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RESPONSE OF CONFEDERATION BRIDGE TO ICE FORCES:
2000 WINTER SEASON

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ABSTRACT

Tilt at two piers of the Confederation Bridge was measured from January to April 2000. Additionally, ice drift, current and ice thickness were measured in a collaborative effort with the Bedford Institute of Oceanography. Time-lapse video records of ice conditions were obtained from a traffic observation camera on bridge. The response of the piers to wind loads was used as a first order means to determine foundation stiffness and convert tilt to ice force. Typical tilt-time records for a two-day period in March are presented. A maximum ice load of 0.9 MN was obtained during a period when ice ridges with keels up to 4 m deep were measured.

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 duration of the ice season in the area is about 90 days long with level ice thickness reaching up to 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.

Because of this combination of environmental conditions and the uniqueness of the structure, an extensive monitoring and research program is being carried out under the auspices of a Natural Sciences and Engineering Research Council (NSERC) Collaborative Research and Development (R&D) Grant (Cheung et al, 1997). In addition to various aspects of bridge performance, that project has been measuring ice forces on two piers towards the New Brunswick end of the bridge since 1997 (Brown et al, 2001). In 1999 a complimentary program

of ice force measurements was initiated on two piers near the central navigation span of the bridge (Kubat and Frederking, 2000). Thus a total of 4 piers are being used to measure response to ice loading. In the NSERC project one of the piers was loaded with a ship in order to calibrate foundation stiffness and provide a means of relating pier tilt to ice load (Bruce et al, 2001). This paper presents an alternate means for calibrating the foundation stiffness and some results from measurements made in the winter 2000 on the two piers adjacent to the navigation span.

MEASUREMENT PROGRAM

Measurement of pier response to ice loading for the winter of 2000 was resumed in January and continued until the middle of April. The same two piers instrumented in 1999, P23 and P24, were used. These piers are close to the navigation span, which is between piers P21 and P22. The two piers instrumented by the NSERC project in 1997 are closer to the New Brunswick end of the bridge at P31 and P32 (1.75 km from P24). Having two sets of piers provides an opportunity to see if there are systematic differences in ice loads depending on location in the Strait. 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 X-axis tilts, Y-axis tilts, temperature of lower level of the pier, and battery voltage were measured. The X-axis tilts are in the longitudinal direction of the bridge (northeast –
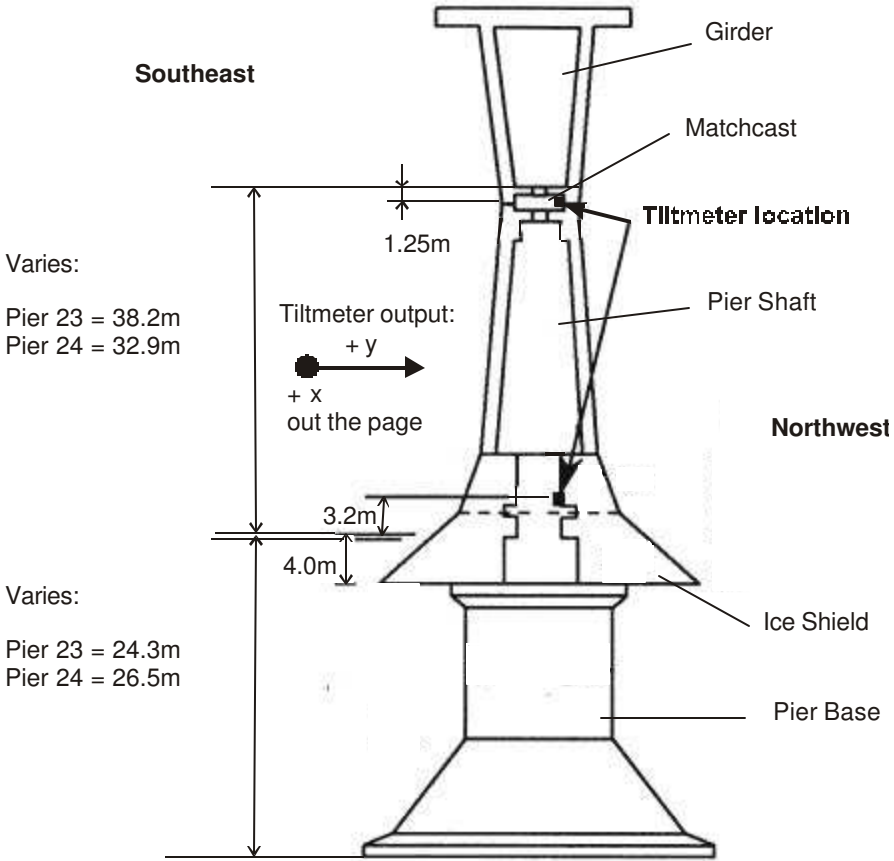

