Reprinted from:
Proceedings 18th International Symposium on Ice, IAHR'06
Vol. 1, pp 231-238, Sapporo, Japan, 2006.

RESPONSE OF TWO PIERS ON CONFEDERATION BRIDGE TO ICE LOADING EVENT OF APRIL 4, 2003

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ABSTRACT

A large piece of shore fast ice approximately 5 by 10 km broke free and drifted through Northumberland Strait on April 4 2003, failing against the piers of the Confederation Bridge. The ice had been surveyed shortly before its break-up and its thickness was about 1 m with many ridges of about 4 m thick when averaged over a 20-m diameter. While the ice was quite thick, it was late in the season and thus soft resulting in the maximum force determined on the two piers only in the order of 2 MN. Hand held videos of the episode provided an overview of the ice failure processes observed.

KEY WORDS: Ice forces; Structure response, Ice failure behaviour, Sea ice.

INTRODUCTION

The Confederation Bridge is a 13 km long bridge that spans the Northumberland Strait, connecting Prince Edward Island and New Brunswick in Canada. The central portion of the bridge comprises 44 main piers at 250-m spacing, in water depths ranging from 10 m to 30 m. The piers have a conical (52° from the horizontal) "ice shield" about 10 m in diameter at the water line. The duration of the ice season in the area is generally 90 days long with level ice thickness reaching 1 m. The Strait is subject to reversing tidal currents that result in about 3000 km of total ice movement past the bridge each winter. These dynamic ice conditions produce ice ridges and numerous ice loading events on the piers supporting the bridge. The bridge is an ideal location for studying and measuring ice forces. Starting in 1997 the response to ice forces of two piers towards the New Brunswick end of the bridge has been measured by Brown (2001). In 1999 a complimentary program of ice force measurements was initiated on two piers adjacent to the central navigation span of the bridge (Kubat and Frederking, 2000).

At the end of the 2003 winter a large piece of landfast ice broke free and drifted through the Strait, impacting the bridge. The landfast ice had been surveyed several days before it broke free, so good quality information on ice thickness is available. Actual on-ice observations of the ice interacting with piers and hand held videos of the episode were also obtained. This paper will describe the ice conditions and ice loads generated during the day, and discuss the relation between them.

INSTRUMENTATION

Measurement of pier response to ice loading is done with tiltmeters. Two tiltmeters were installed inside each pier on the upstream side (northwest), one at the bottom of the pier and one at the top of the pier as shown in Figure 1. The instruments can measure tilt in two directions, X along the longitudinal axis of the bridge (northeast – southwest) and Y, transverse to the bridge axis. The Y direction is the primary axis of ice loading. Data are recorded at a frequency of 1 Hz. Because of limited storage capacity of the data acquisition system, only tilts in the Y direction are recorded. The two piers instrumented, P23 and P24, were immediately adjacent to the navigation span near the middle of the Strait. A detailed description of the instrumentation and of the installation of tiltmeters is given in Kubat and Frederking (2000).

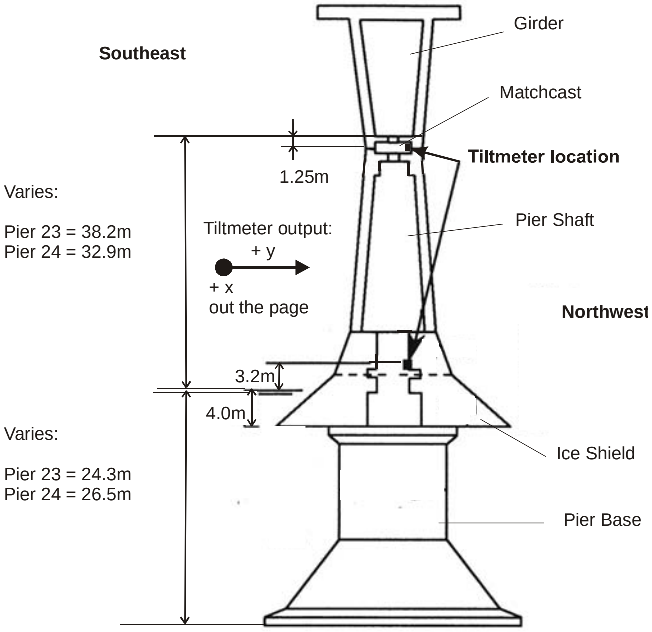

Figure 1 Cross Section of the pier (view from the PEI side)

