Values in kilonewtons for the 2013 data interval

Exceedance	Pier 23 (SE face)	Pier 24 (SE face)	Pier 23 (NW face)	Pier 24 (NW face)
1%	840	590	-1630	-1490
5%	540	360	-770	-550

The data from Table 1 suggests that large loading events, exceeding 1000 kN, occur at a much greater frequency when the ice drift is towards the SE and arriving on the NW face of the bridge piers. This could be indicative of a preferred drift direction.

In an effort to better understand the bridge's response to ice loads, every 3 second averaged load was binned into 10 kN intervals to produce the ice load distribution in Figure 7. For ice loads up to 500 – 600 kN, or approximately the 5% exceedance level, the distribution for both the positive and negative loads for pier 24 and the negative loads for pier 23 for a very similar distribution. The positive ice loads, or those towards the NW, occur in greater numbers for pier 23 over the same range. For larger loads the pier 23 positive load data curve diverges even further from the pier 24 but the negative loads for both piers occur in even greater numbers especially for loads greater than 1000 kN. The pier 23 tilt values are positive, or towards the NW, 58 % of the time and for pier 24 the tilt values were positive 48 % of the time. No positive loads, resulting from ice drift to the NW, exceeded 1600 kN in the data that we examined.

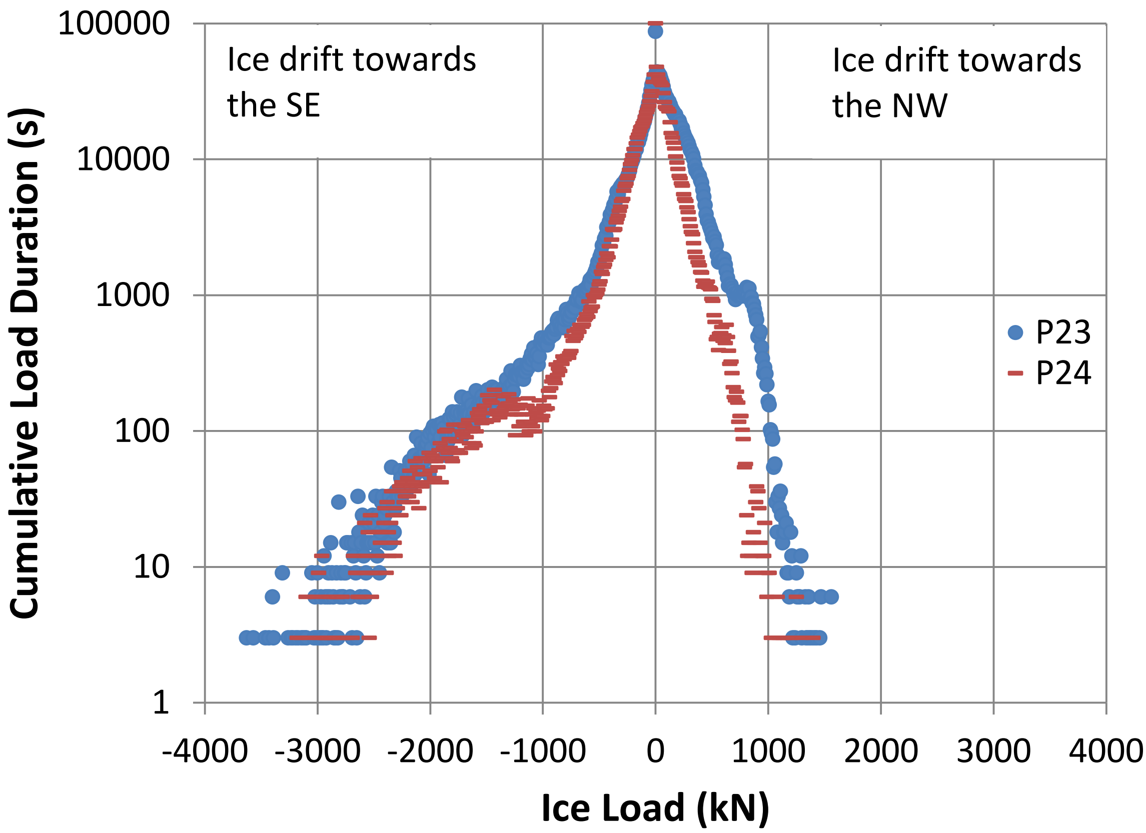

Figure 7. Ice loads distribution; the ice loads from the 2013 ice season data interval have been separated into 10 kN bins.

