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RESPONSE OF THE CONFEDERATION BRIDGE TO WIND LOAD AND ITS INFLUENCE ON ESTIMATION OF ICE LOAD

by

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ABSTRACT

The Confederation Bridge, 12.9 km long across the Northumberland Strait, connects Prince Edward Island to New Brunswick in Atlantic Canada. The harsh weather conditions at the bridge site often subject the bridge structures to severe loading, particularly in the winter season of high ice forces, which represent the governing effect of the lateral load design for the bridge piers. To obtain information of ice forces acting on the bridge pier, an ice load monitoring and research programme at Piers 23 and 24 near the navigation span of the bridge has been implemented and has been collecting data since 1999. The objective of this project is to study the ice load and ice-structure interaction characteristics of the circular bridge piers of the Confederation Bridge. The research data and results help to verify the design assumptions of the bridge, lead to more comprehensive understanding of the ice load characteristics of large circular bridge pier member under severe loading environment. From analysis of the ice load monitoring data, factors which affect the ice loads imposed on the bridge piers under a wide range of ice conditions encountered in ice covered regions of oceans in eastern and arctic Canada may be better understood. The information obtained and knowledge gained from this study are not only important for bridge design and construction but also relevant to offshore construction of oil and gas industry.

The procedure for determination of ice forces from the monitoring data is based on back calculation of the ice forces from measured tilt responses of the bridge piers, wind meteorological data and other load condition observation data such as ice thickness, ice speed and sea current speed. Typically, the measured bridge lateral tilt responses are the

combined effects from the ice forces acting on the pier and the wind loads acting on profile of the bridge structures. A key factor in the accurate evaluation of the ice force on the pier is the correct estimation of the wind-induced tilt responses of the bridge pier from the wind conditions (wind speed and wind directions) at the bridge site. The methodology adopted in previous study assumes a linear relationship between the wind-tilt response of the bridge pier and the wind load (i.e., square of the wind velocity) for the entire range of wind speed.

From analysis of the monitoring data for 2000 and 2001, it is found that the wind tilt response exhibits a hysteretic behaviour. The relationship between the wind tilt responses of bridge pier and the wind load is not a linear function. It is dependent on the wind speed range, loading direction (i.e., loading or unloading), and loading history. The error introduced due to the use of a linear relationship results in some inconsistencies in the correlation between the estimated ice tilt and ice drift direction. Some possible sources of the discrepancy and observed nonlinearity in the behaviour of bridge pier related to wind effects are mentioned. An improved procedure for estimation of wind tilt response is proposed based on a non-linear hysteretic relationship with the use of tri-linear conversion factors to improve the accuracy in the estimation of the wind tilt response from measured wind data. The improved methodology leads to consistent and more accurate estimation of ice force at Piers 23 and 24.

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Dedicated to:

My parents and little sister, with affection

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Chapter 1 Introduction

1.1 General introduction

The Confederation Bridge in Northumberland Strait, a 12.91 km long structure, and one of the world's longest continuous bridges crossing marine water, connects Prince Edward Island to New Brunswick in Atlantic Canada. Its design requirements of 100-year service life and a safety index of 4.0 for multiple-load path load effects and 4.25 for single load-path load effects, which are significantly higher than the normal level of 3.5 for typical highway bridge make the developments of its design criteria and guideline for its construction quality control beyond the common bridge design and construction practices covered in Ontario Highway Bridge Design Code (OHBDC-91) or the Canadian Highway Bridge Code (CAN/CSA-S6-2000). The main bridge structure has 45 main spans of 250 m each and 20 approach spans at different height. The typical height of main span is 40.8 m above mean sea level. The bridge superstructure is a haunch single post-tensioned pre-stressed concrete box girder of variable depth from 4.5 m to 14 m (Tadros 1997). The Northumberland Strait, near the latitude of about 45° N, is subject to seasonal ice every year. Each winter season from December to late April, about 3000 km of ice movements driven by strong wind and significant tidal current pass under the bridge. The dynamic ice changing conditions in the strait result in numerous large ice features impact against the bridge piers. The severe weather conditions and lack of information about the magnitude and characteristics of the ice force at the bridge site

presented significant challenges to the designer of the bridge, particularly in the lateral load design of the bridge against ice forces, which is the governing effect for design of bridge piers of the Confederation Bridge.

After completion of the bridge in 1997, an extensive collaborative research project has been carried out jointly by Carleton University, Public Works and Government Services of Canada (PWGSC) and the Strait Crossing Development Ltd. (SCDL) with funding support from the NSERC, PWGSC and SCDL. This monitoring and research programme is currently on-going, with monitoring sensors collecting data mainly in the section of the bridge between Piers 30 to 33. The objectives of monitoring programme are to monitor and study the short and long-term behaviour and performance of the bridge due to ice force, short-and-long-term deformations, temperatures effects, dynamic responses to traffic, wind, ice and earthquake, and corrosion. Details of the programme have been described by Cheung et al. (1997). As part of the overall research programme, ice forces have been investigated at Piers 31 and 32 by Brown (2001) and others in some recent studies.

In 1999, a complementary ice load monitoring programme was initiated and implemented at Piers 23 and 24 next to the navigation span to obtain additional ice force data and information for verification of the design assumptions of the Confederation Bridge and to provide more information on design ice force due to the extreme ice conditions in eastern Canada. The collaborative project is led by the Canadian Hydraulics Centre of National Research Council of Canada (NRC), in collaboration with Bedford Institute of Oceanography (BIO) of Department of Fisheries and Oceans, and Ottawa-Carleton Bridge Research Institute of Carleton University. The objectives of this complementary

programme are to study the ice forces in temperate marine ice environment and development of ice load determination methodology based on the observed ice load and ice-structure interaction characteristics at Piers 23 and 24.

This thesis describes the ice force research using the monitoring data from Piers 23 and 24, with main concern about improvement to the methodology for the determination of the ice force from the monitoring data. Piers 23 and 24 are adjacent to the navigation span on the New Brunswick side. Because of the variation in the depth of the sea floor, the heights and foundation stiffness of the two piers are different. The foundation of Pier 23 is 24.3 m below the water line and the pier top is 38.2 m above the water level. The foundation of Pier 24 is at 26.5 m below the waterline and its top is 32.9 m above the sea level. The foundation of Pier 24 is about 50% softer than that of the Pier 23. The Piers 23 and 24 and the main span box girder form a rigid frame. Detailed descriptions of the bridge and the instrumented section of the structure are presented in later part of this chapter.

The instruments of the monitoring system at Piers 23 and 24 measure the tilt responses of the piers to environmental loads, record the meteorological data (temperature, local wind speed, wind direction) and data about the ice condition and other oceanographic parameters (tidal current velocity, ice drift velocity, and ice thickness) relevant to the determination of ice loads acting on the bridge piers. The processing of the recorded monitoring data as well as the accompanied meteorological, ice and oceanographic data forms the basis of the procedure of determining the ice forces acting on the bridge piers. The data processing procedures and the data analysis results, and results of the estimated ice forces from Year 2000 and Year 2001 are presented in this thesis.

1.2 Background

1.2.1 Description of the structures

The Confederation Bridge, from Cape Jourimain in New Brunswick, crosses the Northumberland Straits to Borden in Prince Edward Island. It provides the only fixed transportation link between Prince Edward Island and the mainland (Fig. 1.1). The bridge was officially opened to traffic on June 1, 1997. The design criteria of the Confederation Bridge are unique and different from the provisions specified in common bridge design codes because of the following requirements:

- The bridge is required to have a service life of 100 years as opposed to the 50 year service life for typical bridges.
- A target safety index of 4.0 for failure modes of multi-load path and 4.25 for failure modes with single load path. Since the load factors in existing bridge codes are calibrated for a safety index of 3.5, the load and resistance factors required for the design of the Confederation Bridge For the design of the bridge must be specially developed and generated through a full calibration process using probability and reliability techniques.
- The design of the Confederation Bridge must avoid the domino effect: the collapse of a single span should not lead to the collapse of other spans.
- The long span length of the main span of 250 m each is beyond the limit of existing bridge design code provisions.

With a total length of 12.91 km, the Confederation Bridge is one of the world's longest bridges over seawater. The bridge consists of 20 approach spans and 45 main spans of

250 m each in length. The typical elevation of bridge deck is 40.8 m above the mean sea level as shown in Fig. 1.2. The main span of the bridge is constructed by connecting a continuous drop-in span between two 192.5 m double cantilever main girder members of variable depth on top of the supporting bridge piers to form a rigid frame unit (Fig. 1.3). The drop-in spans in adjacent spans are simply supported. Thus the main part of the bridge has alternate rigid and simply supported configuration, which facilitate the expansion and contraction of the bridge due to the thermal loading effects and satisfies one of the key design criteria of preventing catastrophic domino progressive failure of the bridge.

The superstructure of the bridge is a single-cell post-tensioned concrete box girder. As shown in Fig. 1.4, the cross-section of the marine span is a trapezoidal box. The total deck width is 12 m. The roadway width is 11 m. The depth of the box girder varies from 14.5 m at the pier support to 4.5 m at mid-span.

Each caisson-founded bridge pier consists of a piers shaft and a pier base. The pier shaft of the bridge is divided into two parts: a hollow shaft and an ice shield at the bottom of the pier shaft, as shown in Fig. 1.5. The cross section of a hollow shaft varies from a rectangular section of 5 m x 10 m at the top of the shaft to an 8 m octagonal section at the top of the ice shield. The shaft thickness is 600 mm. The conical-shaped ice shield with a 52° inclination at the water level is designed to cause moving ice ridges ride up the sides of the ice shield and crack, break up under the ice weight, thus minimizing the ice force acting on the pier.

A pier shafts is placed on top of a pier base. Difference pier bases have different heights (Fig. 1.6) because of variation of depth water in the strait. Two typical types of footing

ring as shown in Fig. 1.7 are used for the pier bases. For pier bases of depth up to 27 m, circular footing rings of 22 m outside diameter and 14 m inside diameter are used. Oval-shaped rings of dimensions 28 m by 22 m are used in the pier bases of water depth greater than 27 m and up to 35 m.

More details of the structures have been described by Tadros (1997).

1.2.2 Site conditions

Severe environmental conditions at the bridge site present significant challenges for the design and construction of the bridge, especially of the wind and ice conditions. The Northumberland Strait, at latitude of 45° North, is ice-covered in winter. The ice cover in the Strait is described as first-year pack ice, consisting of discrete floes and ridged ice. The formation of ice initially starts in late December along the shore, consolidating into ice floes. Ice cover condition in the Strait normally lasts until April, sometimes until May in an extreme season. The most severe period is from mid-February until March. In severe conditions, ice floes can reach up to 3-4 km in size and the embedded ice keel depth is up to 16 m (Brown et al. 2001). The ice cover in the strait is a dynamic feature influenced by the actions of wind and tidal current. About 1000 km of ice feature movements pass under the bridge each month in a typical ice season. This dynamic nature of the ice environment at the bridge site presented challenges in its ice force design, which is the governing effect for the bridge piers of the bridge. The un-factored ice force used for design of each pier is 16 MN, according to MacGregor et al. (1997). From analysis of meteorological data and model testing carried out at the Boundary Layer Tunnel Laboratory in London, Ontario, the 100-year return period 10-minute mean wind speed at the bridge site is estimated as 29.5 m/s at 10 m above the mean sea level in

open water. The corresponding component perpendicular to the bridge is estimated to be 26.4 m/s for a 100-year return period. Adjusting to the height of the bridge deck at the typical height of 40.8 m and 60.3 m at the navigation span, the corresponding 10-minute mean wind speeds are 34.1 m/s and 35.4 m/s, respectively with the normal components of 30.5 m/s and 31.7 m/s. The strong wind at the bridge site produces an equivalent lateral static force of 8 MN on a typical pier.

The tidal current velocity can reach up to 2.0 m/s, but it is observed to be usually less than 1 m/s. The wave height is 4 m maximum in the strait.

1.3 Objectives and Scope

The objectives of the research presented herein are to develop an improved method for estimation of ice force acting on a bridge pier from the monitoring data, and to estimate the 100-year ice force of the Confederation Bridge. The ice-load measurements are compiled and analyzed to provide information for verification of the bridge design assumptions. The knowledge gained in this study contribute to a more comprehensive understanding of the characteristics of ice loads important for circular bridge pier design, and the factors which affect ice loads for the wide range of ice conditions encountered in Canada's important frontier regions.

The key factors affecting the calculation of ice force is the estimation of the wind tilt response of bridge pier from measured wind velocity. In the determination of wind-induced-tilt response, current analysis assumes a linear relationship between the wind-tilt response of the bridge pier and the square of wind velocity, using a constant conversion factor for wind induced tilt estimation for the entire range of wind speed. This

assumption results in some inconsistencies between the ice tilt and ice drift direction, such as the analysis result of the bridge pier tilting back against the wind direction. This inconsistent behaviour has been observed in the analysis results of the Year 1999 data and again in Year 2000 data.

A new procedure of predicting the wind tilt response from wind conditions at the bridge site considering the loading direction and load history is developed, using tri-linear conversion factors at different ranges of wind speed: less than 6 m/s, 6-10 m/s and above 10 m/s. The study is a part of the ice force monitoring and research programme at Piers 23 and 24. Information obtained on the behaviour of the structures due to the considered environmental effects is also applicable to behaviour at other piers. The proposed method to estimate the wind tilt response from wind data has been incorporated in a MATLAB computer program for analysis.

This thesis is organized into six chapters as follows:

Chapter 1 presents the introduction of the research, background and the objectives and the scope of the thesis.

Chapter 2 presents a review of previous studies relevant to the study of ice load project of the Confederation Bridge.

Chapter 3 describes the instrumentation system of the monitoring program, as well as review of the previous work about ice force project at Piers 23 and 24 of the Confederation Bridge.

Chapter 4 presents the analysis procedures and analysis results of the year 2000 monitoring data, and some conclusions drawn from analysis.

Chapter 5 presents analysis of year 2001 data and the behaviour of bridge piers to wind load by the improved analysis methodology considering the nonlinear wind response behaviour of the bridge piers.

Chapter 6 summarizes the results and conclusions obtained in this study and provides recommendations for future work.

Figure 1-1 Location of the Confederation Bridge

Figure 1-2 The Confederation Bridge Profile

Figure 1-3 Drop-in spans of the Bridge

Figure 1-4 Box girders with variation of the height at different sections

Figure 1-5 Cross section of the bridge pier

Figure 1-6 Foundation Depth Profile of the Bridge

Figure 1-7 Foundation components of the Bridge

Chapter 2 Review of previous works

2.1 General

The effect of ice load on structures from ice feature movements and the associated ice-structure interaction mechanisms is a relative new area of research. Starting in 1960s, research programmes have been carried out in this area on light bridge piers in lakes by Frederking et al. (1991) and rivers by Haynes et al. (1991). Since 1980s, the Arctic has become an area of active research, particular on the problem of the actions of ice forces on structures, as applied to offshore drilling platforms used in petroleum exploration (Wright et al. 1986). Despite these previous research efforts, information available on ice forces acting on medium size structures like bridge piers are much less, particularly in extreme marine dynamic ice environment.