METEOROLOGICAL AND ICE CONDITIONS

The location of the bridge and Northumberland Strait is shown in Figure 2. The 2003 winter season was comparable to other seasons. The total freezing degree-days experienced in Northumberland Strait in 2003 was 726 °C-day, close to the 30-year average. Ice begins to form in bays near shore and by the beginning of January is 10 to 15 cm thick. From mid-February through March ice of thickness up to 1 m is present, however, due to ridging and rafting thicker ice may be present too. Generally by the beginning of April ice is clear of the Northumberland Strait. In 2003 the Ice Analysis Chart for 31 March showed the Strait to be free of ice, with the exception of a number of bays with shore fast ice.

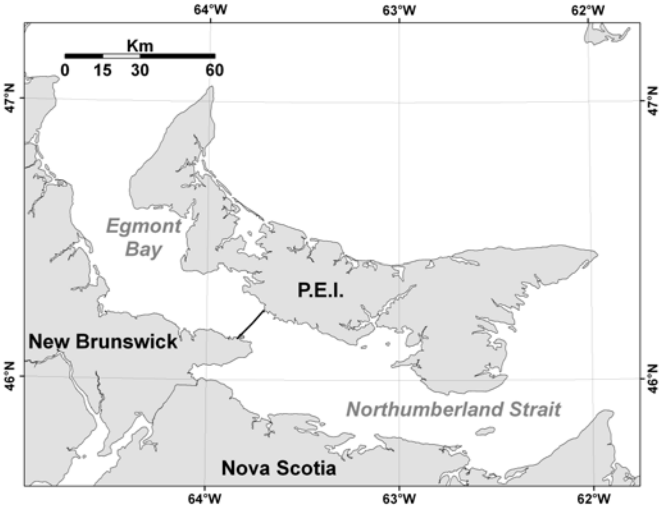

Figure 2 Alignment of Confederation Bridge in Northumberland Strait

On March 28, helicopter-born sensors were used to survey ice thickness in Egmont Bay by Department of Fisheries and Oceans personnel stationed at the Bedford Institute of Oceanography (BIO). The ice thickness sensor (Prinsenberg et al., 2002) measures ice thickness every 4 to 5 m and represents an average thickness over a circular area of diameter about 2.5 times the height of the sensor above the sea water surface. A laser provides the sensor distance to the surface of the surface while the Electromagnetic Induction sensor provides the distance to the top of the sea surface, sea water being the conductor the electromagnetic signal is reflecting from. Surveying at the normal 4 m height above the ice surface, the circular diameter the ice thickness is averaged over is 12.5 m for 1 m-thick ice and 20 m for 4 m-thick ridge structures. Figure 3 presents a survey line about 2.5 km long. The maximum thickness was about 5 m and mean thickness 1.7 m. The survey line shows a number of ridges with spatial mean values over 20 m diameter of 4 m ice thickness. A second survey nearby and over a 2 km length (Figure 4) indicated a slightly greater mean thickness of 2.3 m, a number of ridges of mean thickness of 4 m and about 10 % very thin ice or open water. The thickness profiles indicate an overall ridge spacing of between 100 and 200 m.

Wind speed and direction were measured at the navigation span on the bridge and air temperature records were available from Summerside, about 20 km to the west. For the last 10 days of March the mean daily temperature was above freezing with highs up to 7 °C. The first 4 days of April were characterized by cooler air temperatures, means about –4 °C and daily highs just above zero. Timco and Johnston (2002) showed that ice covers weaken progressively from the time mean daily air temperatures begin to increase, which in 2003 was the beginning of March. The tides reached a maximum height in late March, which could have precipitated the conditions for the land fast ice in Egmont Bay disconnecting from the shore. On April 1 there was wind from the northeast which could have moved the ice out of Egmont Bay into Northumberland Strait where it broke into large floes and one approximately 12 km by 5 km traveled eastwards, encountering the bridge at approximately 07:00 local time (AST) on April 4.

During April 4 the maximum tidal current was 55cm/sec to the southeast at 08:00, it decreased to 0 at 11:00 and reached a maximum of 55 cm/s to the northwest at 14:00 (Dept. Fisheries and Oceans, 2006).