Figure 1 Cross Section of the pier (view from the PEI side)

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southwest) and are primarily in response to the thermal expansion or contraction of the spans.The Y-tilts are perpendicular to the longitudinal axis of the bridge and are in response to ice and wind loading. The readings of tilts were taken every second and a 20-second average was recorded every 20 second. The temperature and battery voltage readings were stored every 3rd hour. The detailed description of the instrumentation and of the installation of tiltmeters was described by Kubat and Frederking (2000).

This season some video records of ice conditions were also obtained. The Confederation Bridge Control Centre uses a number of video cameras to monitor conditions and traffic on the bridge. The signal from a camera above P23 was recorded on a time-lapse video recorder. The videos were useful in determining the presence of ice, direction and speed of drift, any occurrence of jamming and ice failure behaviour on piers.

As in the previous year, the project involved an extensive collaboration with the Department of Fisheries and Oceans through the Bedford Institute of Oceanography (BIO), and Public Works and Government Services Canada (PWGSC). BIO was conducting a program to investigate the ice conditions in Northumberland St. and the affect of the Bridge on them. As part of this study, they have carried out helicopter surveys of ice conditions and measured the ice thickness and drift velocity using an Ice Profiling Sonar (IPS) and Acoustic Doppler Current Profiler (ADCP), respectively. In the previous year the IPS and ADCP were located 200 m and 400 m, respectively, northwest from pier P23. In 2000, the IPS and ADCP were deployed on either side of the pier P24 to reflect the ice conditions on both sides of the bridge pier. Pier P24 was selected for Winter 2000, because its foundation is about 50% softer than that of pier P23, which resulted into higher tilt response to loads induced by ice and wind. Also, the instruments were located closer to the pier: IPSs were about 100 meters from the pier along the main channel axis and ADCPs were few meters further (Figure 2). The detailed description of these instruments and data processing is presented in the paper by Belliveau et al. (2001).
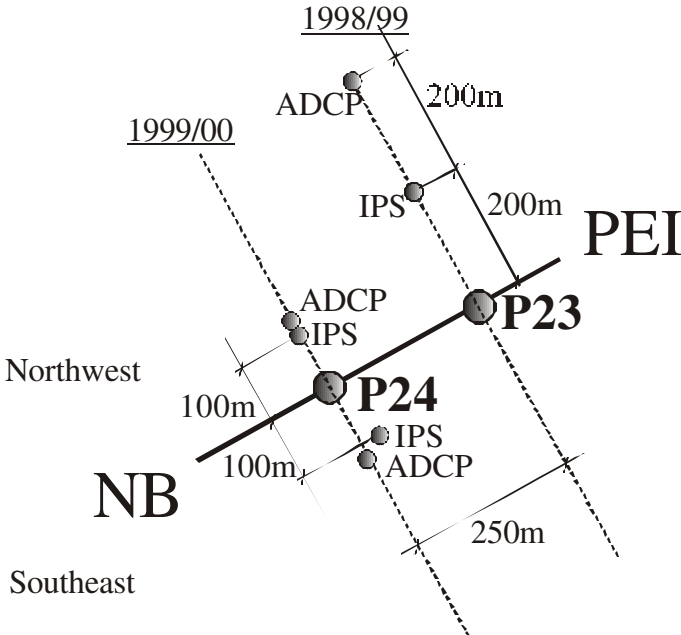

Figure 2 Ice Profiling Sonar and Acoustic Doppler Current Profiler Location

DATA ANALYSIS

This paper presents forces determined for some typical ice loading events. The response of the piers to wind loads was used as a means to determine foundation stiffness and convert tilt to ice force. Since the tiltmeters were installed in January, there was no guarantee that there was no ice loading on the pier during the installation. Therefore the baseline for tilts was set after obtaining all data with the knowledge of conditions where there was no ice acting on the pier. The same correction factors for wind induced tilt as those in the previous year were used. The detailed description of the period selection with no ice loading on the pier is given in paper by Kubat and Frederking (2000).