As stated earlier in Chapter 1, main concerns of the current study are to estimate the ice forces at Piers 23 and 24 of the Confederation Bridge. Considerable research has been carried out on the design ice load and ice-structure interaction mechanism of conical structures for the design of the bridge before its construction. After completion, the bridge is an ideal site for further research, not only for the verification of the design assumptions adopted for its design, but also to obtain information for further improvements to the analysis and design methodologies employed in many aspects of its design and contribution. In 1997, a large scale monitoring research programme was implemented, which includes a component to measure the ice forces at Piers 31 and 32.

In this chapter, some of the previous works reported in the literature related to research on ice forces of bridges are briefly reviewed.

2.2 Studies of ice forces on structures

Brown et al. (1996) studied an approach for determination of the ice loads resulting from ice features in the Northumberland Strait. The paper discusses the characteristics of ice features and the interaction mechanism with the piers of the bridge, the ice and environmental parameters for the determination of ice force and the uncertainties in the estimation of ice load spectrum. The study shows that the ice in the Strait is first year ice pack and the highest ice forces are resulted from partially consolidated ice ridges acting against the bridge piers. The ice forces developed from such encounters have two components: the first component comes from consolidated layer and the second from the rubble pile acting on the pier.

Frederking et al. (1991) have studied the ice forces on 5 light piers of different geometry in the St. Lawrence Seaway System. The study shows there is no significant difference in reduction of ice force acting on 45° conical piers. On the distribution of ice force, after comparison studies using different distribution models of normal, lognormal and Weibull distributions, it is found that lognormal distributions best describes the distribution of maximum peak of ice force.

Langohr and Ghali (1997) have investigated the dynamics loading effects of the ice force on the Confederation Bridge. The study shows that it is not the impact from fast moving ice ridge on the pier that is dominant effect, but it is the brittle failure of the ice floes, driven by the strong wind and current, in interaction with the piers that produces the

maximum ice force and its fluctuation of the bridge piers. Using two analysis models in their study of the ice forces on the piers of the Confederation Bridge, they conclude that the dynamic effects of ice force on the piers are reduced significantly by the conical ice shield because of its shape. And the amplification factor resulting from the dynamic effect of fluctuation of the ice force does not exceed 5%.

2.3 Ice force measurement at Piers 31 and 32 of the Confederation Bridge

The ice force monitoring project implemented at Piers 31 and 32 is part of joint university-government-industry monitoring and research project on the behaviour and performance of the Confederation Bridge started in 1997. The overall project is financially supported by NSERC and PSWGC. Additional information of the bridge has been provided by the bridge developer, Strait Crossing Development Inc. (Cheung et al. 1997). Piers 31 and 32 are closer to the New Brunswick end of the Bridge, about 2.5 km from the navigation span. The ice monitoring programme at Piers 31 and 32 focuses on ice force measurement, observation of ice failure modes and measurement of the dynamic response of the bridge due to ice force using an array of sensors, data loggers, and observation system (Bruce and Brown 2001). The instrumentation used includes three main components:

- Indirect measurement system of the ice force: tiltmeters, wind sensors, accelerometers.
- Direct measurement of the local ice pressure on the conical ice shield by ice pressure panels.

- Observation system to record the ice interaction kinematics and ice conditions.

2.3.1 Instrumentation system

Piers 31 and 32 and the bridge span superstructure form a rigid frame unit of the bridge. The ice force monitoring instrumentation systems installed on Piers 31 and 32 are identical, except the conical ice shield of Pier 31 has ice load panels, as shown in Fig. 2.1.

Currently, there is no technology available to directly measure the total ice load acting on the bridge piers. The global ice force is only determined indirectly by measuring the structural response of the bridge pier and then the ice load causing this response is back calculated through analysis. At each instrumented pier, three Applied Geomechanics Model biaxial tiltmeters have been installed at three different locations as shown in Fig. 2.1. These tiltmeters measure the tilts separately in the lateral and longitudinal directions. The recorded tilt responses are the 17-second averages of 500 readings taken at 0.034 second interval.

To measure the local ice pressure and ice load distribution, ice load panels of a total area of 56 m² (40 m² on the conical ice shield and 16 m² on the pier barrel below the ice shield) have been installed on Pier 31 (Fig. 2.2). These panels are thin-doubled walled “IDEAL” panels with embedded strain-gauged load sensors. An applied load over the area of 0.25 m² can be measured by these panels. The ice load panel can measure load up to 15 m deep below the mean sea level.

The ice condition observation system includes four time-lapse video cameras and two underwater sonars. Three of the four cameras are placed under the bridge deck to monitor the ice interaction with the piers and the remaining camera is used to record the ice conditions at the site, as shown in Fig. 2.3. Two upward-looking underwater sonars are

mounted on the seabed. One is located 40m to the west of Pier 31. The sonars measure the ice keel depth of ice features interacting with the bridge piers.

Wind data are collected by wind sensors installed in the instrumented span of the bridge. Wind speed and wind direction are collected under the normal operation mode at 17-second interval. When an extreme event occurs which triggers the monitoring system, wind data are recorded at the sampling frequency of 1 Hz.

In addition to the ice force instrumentation, data collected from other parts of the monitoring project such as vibration response data recorded by accelerometers, extensometers, and the temperature distributions in bridge structural members are measured by thermocouples' are also used in this research to provide additional information for assessment of the ice force behaviour.

The ice force monitored data are collected by an on-site low-speed data logger system, which are then transferred back to the shore by a fibre-optics network and distributed to the researcher at OCBRI at Carleton University and University of Calgary for further study and analysis.

2.3.2 Data analysis and Ice Force determination

Since previous studies (Brown 2001) have shown that the effects of the tidal current, temperature and traffic on the determination of ice force on the bridge pier are negligible, it is assumed in present study that the measured tilt response of the pier is the result of ice load and wind force on the bridge. The basis steps in procedures for determining the ice force include:

- Baseline correction of the recorded data for evaluation of bridge pier tilt response;

- Estimation of wind induced tilt and ice tilt;
- Estimation of ice load from ice tilt;

A critical step in the procedures, which can affect the accuracy in the ice force estimation, is the evaluation of the wind induced effect in the tilt response of the bridge pier (i.e. wind induced tilt). The ice tilt is determined by subtracting the calculated wind induced tilt response from the recorded total tilt measurement. The ice load is then subsequently evaluated from the ice tilt by a transfer relationship between the ice tilt at the tiltmeter sensor location and the ice load at the ice shield.

2.3.2.1 *Estimation of wind tilt*

For the wind design of the Confederation Bridge, the bridge designer used a transfer relationship for the tilt response at the lower tiltmeter location near water level at Pier 31 from the measured wind velocity at the site based on results of finite element models and wind tunnel tests:

$$T_w = 0.39 V_w^2 \quad (2.1)$$

where V_w is the average normal wind velocity (component perpendicular to the axis of the bridge) in m/s. The tilt response is expressed in units of μrad (10^{-6} radian). Using the transfer relationship given in Eq. 2.1, the effect of the wind induced tilt has been found to be over-estimated, resulting in the inconsistent observation of the pier tilting back against the wind (Brown 2001).

From the analysis of 1998 and 1999 data, Brown (2001) has proposed a correction for the evaluation of the lower tilt at Pier 31 as follow:

$$T_w = 0.19 V_w^2 \quad (2.2)$$

The revised conversion factor of 0.19 derived from the analysis of the events selected with the absence of ice in the strait. More details of the analysis procedures can be found in the references by Brown (2001) and Bruce et al. (2001). Applying the same data analysis procedures, the corresponding conversion factor for Pier 32 is 0.16.

In the analysis of 2001 data at Piers 31 and 32, it is found that the previous conversion factors for estimation of the wind tilt response of the bridge piers derived from data of previous years are not applicable and need to be revised. Instead of using the previous conversion factors, Bruce and Brown (2001) used different conversion factors for wind acting in different directions, whether from northwest to southeast or southeast to northwest direction as follows:

$$T_w = 0.30V_w^2 \text{ (wind from northwest side of the bridge)} \quad (2.3)$$

$$T_w = 0.255V_w^2 \text{ (wind from southeast side of the bridge)} \quad (2.4)$$

In these earlier studies, the transfer relationships given in Eqs. 2.1-2.4 used for estimation of the wind tilt from wind velocity are assumed to be for all wind speed and remain constant throughout the season. The significant difference in the conversion factors as determined from data and analysis of different events of the bridge piers lead to questions regarding the effects and influences of other environmental factors on the wind tilt response of the bridge pier.

2.3.2.2 *Estimation of ice load*

The tilt due to ice force acting on the bridge pier is calculated by removing the wind tilt response from the total response. The ice force at the ice shield level is then back calculated from the estimated ice tilt using developed transfer relationship. In order to get the transfer function that relates the ice tilt to applied ice force, studies and calibration of

the pier flexibility have been conducted. A finite element model (FEM) of the rigid frame consisting of Piers 31 and 32 have been developed for this purpose. In addition, full-scale pull tests of Pier 31 after completion of the bridge before opening to traffic with assistance by the Canadian Coast Guard vessel in applying a lateral load at Pier 31 have been conducted (Bruce and Brown 2001). By comparing the FEM and the recorded pull test results, a linear transfer function for the conversion of ice tilt (T_w) in μrad to ice force (F_{ice}) in MN is derived as follows:

$$F_{\text{ice}} = 0.3T_w \quad (2.5)$$

More details of the derivation of the transfer function for the ice force have been discussed by Bruce and Brown (2001).

Figure 2-1 Location of Instrumentation of Piers 31 and 32

Figure 2-2 Ice shield panels at Pier 31

Figure 2-3 Location and arrangement of cameras

Chapter 3 Ice Force Monitoring at Piers 23&24

3.1 General Description

Since January 1999, an ice force measurement project has been implemented at Piers 23 and 24 of the Confederation Bridge, to provide additional information and observation results on ice load behaviour of the bridge from those collected at Piers 31 and 32. The research programme is led by the Canadian Hydraulics Centre of NRC in collaboration with the Bedford Institute of Oceanography and Public Works and Government Service of Canada, and Carleton University. The two instrumented piers are adjacent to the navigation span, as shown in Fig. 3.1. They are selected for additional measurement of ice load because they have a different height and foundation stiffness from those of the typical piers at Piers 31 and 32. The foundation of Pier 23 is 24.34 m below the water level and the top of the pier at the bottom of the girder is 38.2 m above the mean sea level (MSL). For Pier 24, the foundation is 26.5 m below the waterline and the top of the pier is 32.9 m above the water. The foundation of Pier 24 is a circular ring of 22 m in diameter with stiffness about 50% softer than that of the oval ring at Pier 23. The objectives of the research programme at Piers 23 and 24 are:

- To obtain information on the magnitude, frequency and distribution of ice pressure and ice force, which can be used to validate the ice force design of the structure.
- To obtain observation data on the ice conditions for winter navigation in the strait and information on ice-structure interaction mechanisms of the ice features with bridge piers and relevant the knowledge of ice mechanisms in Eastern and Arctic oceans of Canada.

The installed system to collect data consists of tiltmeters to record the structural responses of measured piers, Acoustic Doppler Current Profiler (ADCP) for measuring current and ice speed, Ice Profiling Sonar for ice thickness, and the weather station for meteorological data.

3.2 Instrumentation system and data acquisition

To measure the tilt responses of the bridge piers and collect relevant environmental data, a reliable, simple, battery-powered system has been installed at Piers 23 and 24 and at adjacent locations as described in this section.

3.2.1 Tiltmeters and tilt responses

The structural response of the bridge pier to loading is measured by the changes of tilt in the lateral and longitudinal direction at two levels of the pier. In each of Piers 23 and 24, two biaxial tiltmeters have been deployed inside the pier on the northwest upstream side of the bridge. One tiltmeter is placed at the bottom of the pier behind the ice-shield 3.2 m above the water level, and the other set of tiltmeter is installed at the top of the pier before the match cast, as shown in Fig. 3.2. Similar to the tiltmeters installed at Piers 31

and 32, the tiltmeter model of Applied Geomechanics 700-Series (Fig. 3.3) is chosen for its high-sensitivity, durability and reliability. The operational range of the tiltmeters is from -30°C to $+70^{\circ}\text{C}$. The tiltmeters have a resolution of $0.1\ \mu\text{rad}$ and a full range scale of $\pm 7500\ \mu\text{rad}$.

The X-axis tilt, Y-axis tilt and the temperature of the tiltmeter sensor and the instrument battery voltage are recorded with time stamp in Universal Time Coordinate (UTC) format, previously known as Greenwich Mean Time (GMT). The local Atlantic Standard Time (AST) at the bridge site is 4 hour behind the UTC. The X-axis tilt taken as the longitudinal direction of the bridge is primarily related to the loading induced by vehicle traffic, thermal expansion or contraction behaviour of the span. The Y-tilt, which is perpendicular to the longitudinal axis of the bridge, is assumed directly related to responses of the bridge to the influences and loading by various lateral load effects such as those resulting from sea current, ice and wind.

In the analysis and discussion of the bridge tilt response, a sign convention for the presentation of the tilt response is adopted as follows:

Tilting in X-axis occurs on the vertical longitudinal plane of the bridge, whereas tilting in the Y- axis occurs on the transverse vertical plane of the bridge. Positive lateral loads from ice or wind are defined in the positive Y-direction, as shown in Fig. 3.4. Correspondingly, a positive tilt response implies bending of the bridge pier in the positive Y-direction, i.e. from southeast to northwest direction. This sign convention implies that ice impact of negative direction from northwest side of the bridge should lead to a negative tilt response or decrease in Y-tilt.

The data acquisition system consists of Campbell Scientific CR10 low-speed dataloggers and two SM716 storage modules for logging, digitizing and storage of the output signals from the tiltmeters at each pier. The tilt response of the pier is measured at 1Hz sampling frequency. But due to the limited capacity of the storage modules, it is programmed that an average value of the recorded tilt is calculated and recorded every 20-seconds. The temperature and the battery voltage are stored every 3 hours. The readings are stored in storage modules on-site and are retrieved for data evaluation and analysis.

A detailed description of the instrumentation and installation of the tiltmeters has been described by Kubat et al. (2000).

3.2.2 Acoustic Doppler and Current Profiler and Ice Profiling Sonar

The information of the ice conditions in the Northumberland Strait used in this study are provided by BIO of the Department of Fisheries and Oceans. The ice thickness, the current velocity and ice drift velocity are measured by the monitoring instrument of Ice Profiling Sonar (IPS) and Acoustic Doppler Current Profiler (ADCP), respectively, as described earlier. The location of ISP and ADCP were adjusted for better capturing the ice conditions of the bridge piers. In 1999, the IPS and ADCP were deployed 200m and 400m from Pier 23, respectively. Also, helicopter surveys of the ice conditions in the Strait were made. In 2000, the IPS and ADCP were relocated to Pier 24 and moved closer to this pier as shown in Fig. 3.4. The new locations of IPS and ADCP instruments at Pier 24 were selected because it was determined that the softer foundation stiffness of the Pier 24 compared to that of Pier 23 would result in a greater resolution of the tilt response data, or in other word a greater sensitivity of the pier tilt response to applied lateral loads. Consequently, higher responses of Pier 24 to loads induced by wind and ice are expected.

The details on the installation of the IPS and ADCP instrumentation have been described by Belliveau et al. (2001) and Kubat et al. (2000).