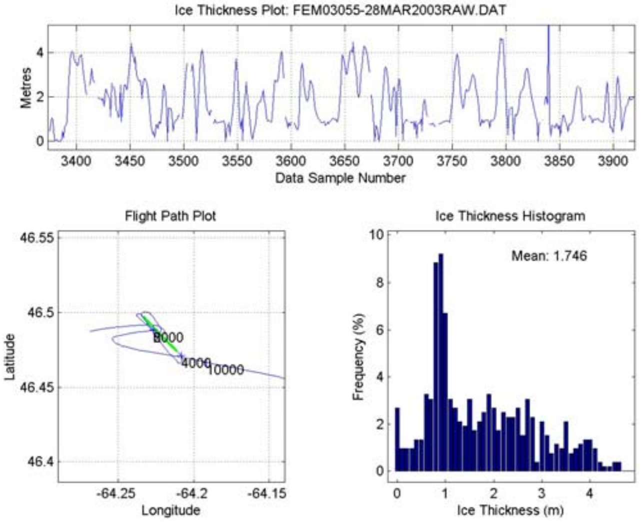

Figure 3 First profile of ice thickness in Egmont Bay, 2003 March 28

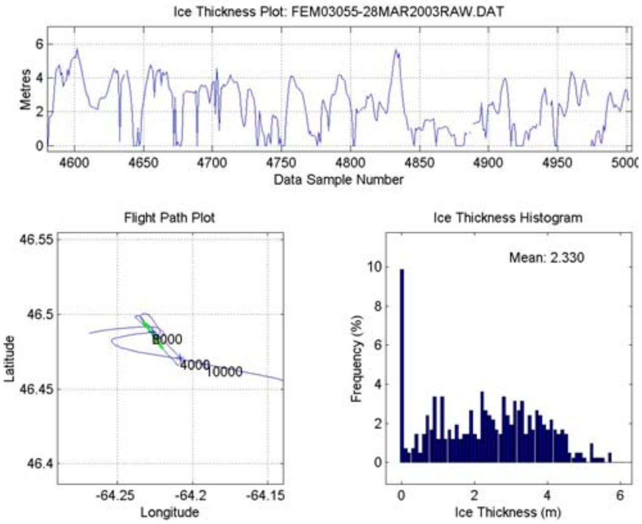

Figure 4 Second profile of ice thickness in Egmont Bay, 2003 March 28

APRIL 4 ICE LOADING EVENT

The April 4 ice loading event is of interest because of the large and relatively thick ice floe that interacted with the bridge. Also there is relatively good information on the thickness of the floe and direct observations of ice failure on the piers. It has been shown in earlier work that wind has a significant effect on the measured tilts. Tilt at the top of the two piers is plotted in Figure 5, as is the normal component of wind to the bridge axis and air temperature. The tilt values plotted here are 20-second averages taken every 20 seconds; which has the effect of filtering the tilt records. The wind started to increase the evening of April 3, reached a maximum of about 25 kt by noon the following day and had fallen off to calm conditions by evening on April 4. The normal wind component was from the northwest and produced negative tilts (tilt towards the southeast). It can be seen that the tilt tracks the wind velocity up to about 06:00. After this time the tilt starts to increase, likely due to the effect of solar radiation warming the southeast side of the bridge piers, and causing the piers to tilt towards the northwest (tilt becomes positive). By mid afternoon the sun is aligned with the bridge and its warming effect on the southeast side diminishes. Note that at 11:49 there is a large step change in tilt of P24 and a smaller step of P23. It is at about this time that the direction of tidal current changes from being towards the southeast to the northwest. This change is rapid, taking only about 1 minute.