Calibration of Foundation Stiffness

The instrumentation of the piers with tiltmeters provides a means of measuring their response to ice and wind loads. To convert the measured tilts to forces, requires a knowledge of the stiffness of the foundation material underlying the pier bases. In the case of pier P31, an actual calibration test was done using an icebreaker to pull on the pier with a known force (Bruce et al, 2001). An alternative approach is to use the wind force as a means of determining foundation stiffness. Because of the long spans of the bridge, 250 m, the girder is necessarily deep, presenting a large area of the bridge to wind action. The girder is 14 m deep at the pier and reduces to a depth of 4.5 m at mid span (see Figure 3).
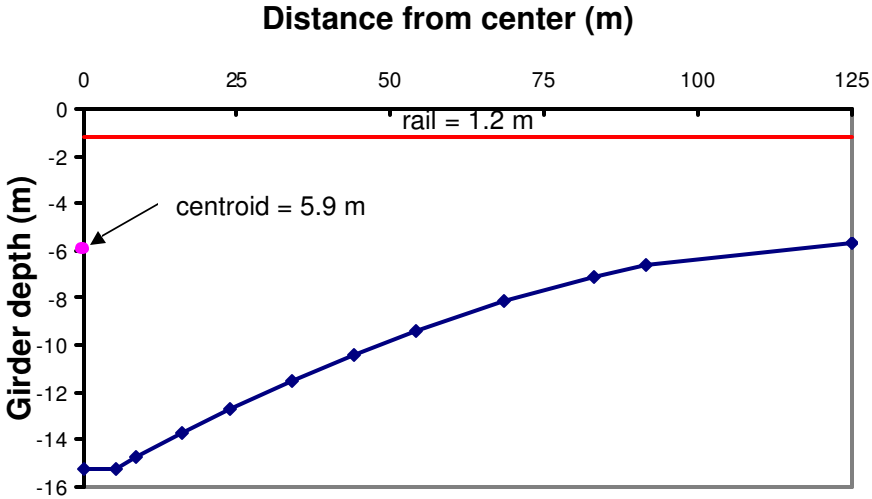

Figure 3 Girder Cross Section

Estimating the guard rail to be 1.2 m high, the cross sectional area of the girder plus rail is calculated to be 2340 m^2. Wind force is given by the following equation

$$F_w = A \, C_D \, ?_a \, V^2/2 \qquad\qquad (1)$$

where A = cross-sectional area, C_D = drag coefficient (assumed = 1), $?_a$ = density of air (1.3 kg/m^3) and V = wind velocity.

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The wind force acts on the centroid of the girder area (9.3 m above the base of the girder) producing a lateral force and moment on the top of the pier, causing the pier shaft and pier base to bend, as well as tilting of the pier on the foundation. The relative bending of the pier shaft and base and tilt about the foundation is a function of the length and diameter of the shaft and base. These relative tilts can be calculated, knowing the dimensions of the piers. The complexity of that calculation, however, is beyond the scope of this paper. As a first order approximation, the amount of tilt measured at the lower tiltmeter will be taken to be a function of the moment applied to the pier.

$$\theta_{lower} = k \, M \tag{2}$$

where k is calibration factor and M is the moment about the base of the pier from wind and ice actions. For the case of only wind acting on the pier

$$M = L \, F_w \tag{3}$$

where L is the distance from the pier base to the point of wind load application and F_w is the wind load as determined from equation (1). A wind loading event with no ice loading on piers P23 and P24 can be used to determine the calibration factor, k, for each pier. For the case of only ice acting on the pier, moment M is a function of the ice force, F_i, and its moment arm, a (distance from pier base to waterline). Substituting the moment due to ice action into equation (2) the ice force is given by the following expression