The ice drift speed and current speed data measured by ADCP instruments were obtained from BIO. The data were recorded at the interval of 15 minutes (900 seconds). In the analysis of data, the time interval was adjusted to take into account the time delay due to the drift distance between the ADCP instrument and the pier of 100 m, according to Belliveau et al. (2001). The original data of current and ice speed measured consists of two components in the directions from north to south and from east to west. Similar procedure has been applied in the processing of the ice speed and current speed, erroneous data have been eliminated by regression from the wind speed and current speed data. The component of the current and ice speed for the directions from northwest to southeast (normal to the longitudinal axis of the bridge) and northeast to southwest (parallel to the bridge) are estimated. The sign convention of the ice speed and current speed is that the positive velocity indicates that the movement of ice (or current) is from southeast to northwest, and vice versa.

The ice thickness data are measured by Ice Profiling Sonar at the sampling rate of 1Hz.

3.2.3 *Wind sensor*

Wind sensors at the bridge site are installed above the light pole of the bridge, about 11m from the bridge deck, which provides the meteorological data required for the projects.

There are two sources of wind data available at the bridge site, measured at two separate locations. Wind sensors are installed at the navigation span of the bridge to measure the wind speed and wind direction at the sampling rate of 1Hz, and these data are record at 10-minutes interval. Another source of wind data is located at mid-span between Pier 31

and Pier 32, measured by the wind sensor belonging to the overall monitoring project. Both sets of wind data are used in this study. The locations of Piers 31 and 32 are about 1.75 km from Pier 24. At this location, 17-second average data are recorded from measurements taken at the sampling rate of 30 Hz. Since the bridge site in the Strait can be considered as an open field, the wind speed and wind direction at Piers 23 and 24 can be considered approximately the same as those at Piers 31 and 32. From analysis of the wind data, it is found that the wind data from the two measurement locations correlate well with each other. Both sets of wind data are used in the present study for correction and repair of erroneous measurements. Wind speed is considered positive when acting from northwest to southeast of the bridge pier.

3.2.4 Videos

Video records of the ice conditions at the bridge site are also obtained from traffic camera. The Confederation Bridge Control Centre uses a number of video cameras to monitor the traffic conditions on the bridge. The signal from the camera above Piers 23 and 24 was recorded on a time-lapse video recorder. The videos are useful to determine the presence of ice, its direction and speed of drift, and any occurrence of jamming and ice failure behaviour on the piers. The video records are stored in videotapes with date and time stamp for later analysis and reference (Fig. 3.5).

3.3 Data analysis at Piers 23&24

Using recorded data from Year 1999 and some sample data of the Year 2000, Kubat et al. (2000) and Kubat and Frederking (2001) have developed a methodology and procedures

for the correction of wind effect and calibration of the flexibility of the piers to establish the transfer relationship between the ice tilt and ice load at Piers 23 and 24.

3.3.1 *Estimation of wind tilt response*

The wind tilt effect, by following procedures similar to those developed for Piers 31 and 32, based on analysis of events with no ice acting on the bridge piers, are evaluated to obtain wind induced tilt response from measured wind velocity. As the effects from traffic, temperature, sea current and waves on ice load are negligible, the tilt response of the bridge piers at event of ice absence is assumed entirely due to the wind effect alone.

Since the drag force assumed to be proportional to wind velocity squared, the force due to wind in transverse direction is taken as proportional to the component of the wind speed normal to the bridge as follows:

$$F_w \sim V_w^2$$

Since the tilt response is assumed to be proportional to the load applied, the wind tilt response of bridge pier can be expressed as a function of square of wind velocity. When the measured wind tilt response is plotted against the smoothed normal wind velocity squared for the period of no ice starting at 12:00 (UTC) on April 24, 1999, a linear trend of relationship between the wind tilt and square of wind velocity has been observed. Applying regression technique yields the constant conversion factor for the relationship between wind velocity and wind tilt as follows:

$$T_w = CV_w^2 \quad (3.1)$$

The factor for the wind tilt at the lower sensor level of Pier 23 is 0.19 and the corresponding factor for Pier 24, at the level near the water line, is 0.3, where the tilt is in μrad and the wind velocity in m/s. These factors are used to determine the effect of wind

for the year 1999 data and some events of the year 2000. Details of the derivation of these factors can be found in the reference by Kubat et al. (2000).

3.3.2 *Estimation of ice load from ice tilt*

In Pier 31, calibration of the pier flexibility has been carried out using the pull test results to find the transfer function for the transfer relationship between ice tilt and ice force. At Piers 23 and 24, an alternative approach has been derived by Kubat and Frederking (2001) to calibrate the flexibility of the piers based on analysis of response data from no-ice events.

In the analysis procedures developed here, a single resultant wind force acting on the bridge pier is the summation of the forces acting on the profiles of the bridge superstructure and pier surface normal to the wind direction. Because of the circular shape of the pier, the wind force acting on the pier is negligible compared to the large area of the girder in resistance to the wind action (Fig. 3.6).

Generally, a wind drag force can be calculated by the following expression:

$$F_w = A C_D r_a V_w^2/2 \quad (3.2)$$

A: Area of cross section=2340 m²

C_D: Drag coefficient =1

r_a: Air density =1.3 kg/m³

V_w: normal wind velocity m/s

The wind drag force is assumed to acts at the centroid of the girder area, 9.3 m above the top of the pier (Fig. 3.6). It causes the pier to lean. The tilting of the pier is a function of the applied force and the stiffness of the pier.

In a first order approximation, it is assumed that the tilt at the lower tiltmeter level is related to the moment at the pier base as follows:

$$T_{\text{lower}} = kM \quad (3.3)$$

For an event of only wind load acting on the bridge pier:

$$M(\text{wind}) = LF_w \quad (3.4)$$

where L is the distance from the pier base to the point where the wind load is applied (i.e. centroid of the girder area) as shown in Fig. 3.7, and F_w is the wind drag force.

From Eqs. 3.3-3.4:

$$k = \frac{T_{\text{lower}}(\text{wind})}{LF_w} \quad (3.5)$$

From analysis of events when the lateral load comes from wind only, the calibration factor k can be obtained.

From analysis of events identified with only ice load acting on the bridge pier and minimal wind effect when the wind condition at the bridge site is calm, the transfer relationship for ice tilt and ice load can be written as follows:

$$M(\text{ice}) = aF_i \quad (3.6)$$

where a is the distance from pier base to the point of the ice load F_i , as shown in Fig. 3.7.

Comparing Eq. 3.3 and Eq. 3.6, the flexibility of the pier for obtaining ice load from ice tilt response is derived:

$$F_i = \frac{T_{\text{lower}}(\text{ice})}{ka} \quad (3.7)$$

Using the wind loading event on March 16, 2000, factors for transferring the measured ice tilt at the lower sensor level to ice force have been determined by Kubat and Frederking (2001):

Pier	Tilt _{wind} (μ rad)	a (m)	L (m)	k, (μ rad/MNm)	1/k a, (MN/ μ rad)
23	16	24.3	73.4	1.0	0.04
24	30	26.5	70.4	1.9	0.02

Table 3-1 Calibration factors for converting ice induced pier tilt to ice force

3.3.3 Observations of pier tilting against wind

Theoretically, the sign (positive or negative) ice tilt indicates the ice drift direction (or direction of ice impact). From the analysis of 1999 data, it has been observed there are some inconsistencies in the relationship between the ice direction and estimated ice tilt. Because of these inconsistent results and behaviour, there is a great need to understand the source of this behaviour, and to develop improved data processing and analysis methodologies for more accurate estimation of ice force imposed on the bridge. This is discussed in more details in the analysis of Year 2000 data in the next chapter.

Figure 3-1 Locations of the Piers 23 and 24

Figure 3-2 Cross section of the piers and locations of tiltmeters

Figure 3-3 Applied Geomechanics tiltmeter and adjusting plate assembly

Figure 3-4 Location of Ice Profiling Sonar and Acoustic Doppler Current Profiler

Figure 3-5 Ice crushing the bridge pier

Figure 3-6 Girder cross section

Figure 3-7 Moment at the pier base and wind (or ice) effect

Chapter 4 Analysis of monitoring data -Year 2000

4.1 Description of the 2000 ice season

The monitoring programme at Piers 23 and 24 has been collecting data every winter season since 1999. The Year 2000 ice season was a mild year in comparison to the 1999 season. The ice started developing in late January. The most severe ice condition occurred in late February and early March. In the middle of March, from 10 to 16 March, there was little ice. From March 31, only minimal ice still remained in the strait and thus they presented negligible ice loads on the bridge piers (Bruce et al. 2001 and Belliveau et al. 2001).

In the Year 2000 season, the maximum recorded ice keel depth at sampling frequency 1Hz is 14.56 m. But in 80% of the events, the ice keel depth was less than 2 m. The number of events having ice draft more than 10 m was 249 (0.0064%). The most severe ice-accumulating period was from mid-February to mid-March.

The sea current is main parameter, which drives the ice features in the strait. Thus the sea current has a potentially significant influence on the ice speed and thus consequently also on the direction and magnitude of ice load on the bridge piers. The tidal current reverses its direction 4 times in a day. During the Year 2000 season, the maximum recorded

current speed normal to the bridge, from January 26 to April 22, 2000, was 133 cm/s, but most of the time it was less than 1m/s (0 to 75 cm/s).

The ice speed is influenced by wind speed and current speed, but in general more significantly affected by the current speed. The ice movement reverses its direction 4 times in a day, almost the same as that of the tidal current. The maximum ice speed from the recorded data is 94.05 cm/s for the current in the northwest to southeast direction or vice versa. The number of events with ice speed exceeding 50 cm/s is 1672, about 20% of all the recorded events. Generally, the ice drift is in the same direction as the current. At the time of reversal of the tide, when the current speed is very small and almost zero, the ice drift is then governed mainly by the wind. From the monitoring video, some of the events of this condition can be identified quite clearly.

The Year 2000 ice load monitoring season, from January 28 to March 31, 2000, did not produce significant information on severe ice load. This year, the conversion factors derived from previous year for converting from ice tilt to ice force are still used: 0.04 and 0.02 for Piers 23 and 24, respectively. In the analysis of the bridge pier tilt response data, a single constant factor has been used for the whole range of the normal wind speed: 0.1681 for Pier 23 and 0.3176 for Pier 24. The analysis of the entire season data has identified 90,972 and 47,941 events in excess of 0.5 MN at Pier 23 and Pier 24, respectively. The number of ice load events exceeding 1 MN at Pier 23 and at Pier 24 is 18,463 and 1871, respectively. For ice load greater than 2 MN, there are only 159 events (0.03%), which occurred on Feb 7, March 18 at Pier 23 and on February 7, February 18 and March 11 at Pier 24. The maximum average ice load estimated is 2.75 MN at 12:19:25 on February 18. Since the analyzed data are only the 20-second average values

of the recorded data, the estimated ice load is therefore only the average value, which in comparison may have a deviation of up to about 20 μ rad tilt response of Pier 23 (which equivalent to 0.8 MN) from the instantaneous peak ice load value. The wind tilts of some events may have been overestimated, resulting some errors in the estimates of the ice drift direction and the ice tilt of the piers.

4.2 Instrumentation system and data acquired of the year 2000

The installed instrumentation system for ice load monitoring has been described in previous chapter of the thesis in the discussion of the analysis of Year 1999 data. Here, only changes from previous year are described. The ADCP and ISP were relocated from Pier 23 in 1999 to Pier 24 in 2000, and were deployed closer to the pier (100 m away from Pier 24). For the Year 2000, the video record of the ice conditions of the bridge piers from 14:21, February 2000 to April 4, 2000 was obtained. Unfortunately, the camera at Pier 23 can not captured the ice conditions right at site of Piers 23 and 24, but only those of the adjacent piers.

4.2.1 Tilt responses and temperatures

The records of the tilt responses and sensor temperature from the tiltmeters are measured in voltage readings. These voltage readings are converted to the tilt response and temperature in engineering unit by conversion factors provided by the sensor manufacturer. The data then are stored in separate data files, labeled by the Julian day of the time when data are collected. Fig. 4.1 and Fig. 4.2 show examples of tilt response measured at the lower and upper sensor locations at Piers 23 and 24. The temperature, which has negligible effect on ice load calibration and measurement, is stored in separate

files from the responses of the piers. In Year 2000, the tilt and temperature data were collected from January 28 to April 17, 2000. The recorded temperature data of the season are plotted in Fig. 4.3.

4.2.2 Wind data

The wind data at the bridge site from January 1 to early May 2000 were obtained and analyzed in conjunction with the ice condition data. Wind sensors are installed at the navigation span of the bridge to measure the wind speed and wind direction at 10-minutes interval. But due to the malfunction of this wind sensor in some days during the ice season of the Year 2000, the wind data measured at navigation span were not used in the data analysis of this study.

More reliable wind data at Pier 31 and Pier 32 measured by the overall monitoring project are used in the analysis. From analysis of the wind data, it is found that the responses of the Piers 23 and 24 are consistent in general with the wind data measured at Piers 31 and 32. However, it is noted that the wind speeds at mid-span between Piers 31 and 32 (51.8 m above mean sea level) have to be corrected in order to obtain wind speed at the navigation span at a height of 71.3 m from the water line.

The wind data at Piers 31 and 32, which are extracted from the daily data files, are recorded in 17-second intervals for the entire year. From analysis of the video records and the instrument data, it is confirmed that, the ice condition after March 31, 2000 is negligible. The analysis of the ice condition and wind data is thus carried out up to March 31, 2000. From the average wind speed and wind direction data, the components of wind velocity perpendicular to the longitudinal axis of the bridge are evaluated. In the processing of the ice load monitoring data, in order to correlate with the tilt response

data, the wind data are re-sampled into 20-second interval. A MATLAB computer program has been written for this procedure based on linear interpolation of the data. Fig. 4.4 presents the wind speed and its normal component recorded on February 19, 2000.

During some events, the wind speed and wind direction data measured at Piers 31 and 32 have very high spike values (up to 52 m/s), which are considered not correct. To correct this problem, the erroneous values in the wind speed and wind direction data are eliminated and replaced by interpolated values from the adjacent wind speed and wind direction data points. A comparison between the original wind data and the corrected wind data by linear interpolation is presented in Fig. 4.5.

The normal component of the wind velocity at the bridge site is mostly found between -10 to 10 m/s, as shown in Fig. 4.6 (the positive wind speed indicates the wind is from northwest to southeast direction, and vice versa). The number of events of wind velocity greater than 15 m/s accounts for about 3.4% of the total number of recorded events.

4.2.3 Ice speed and current speed:

The ice speed and current speed are recorded at 15-minute (900 second) time interval. Similar to the processing of the wind data, the ice speed and current speed data are re-sampled into 20-second interval data by a MATLAB computer programme. The variation of the current and ice velocity from northwest to southeast on Julian Day 57 (February 26, 2000) is shown in Fig. 4.7. The distributions of the current speed and ice speed in the direction perpendicular to the bridge are shown in Fig. 4.8 and Fig. 4.9. In the analysis of the ice speed and current speed data here, the positive sign convention is taken from southeast to northwest.

4.2.4 *Ice keel thickness*

Ice draft information is obtained from BIO. For Year 2000, the data are available from 18:00:00 (UTC) January 26, 2000 to 00:01:44 March 12, 2000, after that the ice conditions is not significant. There are some erroneous values in the raw data from quality check of the data showing negative or large spike values of ice thickness. The data are corrected by applying a small baseline shift of 0.1 m to account for the fluctuation in the ice keel thickness measurement due to the sea waves. After the application of ice thickness baseline correction, all negative ice keel depth data points are ignored in further data analysis (Belliveau et al. 2001). Also unreliably high values of ice draft are eliminated in the processing of the data, and are not included in the analysis.