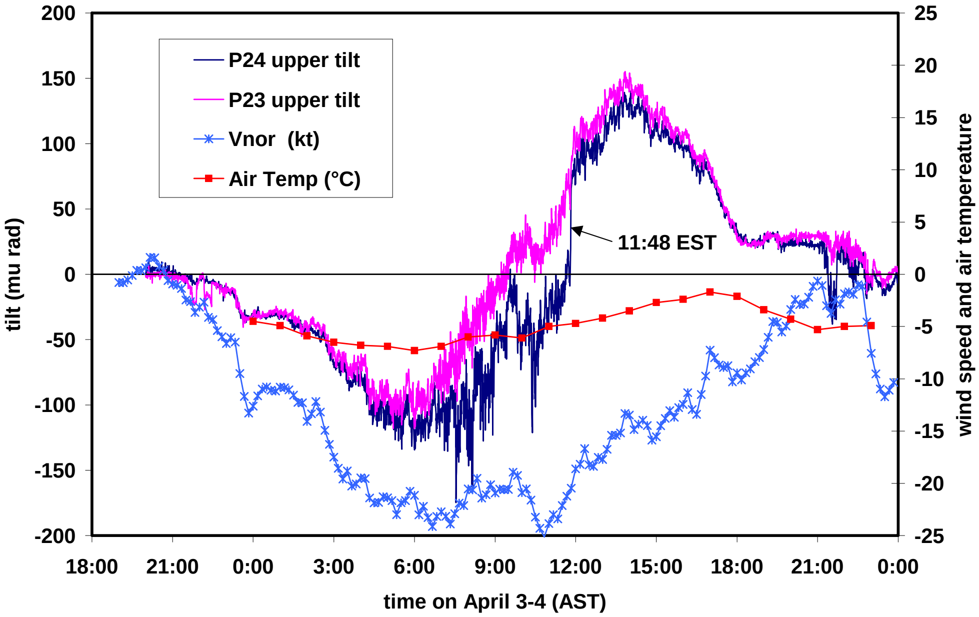

Figure 5 Pier tilts at the upper level for April 4 ice loading event

The tilts measured by the lower level tiltmeters is plotted in Figure 6. If only ice forces at the waterline acted on the piers, the upper and lower tilts should be the same. Later an example of this behaviour for pier P23 at about 21:45 on April 23 will be presented. Comparing Figures 5 and 6, up until about 05:00 on April 4, the upper tilt was about 4 times the lower tilt, reflecting the fact that the wind force was causing the pier shaft to bend. A similar difference was observed in earlier analysis (Kubat et al, 2000). Even after the tidal current and ice drift direction changed at about 11:30, both piers exhibited negative tilt at the lower level in response to wind induced tilt of the piers, as would be expected. Note this is in contrast to the upper level tilt which showed a reverse in the sign of the tilt. A critical factor for determining ice forces from the lower level tilts is establishing a baseline independent of wind effects. This was done in the following manner. A straight line was extended for tilt from 21:00 on April 3 (0 µrad) .to 21:00 on April 4 (-10 µrad). Then a wind induced tilt of the form

$$\text{Tilt}_{\text{wind}} = C\,(V_{\text{nor}})^2$$

where V_{nor} is wind velocity normal to the bridge axis in m/s and coefficient C is –0.19 µrad/(m/s)^2 for pier P23 and -0.3 µrad/(m/s)^2 for pier P24 was superimposed to establish a baseline. In principle, this baseline tracked the normal wind velocity squared, and followed the upper margin of the tilts at the lower level.