$$F_I = \theta_{lower} / k \, a \tag{4}$$

A wind loading event on March 16, 2000 was used to obtain a calibration of pier foundation stiffness. Figure 4 is a plot of the normal wind velocity (m/s) and the tilt measured by the lower tiltmeters on piers P23 and P24.
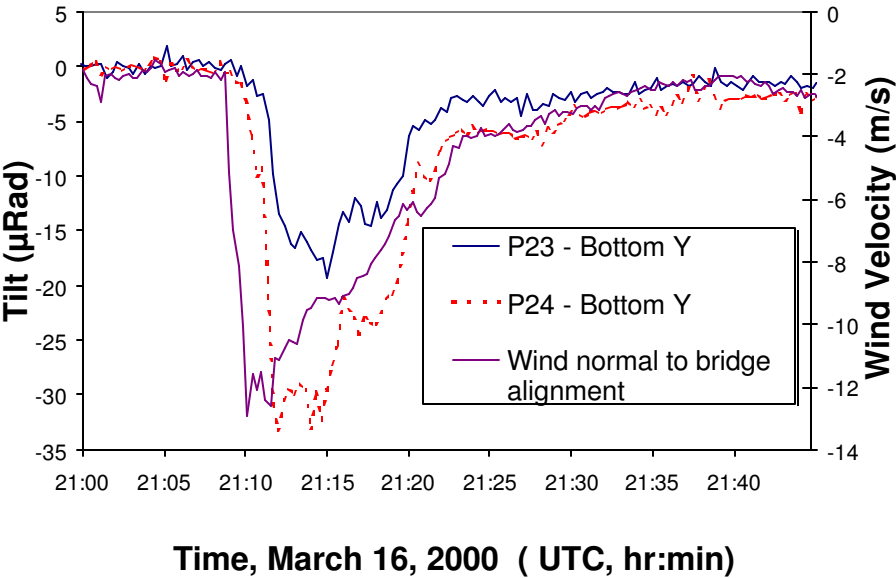

Figure 4 Wind Velocity and Tilt measured at the Bottom of Piers P23 and P24

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The average maximum wind speed during the event is taken to be 12 m/s and when substituted into equations (1) gives a force of 0.22 MN. The corresponding average tilts on piers P23 and P24 are 16 and 30 µrad, respectively. Taking into account pier lengths, L, and load action length, a, factors for converting measured tilt at the lower level to ice force can be determined, as presented in Table 1.

Table 1 Calibration factors for converting ice induced pier tilt to ice force

Pier	$tilt_{wind}$ [µrad]	a [m]	L [m]	k, [µrad /MN-m]	1/(k a), [MN/µrad]
P23	16	24.3	73.4	1.0	0.04
P24	30	26.5	70.4	1.9	0.02

Cheung et al (1997) indicated that an approximate calibration factor for converting tilts measured at the lower level for piers P31 and P32 was 0.03 MN/ µrad, which is in a good agreement with calibration factors we derived.

Sign Convention

A decrease of the tiltmeter output indicates ice impact from the northwest side of the pier. A positive current measured by the ADCP located on the northwest side of the pier is a current to the northwest. On the other hand, a northwest wind blows from the northwest. For wind, the sign convention is that the normal component from the northwest is negative, so that an increasing wind from the northwest will produce an increasing negative tilt.

Ice Loading Events

Eight typical ice loading events are presented in this paper. These events occurred during the period between March 5 and March 7, 2000 (see Figure 5). Note that tilt values have already been corrected for wind effect. For each event the following properties were analyzed: pier tilt induced by ice loading, pier tilt induced by wind loading, ice speed, ice thickness, ice profile, and the current speed. The summary of these events is shown in Table 2. Even though the instruments for measuring the current velocity and keel depth were located closer to the pier than in the previous year, they were still far enough away to have several minutes difference between ice keel draft and tilt response of the pier. Figure 6 shows the typical profile of an ice ridge keel recorded over 1 minute period. Note that in this case the ice keel draft output was shifted to clear the difference between ice keel draft and tilt response of the pier.