The distribution of the ice keel data recorded from January 26 to March 12, 2000 of some 3,909,705 records, are summarized in Fig. 4.10. A large majority of the ice draft falls into the range of less than 2 m, the consolidated ice features. The maximum keel depth observed is 14.56 m. In Fig. 4.11, an example of plot of the ice thickness data measurement in a day is presented. For convenience, the ice thickness corresponding to the tilt response measurement are used for further analysis of the bridge pier behaviour to the ice load.

4.2.5 Summary of the monitoring data measurements

A summary of the ice monitoring data at Piers 23 and 24 obtained during the Year 2000 is presented in Table 4.1.

Instrument	Recorded data	Start Date	End date	Quantity of the data acquired	Sampling rate (Hz)	Number of records
Tiltmeter	Tilt response	1/28/2000	4/17/2000	81 days	0.05 (20 sec interval)	345,627
	Temperature				9.26×10^{-5} (3 hours interval)	-
Video	Video recordings	2/15/2000	4/7/2000	53 days	-	-
Wind sensor (Between Piers 31 and 32)	Wind direction, speed	1/26/2000	3/31/2000	65 days	0.0588 (17 sec interval)	330,331
ADCP	Current speed	1/26/2000	4/22/2000	88 days	1.11×10^{-3}	8338
	Ice speed	1/26/2000	4/22/2000	88days	(15 minutes interval)	8338
IPS	Ice draft	1/26/2000	3/12/2000	46 days	1.0 (1 sec interval)	3,909,705

Table 4-1 Summary of data for 2000 data

4.3 Data analysis

In general, the analysis of the data for the 2000 ice season are carried out by the method employed in previous study by Kubat and Frederking (2001).

4.3.1 *Basic analysis procedures for estimation of ice force:*

The basic data processing and analysis procedures for the estimation of the ice force imposed on the monitoring Piers are listed as follows:

- ❖ Baseline correction
- ❖ Estimation of the wind-induced tilt
- ❖ Calculation of the ice tilt by removing wind tilt from baseline-corrected total tilt
- ❖ Estimation of the ice force from ice tilt.

As discussed earlier, the effects of traffic and temperature on ice load are negligible. In the evaluation of the ice load effect, it is noted that the occurrence of sea waves are not possible at the time of ice floes acting against the bridge pier. Consequently, the effect of sea waves on the tilt response of the bridge pier is only relevant for events with no ice, which may account for some of the uncertainties observed of these events. In the winter season, the current speed is typically less than 1m/s, which translates to a corresponding current force in the order of about 80 kN (Brown et al. 2001). It is therefore noted that the effect of the current on the ice loading on the bridge pier is small in comparison to those from the wind and direct ice load. The influences of the sea current on the ice load acting on the bridge piers is thus be neglected in the present analysis.

Although the tilt responses of the piers are measured at both the lower ice shield level and at the upper top level of the pier, the bottom tilt response data are selected for the analysis

to estimate the ice load since the top tilt response are more susceptible to influences and loading effects induced by the wind and other uncertain effects.

4.3.2 Baseline correction:

The ice force monitoring system only operates during the ice season. After that, the system is turned off to save operational cost, storage and maintenance of the system. Every winter at the beginning of the ice season, at the time when the tiltmeters are powered on, the bridge pier vibrates or tilts in response to the ice load, wind load and other loading effects or conditions at that instant in time. The reading of the tiltmeter sensor is therefore not properly zero. Consequently, it is necessary to establish the correct zero baseline response reading of the monitoring instrument, which is theoretically supposed to correspond to the condition of no load acting on the pier.

Since it is unrealistic to have the hypothetical condition at which the wind, current and ice load all zero at the same time, the baseline is set by considering the ice load and wind load effects only. This assumption is acceptable because the effect of current on the estimation of ice load acting on the pier is small, as discussed earlier. The more substantial influence of the wind load on the tilt response of the pier is eliminated or minimized by a data processing procedure discussed in more detail later in this section. At the time when there is no ice exerting on the pier, the ice tilt (total tilt minuses the wind-induced tilt) is set to zero. The tilt response of the pier at other time during the monitoring period is then reported relative to this baseline. The conditions of the event selected to establish the zero baseline are that there is no ice acting on the pier, wind speed close to zero and there are minimum effects from tidal current.

The identification of events with no ice acting on the pier is carried out using the monitoring data of the video observation and ice thickness information, whenever they are available. Combining with the information from current and wind speed, the events meet the requirements of the baseline reference are sought.

Unfortunately, the baseline determined from different events gives different results. The uncertainties in establishing the zero baselines in the tilt response of the pier are quite significant so that they might have impacts on the accuracy of final results in the estimation of the ice load.

The variations in the baselines for Piers 23 and 24 are shown in Fig. 4.12 and Fig. 4.13, respectively. The maximum difference in the baseline estimate is about $20.8 \mu\text{rad}$ at Pier 23 (equivalent to 0.8 MN) and $33 \mu\text{rad}$ at Pier 24 (equivalent to about 0.66 MN). These uncertainties are quite high and improvement in the procedures for establishing baseline should be considered.

To overcome these variations in baselines, after considering different possible events, which satisfied the requirements discussed earlier and the influences of other parameters, the event selected for the determination of the baseline correction event is 01:45:01 on March 4, 2000 (Julian Day 64). The differences in the baseline estimates can be interpreted as related to the possible error margins in the estimation of ice forces on the bridge Piers. From the video image, obtained on Julian Days 63 and 64, it is noticed that there was almost no ice in the daytime when the condition of the strait was visible. The wind speed and the current as well as the ice drift speed were almost zero. The baseline tilts of Piers 23 and 24 at the bottom tilt sensor location are determined to be $161.8 \mu\text{rad}$ and $-58 \mu\text{rad}$, respectively. The data of the entire season are calculated based on these

baselines. The tilt response data with reference to these baselines are shown in Fig. 4.14 and Fig. 4.15.

4.3.3 Wind effects and estimation of the wind tilt responses

The recorded tilt responses are the combined effects due to wind and ice. The contribution from wind load to the tilt response of the bridge pier is quite significant. Thus the correct estimation of the wind effect plays an important role in obtaining the accurate result of ice force. The task here is to estimate the response of the pier due to wind, so that this can be eliminated from the total response to obtain a more accurate estimate of the ice load from the processed response data.

The estimation the wind tilt from wind data is mostly based on the procedure implemented by Kubat et al. (2000), which has been discussed elsewhere earlier in this thesis. Since the drag force from wind is assumed to be proportional to the square of wind velocity, the tilt due to wind is therefore also a function of the square of the normal component of wind speed. To establish the relationship between the squared normal velocity and the tilt response induced by wind, an event of no ice acting on the pier is selected to derive the conversion factor.

For Year 2000, several events of ice absence are identified for analysis. After analyzing these events, it is realized that the previous wind conversion factors derived by Kubat et al. (2000) from Year 1999 data need to be revised for this 2000 season. A typical event of no ice is selected. The conversion factor for wind tilt is calculated based on the event on Julian Day 64, on which the video and ice draft data show that there was no ice in the strait. The normal wind speed ranged from -2.8 m/s (from southeast to northwest) to

+13.23 m/s (from northwest to southeast) during the duration of the event, as shown in Fig. 4.16.

The measured bottom tilt on Julian Day 64 (March 4, 2000) versus the squared normal wind velocity is plotted on Fig. 4.17 and Fig. 4.18. Neglecting the effect of current, the measured tilt is thus assumed to be the response caused by wind only. Applying the best-fit technique, the conversion factors to estimate the tilt responses of the piers due to wind only are obtained. As shown in the plots, when the wind velocity is below 10 m/s, the slope of the trend of data is approximately constant. For wind velocity above the 10 m/s level, the slope of the data decreases. However, since the wind velocity is mostly within the range from -10 to 10 m/s, a constant conversion factor approach may still give acceptable results in the present analysis. When the wind speed exceeds 10 m/s, the use of these constant conversion factors may overestimate the wind tilts.

The conversion factors used in the analysis of the year 2000 data are 0.1681 and 0.3176 for tilt responses at Piers 23 and 24, respectively. These conversion factors derived are used to calculate the wind tilt responses for the entire season. For comparison, the corresponding factors from the previous year estimates are 0.19 and 0.3.

4.3.4 *Ice tilt:*

Ice tilt is calculated by removing the wind-induced tilt from the total tilt response (after baseline correction). The subtraction or addition depends on the direction of the wind component normal to the bridge. The sign of the ice tilt indicates whether the ice load is from northwest to southeast (negative) or southeast to northwest (positive) direction. The estimated ice tilts on Julian Day 54 (February 23, 2000) at Piers 23 and 24 are shown in Fig. 4.19 and Fig. 4.20.

The estimated ice tilt, in some event is not always consistent with the ice drift direction, as illustrated in Fig. 4.21 and Fig. 4.22. The ice drift speed reverses direction four times a day, almost at the same time with the tidal current, but the direction of the ice tilt according to the sign convention does not always correspond to the change in ice speed direction. This is probably due to uncertainty of the baselines discussed earlier or other reasons which need further investigation.

4.3.5 Ice force conversion factors and estimation of the ice force

To estimate the ice force, a linear transfer function is derived to account for the flexibility of the pier to relate ice force from the ice tilt. Details of the procedures for derivation of the conversion factors have been presented by Kubat et al. (2001) and discussed in Chapter 3 of this thesis.

In the analysis of the year 2000 data, the conversion factors established in the previous year are used. For the conversion of the ice tilt in μrad to the ice force in MN at Piers 23 and 24, the conversion factors of 0.04 and 0.02 have been adopted, respectively. From the ice tilts, absolute values of ice loads estimated by following the established procedures are shown in Fig. 4.23 and Fig. 4.24.

4.4 Results of data analysis of Year 2000

For the year 2000 season, monitoring data have been processed and analyzed. The wind tilts, ice tilts and ice forces have been estimated for entire season from January 28 to March 31. The Year 2000 ice load monitoring season, in general, did not produce significant information on severe ice load. The conversion factors derived from previous year data for relating ice tilt to ice force of 0.04 and 0.02 for Piers 23 and 24,

respectively, are used. The analysis of the entire season data has identified 90,972 and 47,941 events in excess of 0.5 MN at Pier 23 and Pier 24, respectively. The number of ice load events exceeding 1 MN at Pier 23 and at Pier 24 is 18,463 and 1871, respectively. For ice load greater than 2 MN, there are only 159 events (0.03%), which occurred on Feb 7, March 18 at Pier 23 and on February 7, February 18 and March 11 at Pier 24. The table of the events having ice load greater than 2 MN is presented in Appendix A.

The distribution of the ice load based on the ice load determined from the 20-second interval at both piers is plotted in Fig. 4.25.

The maximum average ice load estimated is 2.75 MN which occurred at 12:19:25 on February 18. Since the analyzed data are only the 20-second average values of the recorded data, the estimated ice load is therefore only the average value, which in comparison may have a deviation of up to about 20 μ rad in the tilt response of Pier 23 (which is equivalent to a load of 0.8 MN) from the instantaneous peak ice load value.

For later reference, the output result of each day for each pier (from January 28 to March 31, 2000) is stored in the EXCEL spreadsheet and recorded to a CD, which contains the raw as well as the processed data in the following format:

Date: date stamp of the recorded data in Universal Time coordinate

Time: time stamp of the recorded data in Julian Day fraction number.

Total Tilt Top Y: the recorded tilt of the tiltmeter at the upper level in direction normal to the longitudinal axis of the bridge, before baseline correction.

Total Tilt Bottom Y: the recorded tilt of the tiltmeter at the lower level in direction normal to the longitudinal axis of the bridge, before baseline correction.

Total Tilt Bottom Y (baseline corrected): the recorded tilt of the tiltmeter at the lower level in direction perpendicular to the longitudinal axis of the bridge, after baseline correction.

Wind Speed Y: the component of the wind speed in direction perpendicular to the longitudinal axis of the bridge.

Wind Tilt: tilt in normal direction induced by wind at the lower level of the bridge.

Ice Tilt: total tilt (baseline corrected) after removal of the wind tilt.

Ice Force: estimated ice load from the ice tilt by applying the conversion factor.

Current Speed: the component of the current speed from northwest to southeast (positive) in cm/s.

Ice Speed: the component of the ice speed from northwest to southeast (positive) in cm/s.

4.5 Ice keel depth, ice drift speed and ice force

The ice loads depend on different parameters. But of all these, the relations between ice force and ice keel depth as well as ice speed are of particular interest. A brief discussion on the correlation between the ice load and these ice event parameters provide valuable insights to the response mechanism of the bridge pier to ice loads.

4.5.1 Ice force and ice thickness

Fig. 4.26 and Fig. 4.27 present the relationships between the measured ice loads and the ice keel depths for the cases of the ice speed ranging from 10 to 20 cm/s and from 70 to 80 cm/s, respectively. More detailed plots of the relationships between the ice thickness and ice force at different ice velocities are presented in Appendix B.

The data plotted in Figures 4. 26 and 4.27, as well as those presented in Appendix B, do not show a clear relationship between the maximum ice force and corresponding ice keel depth. However, a trend of decreasing estimated maximum ice force with increasing ice keel depth can be observed from the data plotted in the figures. A similar trend in the behaviour of the data was also observed at Piers 31 and 32 by Brown et al. (2001). One possible reason for this observation is that the ice force is related to the momentum of the impact by the ice ridge at the pier. Since momentum depends on mass and velocity, the ice force can be affected by any one of these parameters. It is possible that a heavier ice ridge moves at a smaller velocity in a steady current flow field. A larger ice ridge with greater ice thickness may move with slow velocity, resulting a smaller ice force on the pier. Further more, another reason is that the mass of the ice feature is not only a function of ice thickness but also depends on plane dimensions of the ice feature. The plane dimensions of the impact ice features are very difficult to obtain and are not measured in this study. It is therefore the relationships between these parameters and ice force are very complex and need to be further studied.

4.5.2 Ice force and ice speed

Similar plots of the relationships between ice force and ice speed for different ice draft thickness between 2 to 4 m and 4 to 6m are shown in Fig. 4.28 and Fig. 4.29. The plots of ice force versus ice velocity at Piers 23 and 24 for different ice draft thickness are presented in Appendix B.

From the data plotted in Fig. 4.28 and Fig. 4.29 (and other figures in Appendix B), the relationship between the ice load and the ice velocity and ice keel depth is not clear. However, some trends in the ice load behaviour can be summarized as follows:

- ❖ For ice speed up to about 40-50 cm/s, the ice load seems to increase with increase of the ice velocity (linear trend).
- ❖ For ice speed beyond 50 cm/s, there is a straight-line reduction trend in the ice load for increasing ice speed.
- ❖ Some ice load estimates of over 1.5 MN are obtained at very low (almost zero) ice speed.

The observation of the relationships between the ice force, ice keel depth and ice speed again confirms the conclusion in an earlier study by Langohr and Ghali (1997) that impact of fast moving ice ridge on the pier does not produce the critical case for the ice force, but the brittle failures of the ice floes, at low speed cause greater ice force. The observation also shows either there is no clear relationship between these parameters or the relationship of the interaction mechanism between the ice thickness, ice speed and ice force is very complex and more research is needed to find more reasonable explanation.