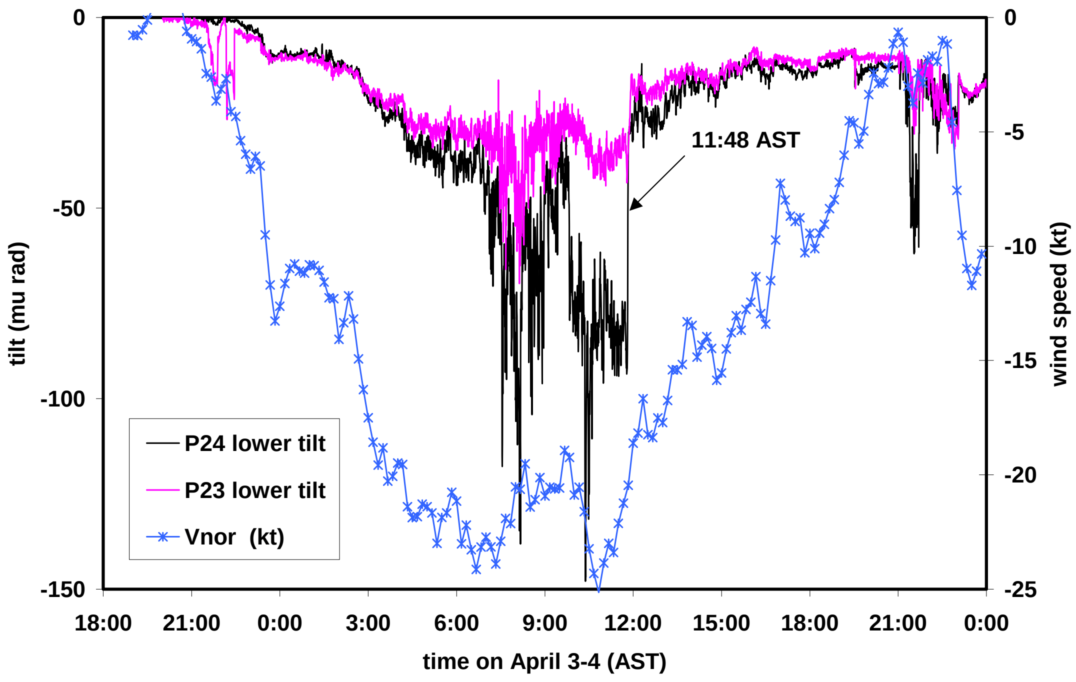

Figure 6 Pier tilts just above waterline for April 4 ice loading event

As mentioned in the Introduction, two approaches to calibrating the stiffness of the piers were used to obtain factors for converting the measured tilt to forces on the piers. The calibration reported by Bruce and Brown (2001) produced a factor of 0.020 MN/ μrad. Kubat and Frederking, (2001) used wind forcing to determine factors of 0.04 MN/μrad for pier P23 and 0.02 MN/μrad for pier P24. The differences are attributed to differences in foundation stiffness. Using the calibration factors for converting tilt to force, ice forces acting on piers P23 and P24 from 06:00 to 12:00 on April 4 are presented in Figure 7. Establishing a baseline for the forces is less certain. Using the approach discussed above and judgement, a baseline force of –0.4 MN for pier P24 and –1 MN for pier P23 is estimated for this time interval. This makes the maximum force on pier P24 about 2.4 MN at about 10:20. The maximum force on pier P23 was 1.8 MN at 08:10.

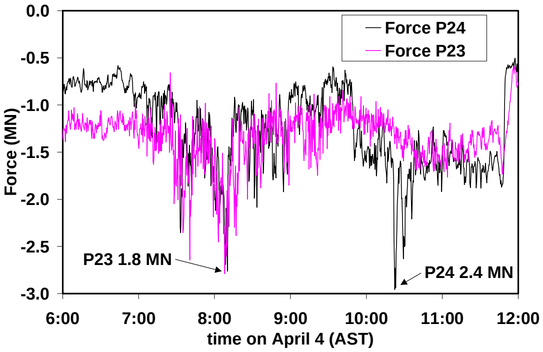

Figure 7 Time series expansion of forces on piers P23 and P24 for April 4 ice loading event (not baseline adjusted)

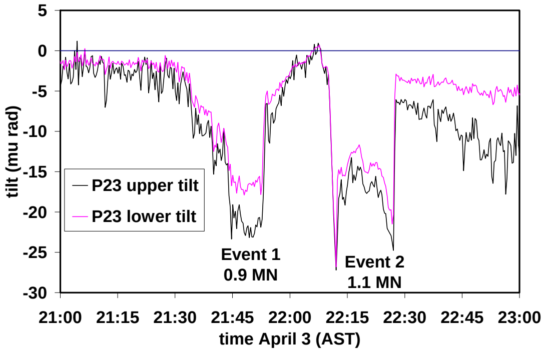

Figure 8 Time series expansion of pier P23 tilts for April 3 ice loading event

Two loading events were observed on pier P23 between 21:30 and 22:30 on April 23 (Figure 8). These are examples of cases where the wind velocity is low, so wind induced tilt is minimal and the upper and lower tilts are almost identical. The first event produced a load of 0.9 MN and the second 1.1 MN. Note that the tilt values plotted here are the 20-second averages at 20-second intervals.

ICE FALURE BEHAVIOUR

As was mentioned earlier, there were handheld videos of the ice failing against the piers and also a limited number of still images taken from a helicopter on the ice near the bridge. Figure 9 shows the ice floe failing against the piers, in what appears to be a crushing mode. Also evident from this figure are the arching tensile cracks running from pier to pier.