Knowing the speed at which the ice was moving, the keel width could be estimated. In this case the ice velocity is 0.8 m/s so the keel width is about 13 m. Figure 7 represents a typical picture from the video record of ice failing against the bridge piers. Two of the events are described in detail below.
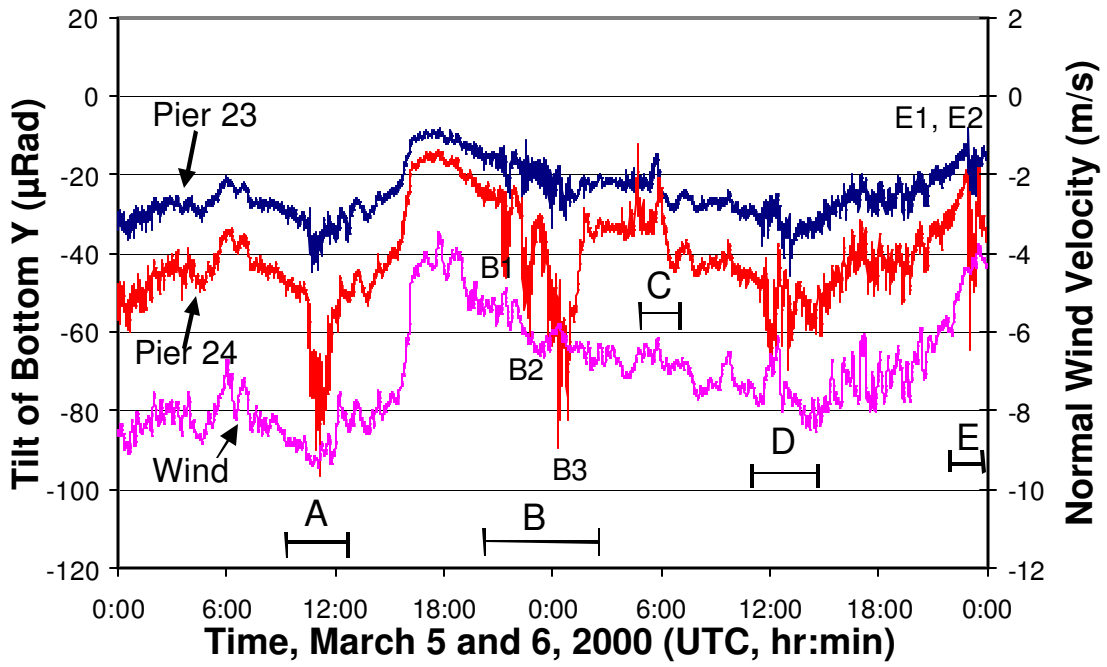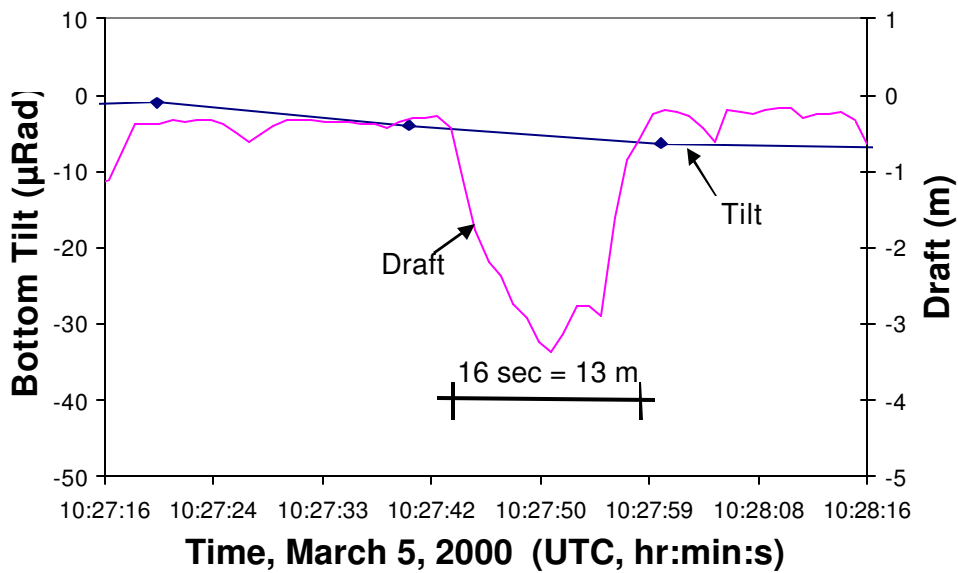
Figure 5 Ice Loading Events

Figure 6 Pier 24 – Tilt at the Bottom of the Pier and Ice Keel Draft over distance 50 m