4.6 Overestimation of the wind tilt response

The uncertainties in the estimate of the baseline, as mentioned before, have significant impact affecting the accuracy of analysis result in the estimation of the ice load. In addition, another problem has also been identified in the analysis of the Year 1999 data, and again in Year 2000 data, namely the tilting back into the wind or inconsistency in the ice drift direction with the ice tilt response.

The ice tilt response should be consistent with the direction of the ice load acting on the pier. According to the sign convention, the ice pushing from the southeast (direction with positive ice drift speed), should result in a tilt response to the northwest, i.e. increasing

tilt value and vice versa. But the data analysis indicates this is not always the case. Fig. 4.30 and Fig. 4.31 present some typical events not following the expected trend in the behaviour of tilt response:

In Fig. 4.30, for the case of the event on February 4, 2000, the ice drifted from the southeast to the northwest. For ice load acting in that direction, the response of the pier to the applied ice load should be in the northwest direction, i.e. the tilt of the pier induced by ice only should produce a more positive tilt response value, and should not decrease or produce result in negative direction according to the sign convention. But from the time period 2:24 to 2:41, February 4 (i.e. Julian Day 35), the ice tilt dropped rapidly to negative values.

Another example is the event on March 16, 2000 as shown in Fig. 4.31, the ice drift speed data indicated that the ice and normal wind components were acting from the northwest direction, and the normal wind component from the northwest to southeast direction. The ice tilt response should be negative or the tendency of the response should decrease in value. Instead, the ice tilt response changed to a positive value.

From the analysis of the data, it is observed that the inconsistencies between the ice tilt and ice drift direction of two events as well as other events having the similar problem occur at times of normal wind velocity exceeding about 10 m/s (or 36 km/h). This may be due to the overestimation of the wind tilt at high wind speed. This observation is in agreement with the observation earlier that when the wind velocity is higher, the wind conversion factor is not constant and should be lower. In the Year 2000 monitoring data, due to the insufficient of no-ice event with strong wind, it is difficult to see the behaviour of the bridge piers in the high wind speed.

4.7 Summary and Conclusions for the Year 2000 data

The data analysis of monitoring season for year 2000 is a continuation of the previous year monitoring project at Piers 23 and 24. The data set of the year 2000 give more information about the response behaviour of the pier from late January to early April 2000. Although there were some problems with the wind data, the monitoring program for the year 2000 has provided the comprehensive data to analyze the ice load and behaviour of bridge pier to the ice. The detailed analysis of the monitoring data applied the previous procedures with the revised wind conversion factors were processed for the whole season from January 28 to March 31, 2000.

For year 2000, the previous approach to estimate the tilt response at the lower level of bridge pier to the wind load is followed. A constant conversion factor for each pier is applied for the whole range of the wind speed. This year the conversion factors are 0.168 for Pier 23 and 0.3176 for Pier 24. For the estimation of ice load from ice tilt, constant conversion factors derived from previous year are used. These factors for Piers 23 and 24 are 0.02 MN/ μ rad and 0.04 MN/ μ rad, respectively.

Year 2000 is a relative light year in terms of ice. The estimated maximum average ice load is 2.75 MN in comparison with about 4 MN for the year 1999. Only 159 events have the ice load greater than 2 MN. Most of the high ice loads are recorded at the slow ice drift speed. The thickest ice keel depth is 14.56 m, but in most of the recorded events the ice keel depth is less than 4 m. The ice drift and current speed are usually less than 1m/s.

Since the analysis of ice load based on the average data obtained at 20-seconds interval, taken as the average of 20 recording at 1Hz, the ice load estimated should considered as

the average lower bound of the actual load. To obtain maximum and more precise load, the higher frequencies data should be recorded.

In year 2000 monitoring, the analysis is performed with the use of adopted constant factor for estimate the wind tilt. However, it is found that the adoption of one conversion factor for the whole range of normal wind speed overestimates the tilt response induced by wind at high wind speed. To obtain more accurate results of the tilt response of wind, i.e. more reliable estimated ice load, the relationship between the wind velocity and wind tilt should be modified and improved. The behaviour of the bridge piers to wind force at the high wind speed range should be observed. Unfortunately, the year 2000 does not have sufficient no-ice events at high wind speed for the analysis. However, the decision to use either different constant at different wind features or the non-linear correlation between square of wind velocity and wind tilt response of bridge pier need to be further studied. This can be done when the monitoring data have information of the response of the bridge piers to the strong wind.

The uncertainties of the baseline have significant impacts on the final result of the estimated ice load of which the deviation can be up to 0.8 MN when the maximum ice load is only 2.75 MN. Procedures to minimize the uncertain effect are necessary to improve the quality of the results of the monitoring program.

The definition of correlation between ice load and key parameters such as ice speed, ice keel depth has not been well recognized. However, some behaviours of bridge piers to ice load have been observed. Further studies are needed to establish the relationship between the ice load and these parameters.

Figure 4-1 Measured Y-tilt responses at two levels of Pier 23- February 21, 2000

Figure 4-2 Measured Y-tilt responses at two levels of Pier 24- February 21, 2000

Figure 4-3 Variation of tiltmeter temperature of Pier 23-Year 2000

Figure 4-4 Wind Speed and its normal components –February 19, 2000

Fig. 4.5 Comparison of the normal wind speed data recorded at Piers 31 and 32 and data after correction

Figure 4-6 Distribution of normal wind speed for Year 2000

Figure 4-7 Current Speed and Ice Drift Speed from northwest to southeast-February 26, 2000

Figure 4-8 Distribution of Current Speed from northwest to southeast-Year 2000

Figure 4-9 Distribution of Ice Drift Speed from northwest to southeast-Year 2000

Figure 4-10 Distribution of Ice Thickness - Year 2000

Figure 4-11 Ice Draft Thickness at Pier 24- February 26, 2000

Figure 4-12 Variation of the baseline at Pier 23

Figure 4-13 Variation of the baseline at Pier 24

Figure 4-14 Total Tilt before and after baseline correction –Julian Day 64(March 4)-Pier 23

Figure 4-15 Total Tilt before and after baseline correction -Julian Day 64(March 4)-Pier 24

Figure 4-16 Wind Speed and Current Speed in Julian Day 64- March 4, 2000

Figure 4-17 Wind Velocities Squared vs. Wind Tilts-March 04-Pier 23

Figure 4-18 Wind Velocities Squared vs. Wind Tilts-March 04-Pier 24

Figure 4-19 Total Tilt, Wind Tilt and Ice Tilt-February 23, 2000- Pier 23

Figure 4-20 Total Tilt, Wind Tilt and Ice Tilt-February 23, 2000- Pier 24

Figure 4-21 Ice Tilt and Ice Drift Speed at Pier 23-February 27, 2000

Figure 4-22 Ice Tilt and Ice Drift Speed at Pier 24-February 27, 2000

Figure 4-23 Ice Tilt and Ice Force-February 21-Pier 23

Figure 4-24 Ice Tilt and Ice Force-February 21-Pier 24

Figure 4-25 Histogram of the Ice Forces

Figure 4-26 Ice Keel Depth vs. Ice Force-Ice Speed is from 10 to 20 cm/s

Figure 4-27 Ice Keel Depth vs. Ice Force –Ice Speed from 70-80 cm/s

Figure 4-28 Ice Speed vs. Ice Force- Ice Keel Depth is from 2-4m

Figure 4- 29 Ice Speed vs. Ice Force- Ice Keel Depth is from 4-6m

Fig 4-30 Phenomenon of tilting back into the wind direction-Julian Day 35 (February 4, 2000)

Figure 4-31 Phenomenon of tilting back into the wind direction-Julian Day 76 (March 16, 2000)

Chapter 5 Response of the Bridge to wind load-Year 2001 data

5.1 Description of ice season and data acquisition of Year 2001

The 2001 ice season is a moderate year in terms of ice severity. The period of significant ice covered in the Strait is longer in 2001 than in previous year. The Strait had significant ice concentration starting in early January, and the ice remained until April 26, 2001. In year 2001, the monitoring instrumentation and data acquisition system used for collection data are the same as these of the year 2000, except that the video cameras are relocated for better observation of the ice conditions at the two monitored Piers. For the monitoring programme at Piers 23 and 24, the ice season for the year 2001 is quite successful. The ice data available for ice load analysis and research are those recorded from January 18 until May 2, 2001.

As in previous years, there are two sources of wind data for analysis, one from navigation span (10 minutes interval) and another from mid-span of Piers 31 and 32 (17 second interval). The wind records for this year are quite reliable, with good agreement of the wind data from the two sources, and consistent and good correlation between the wind data and measured and observed structural responses of the bridge piers. The only slight difficult encountered are data during the period from Julian Days 99 to 101. There are some erroneous values in the wind data recorded at Piers 31 and 32, but they have been corrected by the information obtained from data at the navigation span. For analysis, the

wind data collected at Piers 31 and 32 at a height of 51.8 m from the mean sea level is used as the primary source for wind condition data. This wind data set correlates well with the structural responses of the piers. The wind data set from Piers 31 and 32 covers the period until April 20. The wind data after that day is taken from the wind data set of navigation span by re-sampling wind data into desired interval. It is again noticed that the wind data from the navigation span and from Piers 31 and 32 are recorded at different levels. The wind data from the navigation span (71.3 m above mean sea level) must be adjusted to be consistent with the wind data set at Piers 31 and 32 (51.8 m height from the mean sea level). Study of the meteorological data by King et al. (1994) suggests an exposure correction factor for adjustment of the wind speed with height z above the water level as follows:

$$ECF = \left(\frac{300}{10} \right)^{0.14} \left(\frac{z}{250} \right)^{0.10} \quad (5-1)$$

The ratio between the ECF factors determined from heights at the two wind sensor locations using Eq. 5.1 is 1.03. But from comparison of the recorded wind data as shown in Fig. 5.1, the ratio of the two factors varies from 1.1 to 1.3. The ratio of 1.13 is selected for adjustment of the wind data recorded at the navigation span to wind speed at the bridge deck level in the middle of Piers 31 and 32.

In Year 2001, there have been more strong wind events during the ice season compare to the previous years. The distribution of the normal component of wind speed recorded in 2001 for the monitoring season is shown in Fig. 5.2. The numbers of the events having a normal component of the wind velocity from 10 to 15 m/s, 15 to 20 m/s and above 20 m/s are 57909(12.77% of events), 12334 (2.72%), and 217 (0.05%), respectively. The

maximum normal wind speed recorded during the ice season of the monitoring programme is 25.33 m/s. And many no-ice events with strong wind have been recorded and identified. From analysis of these events, useful information is obtained on the behaviour of the bridge piers subject to high wind effect.

The ice drift speed and current speed data for 2001 are similar to the data collected in 2000. In the direction from northwest to southeast, the maximum current speed observed in 2001 is 1.63 m/s. From the data records on Julian Day 83, the ice drift speeds are extremely high, many events over 2 m/s and the maximum ice drift speed recorded is 3m/s. This observation may not be reliable as this is unusually high compared to the normal range of ice speed. Most of the time during the ice season, current velocity is less than 0.75 m/s (Fig. 5.3), and ice speed is from 0 to 0.75m/s (Fig. 5.4).

The ice condition video monitoring records of the bridge site in Year 2001 provide accurate and useful information at the two instrumentation piers. The ice condition observation records from the video recorded are used to identify events of no ice acting on the bridge piers for baseline processing of the tilt response data and wind data analysis.

5.2 Data analysis

The procedures to estimate the ice forces are similar to those in previous year of 2000:

- ❖ Baseline correction
- ❖ Estimation of the wind-induced tilt
- ❖ Calculation of the ice tilt by removing wind tilt from baseline-corrected total tilt

❖ Estimation of the ice force from ice tilt.

In the data analysis of year 2001, it is found that there is drift in readings of the structural response of the bridge piers due to change in the temperature of the tiltmeter sensors. The available sensor temperature data are taken at 3-hour intervals. The range of temperature change in tiltmeter sensor during the ice season can be up to 20°C and thus can have a significant effect on the accuracy of the tilt response measurement. Fig. 5. 5 and Fig. 5.6 show the variations of the tiltmeter temperature at Piers 23 and 24 at the lower ice shield level. It is noted that the change in temperature of the tiltmeters between 3-hour intervals is small. Therefore it is acceptable to resample the recorded temperature data of the tiltmeters into 20-second interval data for correlation study with the tilt response data. Using information provided by tiltmeter manufacturer, correction for the temperature effect of the measured tilt response has been carried out with the calibration factor K of $1.5 \mu\text{rad}/^\circ\text{C}$.

From analysis of the baseline events in the Year 2001 data, the baseline of $178.05 \mu\text{rad}$ for Pier 23 at 18:37: 04 on Julian Day 92 (April 2, 2001) and $-97.3 \mu\text{rad}$ for Pier 24 at 18:39:54 on Julian 92 (April 2, 2001) are obtained after correction for the temperature effect in the tiltmeters.

As mentioned in the analysis of data from previous year in Chapter 4 of the thesis, the key factor in estimation of the ice tilt and the ice force is the accurate estimation of the wind tilt response. Using the data from Year 2001 recorded of ice-free events coupled with strong wind conditions allow more detailed observation of the behaviour of the bridge piers under different wind speed ranges so that a more accurate relationship of the wind load and the wind induced tilt response can be developed, leading to the

development of a more reliable transfer relationship from the wind data to wind tilt response.

5.3 Response of the bridge pier to wind load

The 2001 ice season data set includes many events with strong wind. These events with the presence or absence of ice are analyzed in details in the present study. By carefully studying the response behaviour of the event with no ice, more understanding of the behaviour of the pier due to wind effect is achieved, which leads to improvements to the ice load estimation methodology.

5.3.1 *Non-linear relationship between wind tilt response and wind load*

The prediction of the response of the bridge pier to wind load is studied from the observations of tilt responses measured during no-ice events. The wind tilt response is plotted against square of wind velocity (which is proportional to the wind load) from no-ice events.

The wind tilt versus wind speed relationships on Julian Day 118 (April 28, 2001), and on Julian Day 120 (April 30, 2001) are plotted in Fig. 5.7 and Fig. 5.8, respectively. It is observed that the relationship between the wind tilt response and wind load is not linear as previously assumed, but shows significant non-linear behaviour. In Fig. 5.7, it shows that the slopes of the plot when the wind speed from zero to about 40 (m/s)^2 is different from that at higher wind speed. The slope of the relationship decreases when the wind speeds increase. This is in good agreement to the previous observation from analysis of the Year 2000 data that when wind speed is higher, the transfer function is smaller. In Fig. 5.8, the plot is a combination of different load paths, which shows different

relationships between the wind tilt response and wind load (or square of wind velocity) depending whether the wind speed increases or decreases. For both of those events, the absence of ice has been confirmed from video records. Other events of ice absence also show similar observations and a non-linear relationship of wind tilt with square of wind velocity. These observations on the behaviour of the wind tilt the relationship lead to conclusion that differences wind conditions have significantly different influences on the transfer function of wind tilt response and wind load. Thus an improvement to previously assumed linear relationship is necessary. A nonlinear relationship between the wind load and wind tilt is derived in the present study.

5.3.2 Relationship of wind tilt response and wind load at different wind conditions-non-linear hysteretic behaviour of wind tilt response.