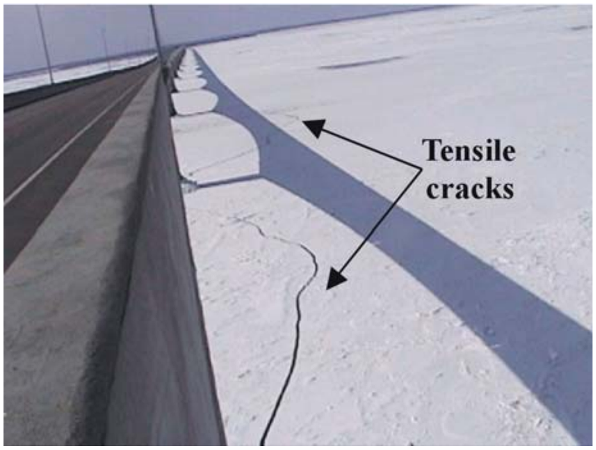

Figure 9 Ice crushing on piers and tensile cracks, from pier P24 looking southwest towards New Brunswick

To illustrate that there were different failure modes against the piers, Figure 10 (a) shows a flexural type of behaviour with relatively large ice pieces, while Figure 10 (b) shows crushing behaviour with small ice pieces.

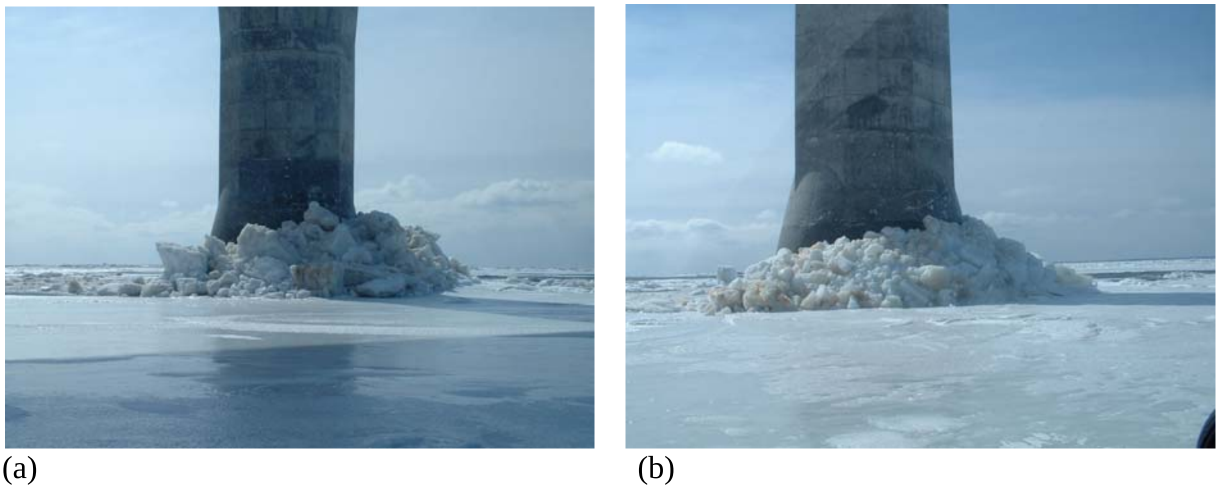
(a) (b)

Figure 11 Contrast of ice failing to produce large ice pieces (a) or small ice fragments (b)

SUMMARY AND CONCLUSION

The April 4 event provided a good combination of ice load data, ice cover thickness information and direct video observations. Prior thickness measurements of the ice floe that impacted the bridge indicated average ice thickness of 1.5 m with numerous ridges (spacing 200 m) of thickness 4 to 6 m. During the main movement of the ice floe past the bridge between 07:00 AST and 12:00 on April 4, the maximum ice force measured was 2.4 MN and the average was between 0.5 MN and 1 MN. In spite of the relatively thick ice floe, surprisingly low ice forces on piers P23 and P24 were measured. Warming air temperatures during March resulted in the ice floe being substantially weakened by the time it impacted the bridge. This is the most reasonable explanation for the low ice forces. This reinforces the need for good climatic and ice strength information in predicting ice loading on structures.

ACKNOWLEDGEMENTS

The assistance of Murray Scotney of the Bedford Institute of Oceanography for the recovery of tilt data from the bridge is greatly appreciated. The collaboration of Strait Crossing Bridge Inc. in providing a copy of the video of ice interactions is gratefully acknowledged. Funding support from the Program of Energy Research and Development facilitated this work.

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