Table 2 Ice Loading Events Summary

Event	Date	Time UTC	Peak Load (MN) P23	P24	Tilt Direction	Ice Drift Speed (m/s) Northwest	Southeast	Ice Thickness (m) Northwest	Southeast	Video observation
A	March 5	9:36 - 12:00	0.48	0.86	from NW	0.8 slowing slightly	0.8 slowing slightly	open water, then 1-3m	open water, then 1-3m	Ice floes with occasional fog, ice drift slowed by 11:45, stopped after 12:00
B1	March 5	20:53 - 22:05	0.52	0.48	from NW	0.8 slowing	0.8 slowing	2 - 6m with open water	2 - 5m with open water	ice floes
B2	March 5	22:05 - 23:00	0.4	0.66	from NW	0.8 slowing	0.8 slowing	2 - 6m with open water	2 - 5m with open water	ice floes
B3	March 5	0:20 - 0:35	0.44	0.74	from NW	0.8 slowing	0.8 slowing then stopped	2 - 6m with open water	2 - 5m with open water	dark, Ice floes moving towards SE, Ice drift stopped at 1:40,
C	March 6	5:31 - 5:45	0.4	0.28	from SE	0.4 slowing	0.2 stopping	4m then open water	1 - 2m then 1 m (ice stopped)	very dark, ice slowing
D	March 6	11:45 - 12:14	0.2	0.4	from NW	0.6 slowing	0.7 slowing	1 - 3m	1 - 3m	ice slowing, at 12:43 very slow at 13:35 ice stopped; very good view on ice piling up the piers
E1	March 6	22:55	0.64	0.4	from NW	0.8	0.8	1 - 4m continuous	1 - 4m continuous	dark
E2	March 6	23:04	0.52	0.9	from NW	0.8	0.8	1 - 4m continuous	1 - 4m continuous	dark

Figure 7 Ice piling on the bridge piers

Event B2 lasted for 1 hour from 22:05 to 23:00 UTC on March 5th. The peak load recorded at pier P23 was 0.4 MN and at the pier P24 it was 0.66 MN. The ice was moving from the northwest with speed 0.8 m/s. The speed was slowing during the event. The same speed was recorded by the ADCP on the southeast side of the pier also slowing and then coming to a stop at the end of the event. The IPS on the northwest side indicated that there was ice with keel depth 2-6m (ridges) and also open water during the event. The IPS on the southeast side indicated that the maximum keel depth of the ice was up to 2-5m with open water. Since the ice was moving from the northwest, the ice floe properties measured by IPS on the northwest side of the pier represent the ice that hit the pier 2 minutes after the keel draft measurements were taken (based on the speed of ice) and on the southeast side the keel depth of the floe that hit the pier 2 minutes before the tilt measurements were taken. According to video records there were ice floes around the piers moving towards the southeast. The ice drift stopped at 1:40 UTC on March 6.

Event C lasted for 15 minutes from 5:31 to 5:45 UTC on March 6th. The peak load at pier P23 was 0.4 MN and at pier P24 it was 0.28 MN. The ADCP located on the northwest side indicated that the ice was moving from southeast with speed 0.4 m/s and then slowing. The ADCP located on the southeast side of the pier indicated that the ice was moving with speed 0.2m/s at the beginning of the event and then stopped. The IPS on the southeast side indicated that the keel depth of the ice was up to 4 m at the beginning of the event and then changed to open water, the IPS on the northwest side indicated that the keel depth of ice was 1-2 m at the beginning of the event and then 1m. The ice was moving from the southeast during this event. The thickness of the ice floe obtained from the IPS on the northwest side represents the keel depth of the ice 100 m away from the pier. Therefore the keel depth of the floe measured was the keel depth of the floe that hit the pier 4 minutes before that for which the tilts were measured by the tiltmeters at that time. The keel depth obtained from IPS on the southeast side of the bridge represents the keel depth of the ice floe that would hit the pier 8 minutes later. According to

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video records there were ice floes moving towards the northwest with decreasing speed. The visibility, however, was not very good since it was dark.

SUMMARY AND CONCLUSION

During this monitoring program the magnitude of the pier tilt was recorded from January to April 2000. Additional information on wind, ice and current drift, keel depth, and video records were obtained for analyzing the ice loads on the piers. A method was derived to determine foundation stiffness and convert tilt to ice force. Factors for converting measured tilt at the lower level of the pier to ice force are 0.04 MN/µrad and 0.02 MN/µrad for pier P23 and pier P24, respectively. A maximum ice load of 0.9 MN was obtained during a period when ice ridges with keels up to 4 m deep were measured. The results obtained here are not in sufficient detail to make a direct comparison of ice loading and ice feature size. Closer positioning of the IPS at the piers would remove some uncertainty.

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