By analyzing many no-ice events of the Year 2000 and 2001 monitoring data, the behaviours of the bridge piers to wind loading are found to be quite different from one event to another depending on the conditions of wind loading, which include the loading direction with increasing wind speed, unloading direction with decreasing wind speed and reloading direction with wind speed increases after decreasing. These behaviours are discussed in more detail as follows:

5.3.2.1 Loading condition: tri-linear relationships

As previously mentioned, the relationship between the wind tilt response and wind velocity squared is non-linear. It is found that the conversion factor for transfer of the wind velocity to wind tilt is smaller at a higher wind speed. When the wind speed increases from zero to the maximum range of recorded wind speed of the year 2000 and 2001, which may be up to 15 m/s for the events without ice, the non-linear relationship

can be approximated by a tri-linear curve, i.e. a constant conversion factor is adopted within each linear range of wind speed. These wind speed regions are: 0 to 6 m/s, 6 to 10 m/s and above 10 m/s. Plotting the wind speed data separately for the different ranges of wind speed level, different conversion factors are established for data in different wind speed ranges. In Figs. 5.9, 5.11, and 5.13, the relationships for loading direction for the 3 separate ranges of wind speed at Pier 23 are presented. Other plots for the different ranges of wind speed from other events are presented in Appendix C. They give similar transfer relationships.

As shown in the plots, the derived conversion factors for different events in the ranges of wind speed are quite close. The slight changes in the conversion factors may be due to an effect of the variation of the wind speed as well as some other uncertainties. Since it is unlikely to expect an ideal monotonic loading condition, the conversion factors derived here is as good as can be expected for analysis of the wind data. With more data available in subsequent monitoring season, more accurate calibration of the conversion factor can be obtained leading to better transfer function for the wind response analysis.

5.3.2.2 *Unloading direction*

When plotting the wind tilt of the bridge piers versus the square of wind velocity in periods of decreasing wind speed, the relationship between the wind tilt and square of wind velocity does not follow the same non-linear relationship in the loading direction when wind speed increases. As shown in Figs 5.15, 5.17, 5.19, for some events at Pier 23 under different wind conditions (Figs. 5.16, 5.18 and 5.20, respectively), the relationships seem to be constant linear regardless of the wind speed level. It can be observed that the slopes of the transfer function vary for different events, depending on the wind speed

level at the start of unloading, and they are not the same as those in the loading direction at the same level of wind speed. As from the derived conversion factors, the slopes of the relationship between the wind speed and wind tilt response are smaller when the wind speeds at the initiation of unloading are higher. For the 2000 and 2001 data, not all levels of wind speed in unloading direction have been recorded. Thus only some conversion factors at certain levels at the start of wind loading are obtained. The factors derived for unloading event is very sensitive to the variation of the wind speed, so the estimation of the transfer function in unloading event must be taken with care.

5.3.2.3 Reloading direction

For periods when wind speed increases after decreasing, only few events have been identified in the monitoring data of Year 2000 and 2001. Fig. 5.21 shows one of those events at Pier 23 on February 23, 2001. The wind tilt response of the reloading period comes back almost the same as before unloading, when the wind speed reaches the level before decreasing. The slopes of relationship between wind response and square of wind speed of reloading and that of unloading are almost the same.

There is very limited or no information available from Year 2000 and 2001 data to observe the behaviour of bridge pier to wind load when the wind speed in reloading direction exceeds the wind speed at the start of unloading. But the observations of the behaviour of bridge piers in loading and unloading directions show a hysteretic behaviour similar to relationship described in Park and Paulay (1975) and Takeda et al. (1970) for reinforced concrete structures. According to the hysteretic model of reinforced concrete, when the load exceeds the level of unloading, the relationship follows that of loading direction, in which the conversion factor depends on the level of wind speed of the event.

The non-linear hysteretic relationship of response of pier to wind effect of the Confederation Bridge at Piers 23 and 24 explains the observed behaviour due to overestimation of the wind tilt response at high wind speed at some events of the Year 2000 data discussed in Chapter 4 earlier, which causes some inconsistencies between the ice drift and estimated ice tilt response at high wind speed. The analytical results using new proposed procedure for estimation of wind tilt response based on the proposed non-linear relationship described in the following section confirm this conclusion. Also, different transfer functions at different wind conditions may cause the tilt response of the pier not return to initial state when the wind speed decreases to zero. This may be a part of reason of baseline drift, in which different baseline values are observed from different baseline events.

5.4 Estimation of the wind tilt response-the use of tri-linear conversion factors.

From the analysis and observation of behaviour of bridge piers as discussed, the procedure for estimation of the wind tilt response that best represents the non-linear relationship between the response of the bridge pier and wind loading is developed. For Pier 23, the procedure is summarized as in Table 5.1.

Only the conversion factors at certain levels of unloading wind speed from limited identified events of the data are derived. The behaviour and variation of the conversion factor at other wind speeds for unloading direction are obtained by interpolation between the known factors as presented in Table 5.2 and Appendix C. When more data are

available, more accurate conversion factors at different wind speeds for unloading can be derived.

Loading direction	Unloading direction	Reloading direction
$T_w = C_L V_w^2 \quad (5-2)$	$T_w = C_U V_w^2 \quad (5-3)$	$T_w = C_R V_w^2 \quad (5-4)$
$V_w < 6 \text{ m/s}: C_L = 0.23594$ $6 \leq V_w < 10 \text{ m/s}: C_L = 0.13834$ $V_w \geq 10 \text{ m/s}: C_L = 0.1042$	$C_U: C_U = f(V_U)$ V_U : wind speed at the beginning of unloading.	$V_w \leq V_U: C_R = C_U$ $V_w > V_U$: $V_w < 6 \text{ m/s}: C_R = 0.235$ $6 \leq V_w < 10 \text{ m/s}: C_R = 0.13834$ $V_w \geq 10 \text{ m/s}: C_R = 0.1042$

Table 5-1 Estimation of wind tilt response at Pier 23

Square of wind velocity at start of unloading $(\text{m/s})^2$	Conversion factor Pier 23	Conversion factor Pier 24
20.71	0.30155	0.445
24.46	0.27747	0.471699
32.17	0.23747	0.3541
70	0.1761	0.25946
100	0.15339	0.2102
120.5	0.14296	0.28029
132	0.13822	0.26622

Table 5-2 Conversion factors of unloading at Piers 23 and 24

For reloading, when wind speed is smaller than wind speed at the beginning of unloading, conversion factor of reloading is the same as that of corresponding unloading period. But

when wind speed increases beyond this unloading level, the assumption is that the reloading comes back to primary curve, and conversion factors are the same as loading direction, which are 0.235, 0.1384 and 0.1042 depending on the normal wind speed of the event. The procedure for estimation of wind tilt response of Pier 23 is presented by a model as shown in Fig. 5. 22.

For Pier 24, the same behaviours of the pier to wind loading are also observed. And the corresponding wind conversion factors are derived for the new procedure of estimation of wind tilt response of Pier 24. In the loading direction, the slopes of transfer functions are 0.41, 0.28618 and 0.17016 for wind speed ranges: 0 to 6 m/s, 6 to 10 m/s and above 10 m/s, respectively. From the design of the bridge and the calibration of previous studies by Kubat et al. (2000), Kubat et al. (2001) and Luu and Lau (2002), the foundation stiffness of Pier 23 is about 1.4-1.9 times stiffer than that of Pier 24. It is expected that the ratios between conversion factors of Pier 24 and that of Pier 23 be from 1.4 to 1.9. But while most of the conversion factors of Piers 23 and 24 in unloading direction are in this range, there are some factors derived from Pier 24 are out of the expected range compare to the factors of Pier 23, which may result from the uncertainties of the measured data. For the analysis, these suspected factors are replaced by using the corresponding conversion factors of Pier 23 with appropriate scaling factors. Whenever more data available, the more accurate factors at Pier 24 can be derived.

For the estimation of the wind tilt responses, ice tilts and ice forces following new procedure, a computer programme in MATLAB has been written for analysis to model the non-linear behaviour of the wind tilt response. The results from analysis of some

events of Year 2001 data are discussed in the following section for verification of the improved procedure.

5.5 Comparison of results

The results of analysis for some events of high wind speed are presented to compare the estimated ice tilts from the two methods of estimation for wind tilt responses. The first method based on a constant linear relationship between wind load and wind tilt response of the bridge pier. The second improved method, developed in the present study, is based on the assumption that the wind tilt behaviour is non-linear and load path and load history dependent. A tri-linear relationship between the wind load and wind tilt response is considered in this study. The load path and load history dependency of the behaviour are modeled by a hysteretic model.

As shown in Fig. 5.23, of an event on Julian Day 41 (February 10, 2001), the ice tilts calculated using the improved procedures of wind tilt estimation considering the non-linear behaviour provide a more consistent correlation between the estimated ice tilt and ice drift direction. It is noted that the ice tilt results obtained by the improved method are consistent in direction with the ice drift speed from southeast to northwest, which is not the case of the results from the linear method.

Similar example is presented in Fig. 5. 24, of an event on Julian Day 46 (February 15, 2001). The ice drift direction is from northwest to southeast, and the ice tilt estimated from improved method is in the same direction with the ice drift, while the ice tilt calculated from linear method is not consistent with ice drift, but in other direction.

Figure 5-1 Normal Wind Speed at navigation span and Piers 31 and 32 - March 16, 2001

Figure 5-2 Distribution of the normal wind speed of Winter 2001

Figure 5-3 Distribution of current speed from northwest to southeast-Winter 2001

Figure 5-4 Distribution of ice drift speed from northwest to southeast-Winter 2001

Figure 5-5 Variation of the tiltmeter temperature at Pier 23 - 2001 Winter season

Figure 5-6 Variation of the tiltmeter temperature at Pier 24 - 2001 Winter season

Figure 5-7 Relationship between wind tilt and wind load at Pier 23 –April 28, 2001

Figure 5-8 Relationship between wind tilt and wind load at Pier 23 –April 30, 2001

Figure 5-9 Wind tilt vs. wind speed at Pier 23 –loading direction

Figure 5-10 Wind tilts and wind speeds and at Pier 23 –April 28, 2001

Figure 5-11 Wind tilt vs. wind speed at Pier 23 –loading direction

Figure 5-12 Tilt responses and wind speeds at Pier 23 –April 12, 2001

Figure 5-13 Wind tilt vs. wind speed at Pier 23 –loading direction

Figure 5-14 Tilt responses and wind speeds at Pier 23 –May 02, 2001

Figure 5-15 Wind tilt vs. wind speed at Pier 23 –unloading direction

Figure 5-16 Tilt responses and wind speeds at Pier 23 –April 26,2001

Figure 5-17 Wind tilt vs. wind speed at Pier 23 –unloading direction

Figure 5-18 Tilt responses and wind speeds at Pier 23 –April 9, 2001

Figure 5-19 Wind tilt vs. wind speed at Pier 23 –unloading direction

Figure 5-20 Tilt responses and wind speeds at Pier 23 –April 28,2001

Figure 5-21 Wind tilt response, wind speed at Pier 23 –February 23, 2001

Figure 5-22 Relationship of wind tilt and wind speed at Pier 23-proposed procedure.

Figure 5-23 Comparison of estimated ice tilts between two methods at Pier 23-February 10, 2001

Figure 5-24 Comparison of estimated ice tilts between two methods at Pier 23-February 15, 2001

Chapter 6 Summary and Conclusions

6.1 Summary and conclusions

A research has been undertaken to develop the methodologies and procedures for the estimation of the ice force acting on circular bridge piers of the Confederation Bridge. The study of ice force estimation is based on the monitoring data recorded by the monitoring system at Piers 23 and 24 of the Bridge, which has been installed since 1999. The recorded data include: structural tilt response of the bridge pier, wind speed and wind direction, current and ice speed, ice thickness, temperature data and video record. To improve the accuracy on the ice force estimates, detailed studies about the responses of the bridge piers due to wind effects have been carried out.

Detailed analysis of the monitoring data to estimate the ice forces in the winter season of Year 2000 has been conducted using the procedures developed in previous studies, considering the assumption of linear relationship between the wind tilt response and wind load for determining the wind response of a bridge pier. From the analysis, ice forces imposed on Piers 23 and 24 in Year 2000 are obtained. The results show that the use of a linear relationship between the wind tilt response of the bridge pier and wind load may cause some erroneous results in the estimation of ice forces. An improved procedure is developed in this study to estimate the tilt response of the pier due to wind from the observation of the response of bridge pier to wind load using the 2000 and 2001 monitoring data. The new procedures better represent the behaviour of bridge pier to

wind load, predict more accurately the behaviour of wind tilt response of bridge pier and thus show better agreement between the estimated ice load and recorded ice drift direction. The findings of this study provide a better understanding of the behaviour of bridge pier subjected to wind loads, and lead to more reliable and accurate predictions of ice forces of the Confederation Bridge. The conclusions obtained from this study are summarized as follows:

- Processing results and analysis of the monitoring data show that the assumption of linear relationship between the wind tilt response of the bridge pier and wind load (which is proportional to square of wind velocity) gives erroneous estimates of the wind tilt response of the bridge pier under some wind conditions, especially during events of high wind speed. This causes inconsistencies in the calculated results of the ice tilts and ice drift directions.
- Detailed studies of the behaviour and relationship between wind tilt response and wind load of the bridge pier shows that the wind tilt response behaviour is more complex and involves non-linear hysteretic behaviour with dependence on load path and load history.
- For loading direction with increasing wind speed, it is found the slope of the transfer function (or wind conversion factor) is smaller at a higher wind speed. The relationship between the wind tilt response and wind load in loading direction may be represented by a tri-linear function divided into 3 separate wind speed ranges: 0 to 6m/s, 6 to 10 m/s and above 10m/s.

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- In unloading direction with decreasing wind velocity, it is found the relationship between the wind tilt response and wind load does not depend on the level of wind speed of the event itself but on the wind speed at the start of unloading. When the wind speed at the start of decreasing wind speed is higher, the slope of the transfer function is smaller.
 - When wind speed increases after decreasing in reloading direction, the slope of the reloading path is almost identical to that of the unloading direction until wind speed reaches the level of at the start of the previous decreasing. After that, when the wind speed exceeds the level at the initiation of unloading, the transfer relationship in the original loading direction applies.
 - This non-linear behaviour of wind tilt response of the bridge piers is observed at Piers 23 and 24. The possible sources of nonlinearity may be as follows:
 - Foundation: the nonlinear behaviour of soil and concrete materials.
 - Structural components of the structures: the nonlinear hysteretic behavior of material of structural members of bridge piers.
 - Flow field of wind and current: the high turbulence of the wind at the level below the bridge deck and the turbulence of the current flow may contribute to the observed nonlinear hysteretic behaviour of bridge pier to loading effect.
 - The baseline set up has significant effect on the result of the estimation of ice force. The non-linear behaviour of wind tilt response may explain as part of the cause for the observed drift of the baseline of the measured tilt response of the

bridge over the winter season. However, the other reasons or factors which may contribute to the drift of the baseline need to be investigated in further study.

- The relationships between ice force and other ice feature parameters such as ice speed and ice thickness have not shown clearly identifiable trends. But it is observed that a high ice force occurred not only as the result of high impact load from fast moving ice features but is also significantly affected by the failure mode mechanism of the ice floes. Consequently, an ice floe moving at a slow speed can potentially also cause a high ice force. It is also observed that ice thickness does not play a significant influence as expected on the ice force of the bridge pier.