Figure 8 shows the empirical cumulative distribution function calculated for force magnitudes for each pier-force direction pair. Note the asymmetry of the curves for the two piers and the two force directions. Cumulative distribution function is the largest at any given force magnitude for P24 when forces are towards NW. A statistical analysis was performed on each pier-force direction pair dataset to find the best distributions to fit the datasets. Several distributions were considered including Normal, Logistic, Extreme value, Gamma, Weibull, t location-scale, Exponential, and Generalized Pareto distributions, to name a few. The Bayesian Information Criterion, widely used for model selection in statistical data analyses, was used to select the best fit. The Generalized Pareto distribution was the best fit for all of the four pier-force direction pair datasets. Other good fits were Exponential (for forces towards NW), Logistic (for forces towards SE), Weibull, and Gamma distributions.

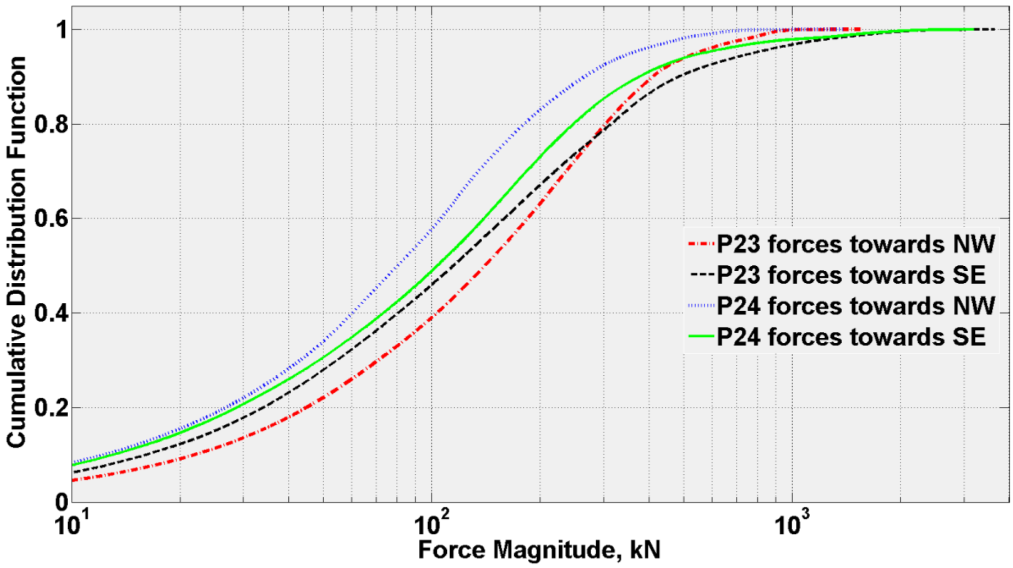

Figure 8. Cumulative distribution function for each pier-force direction pair dataset

CONCLUSIONS AND FUTURE WORK

Two large ice loading events were described in this paper that simultaneously affected two piers on the single structure. The maximum total load observed at the two piers was 40 and 65 % greater than the maximum observed load on a single pier. The maximum load observed on a single pier for the 2013 season was 3640 kN and the maximum total load on two piers was 5130 kN.

The observed average absolute ice loads and the exceedance values for pier 23 are greater than those of pier 24. This could reflect a need to further refine the force and wind constants for the two piers or it could be an artefact of an asymmetry in the pier response to loading which would need to be better understood.

Asymmetries in Figure 7, the ice load distribution, could be reflective of a predominant ice drift direction or an asymmetrical response from the bridge piers. Figure 4 from Brown et al. (2010) is suggestive of a predominant current from the NW which suggests that negative loads should be dominant such as is observed at Pier 24 and for higher loads on both piers in as seen in Figure 7 and Table 1. The greater number of observations of positive loads for lower forces at pier 23 may be suggestive of an asymmetrical response to loading. Further analysis of the data would be required to make this determination.

The next step for our group is to automate the video review process to determine the presence of ice. This should allow for a better understanding of the differences between wind and ice loading on the two piers and hopefully lead to a refinement of the wind and load coefficients for each pier.

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