6.2 Recommendations for future work

- As mentioned in previous sections, the further studies and improvement to the procedure in determining the baseline are recommended. This will contribute to more accurate results of the ice force.
- Calibration of the conversion factors in the loading direction, unloading direction should be refined when more data are available. Since 2000 and 2001 data do not have many events similar to monotonic loading conditions, the variation of the wind speed may have some effect on the estimated conversion factors. The monotonic loading condition can theoretically give more accurate conversion factors of the tri-linear transfer function between the wind tilt response and wind load.
- Also, for unloading condition, the unloading behaviour at different levels of unloading wind speed should be studied in more details to give better

approximations at all levels of wind speed. It is noticed that the conversion factor of unloading is very sensitive to the change in wind condition. Therefore, the derivation of the transfer function should be taken with care and assessment.

- For reloading direction, when more data are available in these conditions, the behaviour of the bridge pier to wind load when wind speed exceeds the level of start of unloading should be studied in more details.
- The previous studies use transfer function to estimate ice force from ice tilt response by calibrating the flexibility of bridge pier, assuming the relationship between ice force and ice tilt is linear. As a possible source for the observed nonlinear hysteretic behaviour of the response of the bridge pier, the relationship between ice force and ice tilt should be studied in more details considering the possibility of any non-linear behaviour in order to further improve the accuracy of the estimated ice forces.
- For verification of the design assumption, using the monitoring data, design spectra of ice force for a 100-year design service life can be derived to ice force estimate in probabilistic sense. The proper distribution model use for ice force on bridge pier needs to be explored in future study of the research.

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APPENDIX A
Detail Event Data
(Events with Ice Force greater than 2MN)

Table A. List of events with ice load greater than 2MN
(Sorted from largest to smallest ice load)

Date	Time	Pier Number	Total tilt (baseline corrected) (μ R)	Wind speed (m/s)	Wind tilt (μ R)	Current speed northwest (cm/s)	Current speed northeast (cm/s)	Ice speed northwest (cm/s)	Ice speed north east (cm/s)	Ice tilt (μ R)	Ice force (MN)	Ice draft thickness (m)
18-Feb-00	12:19:38	24	-157.8979	8.04	20.54	-19.29	1.00	-14.21	-12.06	-137.36	2.75	0.01
18-Feb-00	12:19:18	24	-158.6687	8.26	21.69	-19.56	1.00	-14.39	-12.31	-136.98	2.74	0.00
7-Feb-00	22:23:18	24	-141.3275	5.57	9.84	-75.69	4.84	-52.89	-55.24	-131.48	2.63	0.90
7-Feb-00	22:23:38	24	-140.7494	5.51	9.65	-75.98	4.77	-53.13	-55.57	-131.10	2.62	1.37
7-Feb-00	22:17:21	23	-72.3838	6.53	7.17	-70.19	2.94	-48.20	-50.56	-65.22	2.61	0.24
7-Feb-00	22:15:41	23	-72.5619	6.80	7.77	-68.64	2.27	-46.86	-49.31	-64.79	2.59	1.54
7-Feb-00	22:17:01	23	-70.5135	6.58	7.29	-69.88	2.81	-47.93	-50.31	-63.23	2.53	0.56
7-Feb-00	22:19:01	23	-69.6229	6.26	6.59	-71.75	3.61	-49.53	-51.82	-63.03	2.52	0.21
7-Feb-00	22:10:21	23	-72.3838	7.66	9.87	-63.66	0.14	-42.59	-45.28	-62.51	2.50	2.59
7-Feb-00	22:23:01	23	-67.7526	5.61	5.30	-75.45	4.90	-52.69	-54.96	-62.46	2.50	0.78
7-Feb-00	22:16:01	23	-69.8010	6.75	7.65	-68.95	2.41	-47.13	-49.56	-62.15	2.49	0.54
7-Feb-00	22:10:41	23	-71.8494	7.61	9.73	-63.97	0.27	-42.86	-45.53	-62.12	2.48	0.53
7-Feb-00	22:14:18	24	-139.0153	7.02	15.67	-67.35	1.72	-45.75	-48.26	-123.35	2.47	0.16
7-Feb-00	22:24:21	23	-66.3277	5.40	4.90	-76.60	4.63	-53.63	-56.28	-61.43	2.46	0.13
7-Feb-00	22:11:01	23	-70.9588	7.56	9.60	-64.28	0.41	-43.12	-45.79	-61.36	2.45	1.29
7-Feb-00	22:17:41	23	-67.6636	6.48	7.05	-70.50	3.07	-48.47	-50.81	-60.61	2.42	0.27
7-Feb-00	22:24:41	23	-65.3480	5.34	4.80	-76.89	4.56	-53.87	-56.61	-60.55	2.42	0.15
7-Feb-00	22:24:01	23	-65.4371	5.45	5.00	-76.31	4.70	-53.40	-55.95	-60.44	2.42	0.60
7-Feb-00	22:16:21	23	-67.8417	6.69	7.53	-69.26	2.54	-47.40	-49.81	-60.31	2.41	1.40
7-Feb-00	22:22:41	23	-65.6152	5.67	5.40	-75.16	4.96	-52.46	-54.63	-60.22	2.41	0.64
7-Feb-00	22:21:01	23	-65.8824	5.94	5.92	-73.62	4.41	-51.14	-53.33	-59.96	2.40	0.13
7-Feb-00	22:23:41	23	-64.9918	5.51	5.09	-76.02	4.76	-53.16	-55.62	-59.90	2.40	1.19
7-Feb-00	22:10:01	23	-69.8901	7.72	10.01	-63.35	0.01	-42.32	-45.03	-59.88	2.40	3.76
18-Feb-00	12:18:58	24	-141.1348	8.24	21.58	-19.83	1.00	-14.56	-12.57	-119.55	2.39	0.00
7-Feb-00	22:23:58	24	-128.8033	5.46	9.47	-76.27	4.71	-53.36	-55.90	-119.34	2.39	2.32
7-Feb-00	22:21:41	23	-65.3480	5.83	5.71	-74.24	4.67	-51.67	-53.83	-59.64	2.39	0.57
7-Feb-00	22:14:58	24	-133.8129	6.92	15.19	-67.97	1.99	-46.29	-48.76	-118.62	2.37	0.66
7-Feb-00	22:18:01	23	-65.9714	6.42	6.93	-70.82	3.21	-48.73	-51.07	-59.04	2.36	0.41
7-Feb-00	22:13:38	24	-133.9093	7.13	16.15	-66.72	1.45	-45.22	-47.76	-117.76	2.36	0.83
7-Feb-00	22:15:21	23	-66.7730	6.85	7.90	-68.33	2.14	-46.60	-49.05	-58.88	2.36	0.25
7-Feb-00	22:16:18	24	-131.7898	6.70	14.26	-69.21	2.52	-47.36	-49.77	-117.53	2.35	0.63

Table A. List of events with ice load greater than 2MN
(Sorted from largest to smallest ice load)

Date	Time	Pier Number	Total tilt (baseline corrected) (μR)	Wind speed (m/s)	Wind tilt (μR)	Current speed northwest (cm/s)	Current speed northeast (cm/s)	Ice speed northwest (cm/s)	Ice speed north east (cm/s)	Ice tilt (μR)	Ice force (MN)	Ice draft thickness (m)
7-Feb-00	22:14:38	24	-132.8495	6.97	15.43	-67.66	1.85	-46.02	-48.51	-117.42	2.35	1.01
7-Feb-00	22:22:58	24	-127.0691	5.62	10.03	-75.40	4.91	-52.66	-54.91	-117.03	2.34	0.73
7-Feb-00	22:18:38	24	-129.2850	6.32	12.70	-71.39	3.45	-49.23	-51.53	-116.59	2.33	0.18
7-Feb-00	22:13:58	24	-132.4642	7.08	15.91	-67.04	1.59	-45.49	-48.01	-116.55	2.33	0.51
7-Feb-00	22:09:38	24	-135.6434	7.78	19.22	-62.99	-0.15	-42.01	-44.74	-116.42	2.33	2.77
7-Feb-00	22:18:41	23	-64.8137	6.31	6.70	-71.44	3.47	-49.27	-51.57	-58.11	2.32	0.18
7-Feb-00	22:20:21	23	-64.1012	6.04	6.14	-72.99	4.14	-50.60	-52.83	-57.96	2.32	1.06
7-Feb-00	22:18:58	24	-127.8399	6.27	12.48	-71.70	3.59	-49.49	-51.78	-115.36	2.31	0.18
7-Feb-00	22:20:01	23	-63.9231	6.10	6.25	-72.68	4.01	-50.34	-52.57	-57.67	2.31	1.15
7-Feb-00	22:22:01	23	-63.2106	5.77	5.61	-74.55	4.81	-51.94	-54.08	-57.60	2.30	0.80
7-Feb-00	22:21:21	23	-63.2996	5.88	5.82	-73.93	4.54	-51.40	-53.58	-57.48	2.30	0.14
7-Feb-00	22:24:18	24	-124.0826	5.41	9.28	-76.56	4.64	-53.60	-56.23	-114.80	2.30	0.12
7-Feb-00	22:11:21	23	-66.7730	7.50	9.46	-64.59	0.54	-43.39	-46.04	-57.31	2.29	3.83
7-Feb-00	22:15:18	24	-129.5740	6.86	14.95	-68.28	2.12	-46.56	-49.02	-114.62	2.29	0.59
7-Feb-00	22:09:58	24	-133.3312	7.73	18.95	-63.30	-0.01	-42.28	-44.99	-114.38	2.29	2.72
7-Feb-00	22:04:21	23	-69.6229	8.63	12.53	-57.43	-1.00	-37.93	-40.61	-57.09	2.28	0.25
7-Feb-00	22:11:41	23	-66.4167	7.45	9.32	-64.90	0.67	-43.66	-46.29	-57.09	2.28	0.90
7-Feb-00	22:19:41	23	-63.3887	6.15	6.36	-72.37	3.87	-50.07	-52.32	-57.03	2.28	0.57
18-Feb-00	11:53:58	24	-133.9093	7.96	20.10	-39.83	-2.61	-28.16	-31.42	-113.81	2.28	0.00
18-Mar-00	14:04:01	23	-68.1089	8.29	11.54	35.84	-4.54	25.77	21.81	-56.57	2.26	NaN
7-Feb-00	22:25:21	23	-61.1622	5.24	4.61	-77.47	4.43	-54.34	-57.27	-56.55	2.26	0.11
7-Feb-00	22:16:38	24	-127.0691	6.65	14.03	-69.52	2.65	-47.62	-50.02	-113.04	2.26	2.08
7-Feb-00	22:26:41	23	-60.6278	5.02	4.24	-78.63	4.16	-55.28	-58.59	-56.39	2.26	0.51
7-Feb-00	22:15:38	24	-127.4545	6.81	14.72	-68.59	2.25	-46.82	-49.27	-112.73	2.25	1.26
18-Feb-00	12:19:58	24	-132.2715	7.88	19.74	-19.03	1.00	-14.04	-11.81	-112.54	2.25	0.01
18-Feb-00	11:54:18	24	-131.1154	7.69	18.77	-39.56	-2.52	-27.97	-31.17	-112.35	2.25	0.00
7-Feb-00	22:25:18	24	-120.8070	5.24	8.73	-77.43	4.44	-54.31	-57.22	-112.08	2.24	0.12
7-Feb-00	22:27:01	23	-59.9154	4.97	4.14	-78.91	4.10	-55.52	-58.92	-55.77	2.23	0.16
7-Feb-00	22:19:18	24	-123.6972	6.21	12.27	-72.01	3.72	-49.76	-52.03	-111.43	2.23	2.23
7-Feb-00	22:24:38	24	-120.3253	5.35	9.10	-76.85	4.57	-53.83	-56.56	-111.23	2.22	0.12
7-Feb-00	22:25:01	23	-60.2716	5.29	4.70	-77.18	4.50	-54.10	-56.94	-55.57	2.22	0.12

Table A. List of events with ice load greater than 2MN
(Sorted from largest to smallest ice load)

Date	Time	Pier Number	Total tilt (baseline corrected) (μ R)	Wind speed (m/s)	Wind tilt (μ R)	Current speed northwest (cm/s)	Current speed northeast (cm/s)	Ice speed northwest (cm/s)	Ice speed north east (cm/s)	Ice tilt (μ R)	Ice force (MN)	Ice draft thickness (m)
18-Mar-00	15:32:41	23	-64.6355	7.39	9.17	60.64	-0.32	37.65	42.91	-55.47	2.22	NaN
7-Feb-00	22:27:21	23	-59.4701	4.91	4.06	-79.20	4.03	-55.76	-59.25	-55.41	2.22	0.30
7-Feb-00	22:26:01	23	-59.8263	5.13	4.42	-78.05	4.30	-54.81	-57.93	-55.41	2.22	1.98
7-Feb-00	22:19:21	23	-61.8747	6.21	6.48	-72.06	3.74	-49.80	-52.07	-55.40	2.22	2.75
7-Feb-00	22:18:18	24	-123.6009	6.38	12.91	-71.08	3.32	-48.96	-51.28	-110.69	2.21	0.33
18-Feb-00	11:52:38	24	-128.7069	7.56	18.15	-40.89	-2.96	-28.92	-32.43	-110.56	2.21	0.01
7-Feb-00	22:22:21	23	-60.7169	5.72	5.50	-74.86	4.94	-52.20	-54.33	-55.21	2.21	0.26
7-Feb-00	22:15:58	24	-124.3716	6.75	14.49	-68.90	2.39	-47.09	-49.52	-109.88	2.20	0.44
18-Mar-00	14:03:41	23	-66.0605	8.18	11.25	35.73	-4.49	25.60	21.73	-54.82	2.19	NaN
18-Feb-00	11:53:18	24	-131.6935	8.35	22.14	-40.36	-2.79	-28.54	-31.92	-109.55	2.19	0.00
18-Feb-00	11:52:58	24	-129.1886	7.90	19.81	-40.63	-2.88	-28.73	-32.17	-109.38	2.19	NaN
7-Feb-00	22:13:18	24	-125.6240	7.19	16.40	-66.41	1.32	-44.95	-47.51	-109.23	2.18	0.34
7-Feb-00	22:20:41	23	-60.6278	5.99	6.03	-73.30	4.27	-50.87	-53.08	-54.59	2.18	1.25
7-Feb-00	22:09:18	24	-128.4179	7.83	19.49	-62.68	-0.28	-41.75	-44.49	-108.93	2.18	2.26
7-Feb-00	22:17:58	24	-122.0595	6.43	13.13	-70.77	3.19	-48.69	-51.03	-108.93	2.18	0.26
18-Feb-00	12:16:18	24	-120.1327	5.98	11.36	-21.96	1.00	-15.94	-14.58	-108.77	2.18	NaN
7-Feb-00	22:14:01	23	-62.6762	7.07	8.40	-67.08	1.61	-45.53	-48.05	-54.27	2.17	0.58
7-Feb-00	22:18:21	23	-61.0731	6.37	6.82	-71.13	3.34	-49.00	-51.32	-54.26	2.17	0.19
7-Feb-00	22:24:58	24	-117.3388	5.30	8.91	-77.14	4.51	-54.07	-56.89	-108.43	2.17	0.12
7-Feb-00	22:07:01	23	-65.4371	8.20	11.31	-60.45	-1.00	-39.94	-42.75	-54.13	2.17	3.61
7-Feb-00	22:23:21	23	-59.1138	5.56	5.19	-75.74	4.83	-52.93	-55.29	-53.92	2.16	0.42
18-Feb-00	11:53:38	24	-131.3081	8.61	23.53	-40.09	-2.70	-28.35	-31.67	-107.78	2.16	0.06
7-Feb-00	22:15:01	23	-61.6075	6.91	8.02	-68.02	2.01	-46.33	-48.80	-53.59	2.14	0.21
7-Feb-00	22:16:41	23	-60.8950	6.64	7.41	-69.57	2.67	-47.66	-50.06	-53.49	2.14	3.25
7-Feb-00	22:17:38	24	-120.2290	6.48	13.35	-70.46	3.05	-48.43	-50.78	-106.87	2.14	0.27
18-Feb-00	12:16:38	24	-119.8436	6.42	13.10	-21.69	1.00	-15.77	-14.32	-106.74	2.13	0.02
7-Feb-00	22:27:38	24	-114.2559	4.87	7.52	-79.45	3.97	-55.96	-59.53	-106.74	2.13	0.21
7-Feb-00	22:25:58	24	-114.8340	5.14	8.38	-78.00	4.31	-54.78	-57.88	-106.46	2.13	2.48
18-Feb-00	11:52:18	24	-124.8533	7.62	18.43	-41.17	-2.97	-29.10	-32.46	-106.42	2.13	0.00
7-Feb-00	22:14:41	23	-61.3403	6.96	8.15	-67.70	1.87	-46.06	-48.55	-53.19	2.13	0.81
11-Mar-00	4:11:58	24	-107.5121	2.09	1.38	-28.02	-5.40	-7.51	-16.22	-106.13	2.12	1.80

Table A. List of events with ice load greater than 2MN
(Sorted from largest to smallest ice load)

Date	Time	Pier Number	Total tilt (baseline corrected) (μ R)	Wind speed (m/s)	Wind tilt (μ R)	Current speed northwest (cm/s)	Current speed northeast (cm/s)	Ice speed northwest (cm/s)	Ice speed north east (cm/s)	Ice tilt (μ R)	Ice force (MN)	Ice draft thickness (m)
7-Feb-00	22:20:38	24	-117.5315	6.00	11.43	-73.26	4.25	-50.83	-53.04	-106.10	2.12	2.19
7-Feb-00	22:12:01	23	-62.2309	7.39	9.19	-65.22	0.81	-43.92	-46.54	-53.04	2.12	0.40
18-Feb-00	12:07:18	24	-119.2656	6.48	13.32	-29.16	0.95	-20.62	-21.36	-105.95	2.12	0.10
18-Feb-00	12:18:38	24	-126.3948	8.04	20.54	-20.09	1.00	-14.73	-12.82	-105.85	2.12	0.00
7-Feb-00	22:25:38	24	-114.3523	5.19	8.55	-77.72	4.37	-54.54	-57.55	-105.80	2.12	1.58
7-Feb-00	22:13:41	23	-61.4294	7.12	8.53	-66.77	1.47	-45.26	-47.80	-52.90	2.12	0.02
7-Feb-00	22:16:58	24	-119.4583	6.59	13.80	-69.84	2.79	-47.89	-50.27	-105.66	2.11	0.58
18-Mar-00	15:33:01	23	-60.3607	6.71	7.57	60.60	-0.30	37.54	42.92	-52.79	2.11	NaN
18-Feb-00	12:05:18	24	-116.3754	5.84	10.84	-30.76	0.41	-21.75	-22.87	-105.54	2.11	NaN
18-Mar-00	10:07:41	23	-65.0808	8.59	12.40	-97.90	-3.05	-58.70	-77.69	-52.69	2.11	NaN
7-Feb-00	22:10:18	24	-123.8899	7.67	18.69	-63.61	0.12	-42.55	-45.24	-105.20	2.10	2.06
7-Feb-00	22:27:58	24	-112.5218	4.81	7.35	-79.74	3.91	-56.19	-59.86	-105.17	2.10	0.89
7-Feb-00	22:06:41	23	-63.9231	8.26	11.46	-60.07	-1.00	-39.69	-42.48	-52.46	2.10	2.44
18-Mar-00	14:58:01	23	-62.4090	7.76	10.12	56.37	-2.37	36.58	36.84	-52.30	2.09	NaN
18-Mar-00	14:10:21	23	-61.1622	7.27	8.89	38.71	-4.43	28.25	24.10	-52.28	2.09	NaN
7-Feb-00	22:25:41	23	-56.6201	5.18	4.51	-77.76	4.36	-54.58	-57.60	-52.11	2.08	1.33
18-Mar-00	12:51:01	23	-60.0044	6.89	7.98	-3.79	-5.80	0.01	-5.86	-52.03	2.08	NaN
7-Feb-00	22:17:18	24	-117.6278	6.54	13.58	-70.15	2.92	-48.16	-50.53	-104.05	2.08	0.23
18-Mar-00	14:13:01	23	-61.9637	7.70	9.97	40.31	-3.90	28.88	25.49	-52.00	2.08	NaN
18-Mar-00	13:08:21	23	-62.2309	7.81	10.26	1.62	-6.77	5.27	-3.10	-51.98	2.08	NaN
18-Mar-00	9:20:01	23	-67.0402	9.47	15.09	-106.84	-9.17	-64.59	-87.46	-51.96	2.08	NaN
18-Mar-00	15:53:21	23	-63.7449	8.38	11.82	55.60	0.83	37.20	40.57	-51.93	2.08	NaN
18-Mar-00	15:20:41	23	-61.6966	7.63	9.79	61.39	-1.24	40.58	41.91	-51.91	2.08	NaN
7-Feb-00	22:26:21	23	-56.1748	5.07	4.33	-78.34	4.23	-55.05	-58.26	-51.85	2.07	0.18
7-Feb-00	22:19:58	24	-115.5083	6.11	11.84	-72.63	3.99	-50.30	-52.54	-103.66	2.07	1.44
18-Feb-00	12:05:38	24	-116.8571	6.46	13.23	-30.49	0.50	-21.56	-22.62	-103.62	2.07	NaN
18-Feb-00	12:17:58	24	-125.6240	8.36	22.17	-20.63	1.00	-15.08	-13.32	-103.45	2.07	0.00
18-Mar-00	13:08:41	23	-63.1215	8.24	11.41	1.87	-6.68	5.40	-2.92	-51.72	2.07	NaN
18-Mar-00	14:32:21	23	-59.5591	6.83	7.85	48.63	-2.00	34.36	30.41	-51.71	2.07	NaN
18-Mar-00	14:57:41	23	-60.4497	7.22	8.75	56.35	-2.35	36.55	36.80	-51.70	2.07	NaN
7-Feb-00	22:08:58	24	-123.1192	7.89	19.76	-62.37	-0.41	-41.48	-44.24	-103.36	2.07	2.37

Table A. List of events with ice load greater than 2MN
(Sorted from largest to smallest ice load)

Date	Time	Pier Number	Total tilt (baseline corrected) (μ R)	Wind speed (m/s)	Wind tilt (μ R)	Current speed northwest (cm/s)	Current speed northeast (cm/s)	Ice speed northwest (cm/s)	Ice speed north east (cm/s)	Ice tilt (μ R)	Ice force (MN)	Ice draft thickness (m)
7-Feb-00	22:19:38	24	-115.3157	6.16	12.05	-72.32	3.85	-50.03	-52.28	-103.26	2.07	0.74
7-Feb-00	22:32:01	23	-52.1671	2.00	0.67	-83.25	3.10	-59.05	-63.87	-51.49	2.06	0.14
7-Feb-00	22:32:21	23	-52.2562	2.15	0.78	-83.54	3.03	-59.29	-64.20	-51.48	2.06	0.28
18-Feb-00	11:51:58	24	-121.1924	7.60	18.35	-41.46	-2.93	-29.27	-32.35	-102.84	2.06	0.00
7-Feb-00	22:20:58	24	-113.7742	5.94	11.22	-73.57	4.39	-51.10	-53.29	-102.55	2.05	0.15
7-Feb-00	22:26:58	24	-110.2096	4.97	7.86	-78.87	4.11	-55.48	-58.87	-102.35	2.05	0.18
18-Feb-00	12:15:58	24	-115.6047	6.47	13.30	-22.23	1.00	-16.12	-14.83	-102.30	2.05	0.00
7-Feb-00	22:12:21	23	-60.1825	7.34	9.06	-65.53	0.94	-44.19	-46.79	-51.13	2.05	0.85
18-Mar-00	15:00:41	23	-57.7779	6.29	6.66	56.55	-2.55	36.83	37.22	-51.13	2.05	NaN
7-Feb-00	23:28:21	23	-57.8670	6.34	6.75	-124.39	-6.00	-79.20	-97.86	-51.11	2.04	0.11
18-Mar-00	14:40:21	23	-65.7933	9.36	14.72	51.14	-2.00	36.06	31.48	-51.08	2.04	NaN
18-Feb-00	11:58:38	24	-114.2559	6.21	12.25	-36.09	-1.36	-25.52	-27.90	-102.01	2.04	0.00
7-Feb-00	22:07:21	23	-62.0528	8.15	11.16	-60.83	-1.00	-40.19	-43.01	-50.89	2.04	2.97
7-Feb-00	22:10:38	24	-120.1327	7.62	18.43	-63.92	0.25	-42.82	-45.50	-101.70	2.03	0.82
18-Feb-00	11:51:38	24	-117.4351	7.06	15.82	-41.75	-2.88	-29.44	-32.24	-101.61	2.03	0.05
18-Feb-00	12:07:38	24	-116.4717	6.85	14.91	-28.89	1.00	-20.44	-21.11	-101.57	2.03	0.03
18-Mar-00	15:21:01	23	-60.0935	7.45	9.32	61.51	-1.20	40.66	42.01	-50.78	2.03	NaN
18-Mar-00	15:01:01	23	-58.3123	6.73	7.60	56.57	-2.57	36.87	37.27	-50.71	2.03	NaN
7-Feb-00	22:27:41	23	-54.6608	4.86	3.97	-79.49	3.96	-55.99	-59.58	-50.69	2.03	0.25
7-Feb-00	22:12:58	24	-117.9168	7.24	16.65	-66.10	1.19	-44.69	-47.26	-101.27	2.03	1.22
18-Mar-00	15:33:21	23	-59.6482	7.33	9.03	60.55	-0.28	37.43	42.94	-50.62	2.02	NaN
18-Mar-00	15:35:01	23	-58.6685	6.94	8.09	60.33	-0.17	36.88	43.02	-50.59	2.02	NaN
18-Feb-00	12:06:58	24	-116.3754	6.92	15.20	-29.43	0.86	-20.81	-21.62	-101.17	2.02	0.07
7-Feb-00	22:20:18	24	-112.7145	6.05	11.64	-72.95	4.12	-50.56	-52.79	-101.08	2.02	1.76
18-Feb-00	12:16:58	24	-118.4949	7.43	17.54	-21.43	1.00	-15.60	-14.07	-100.96	2.02	NaN
18-Mar-00	15:32:21	23	-63.6559	8.86	13.19	60.69	-0.34	37.76	42.89	-50.48	2.02	NaN
11-Mar-00	4:11:38	24	-103.0805	2.59	2.13	-28.25	-5.45	-7.63	-16.49	-100.95	2.02	2.36
18-Feb-00	12:18:18	24	-124.1789	8.56	23.25	-20.36	1.00	-14.91	-13.07	-100.93	2.02	NaN
18-Feb-00	12:04:58	24	-113.0998	6.21	12.24	-31.03	0.32	-21.94	-23.12	-100.86	2.02	0.01
18-Feb-00	12:08:18	24	-114.8340	6.64	14.01	-28.36	1.00	-20.09	-20.61	-100.82	2.02	0.01
18-Feb-00	11:54:38	24	-118.5912	7.51	17.93	-39.29	-2.43	-27.78	-30.92	-100.66	2.01	0.00

Table A. List of events with ice load greater than 2MN
(Sorted from largest to smallest ice load)

Date	Time	Pier Number	Total tilt (baseline corrected) (μ R)	Wind speed (m/s)	Wind tilt (μ R)	Current speed northwest (cm/s)	Current speed northeast (cm/s)	Ice speed northwest (cm/s)	Ice speed north east (cm/s)	Ice tilt (μ R)	Ice force (MN)	Ice draft thickness (m)
18-Feb-00	12:05:58	24	-117.3388	7.27	16.81	-30.23	0.59	-21.37	-22.37	-100.53	2.01	NaN
18-Feb-00	12:08:38	24	-114.8340	6.73	14.37	-28.09	1.00	-19.92	-20.36	-100.46	2.01	0.01
18-Mar-00	15:01:21	23	-58.6685	7.10	8.48	56.59	-2.59	36.90	37.31	-50.19	2.01	NaN
18-Feb-00	12:20:18	24	-120.1327	7.92	19.90	-18.76	1.00	-13.87	-11.56	-100.23	2.00	0.00

Note: NaN in ice draft thickness indicates that the ice draft thickness value is unreliable(negative)!

APPENDIX B

Ice Draft Thickness vs. Ice Force

Ice Drift Speed vs. Ice Force

Figure B-1 Ice Keel Depth vs. Ice Force-Ice Speed is less than 10 cm/s

Figure B-2 Ice Keel Depth vs. Ice Force-Ice Speed is from 10 to 20 cm/s

Figure B-3 Ice Keel Depth vs. Ice Force-Ice Speed from 20-30cm/s

Figure B-4 Ice Keel Depth vs. Ice Force-Ice Speed from 30-40cm/s

Figure B-5 Ice Keel Depth vs. Ice Force-Ice Speed from 40-50cm/s

Figure B-6 Ice Keel Depth vs. Ice Force-Ice Speed from 50-60cm/s

Figure B-7 Ice Keel Depth vs. Ice Force –Ice Speed from 60-70 cm/s

Figure B-8 Ice Keel Depth vs. Ice Force –Ice Speed from 70-80 cm/s

Figure B-9 Ice Keel Depth vs. Ice Force –Ice Speed from 80-90 cm/s

Figure B-10 Ice Speed vs. Ice Force- Ice Keel Depth is from 0-2m

Figure B-11 Ice Speed vs. Ice Force- Ice Keel Depth is from 2-4m

Figure B-12 Ice Speed vs. Ice Force- Ice Keel Depth is from 4-6m

Figure B-13 Ice Speed vs. Ice Force- Ice Keel Depth is from 6-8m

Figure B-14 Ice Speed vs. Ice Force- Ice Keel Depth is greater than 8m

APPENDIX C

Wind Tilt vs. Wind Velocity Squared

Figure C-1 Wind tilt vs. wind speed-April 8, 2001

Figure C-2 Wind tilt vs. wind speed-April 14, 2001

Figure C-3 Wind tilt vs. wind speed-April 4, 2001

Figure C-4 Wind tilt vs. wind speed-April 29, 2001

Figure C-5 Wind tilt vs. wind speed-May 01, 2001

Figure C-6 Wind tilt vs. wind speed-April 12, 2001

Figure C-7 Wind tilt vs. wind speed-April 16, 2001

Figure C-8 Wind tilt vs. wind speed-April 13, 2001

Figure C-9 Wind tilt vs. wind speed-April 29, 2001