POAC'11
Montréal, Canada

Proceedings of the 21st International Conference on
Port and Ocean Engineering under Arctic Conditions
July 10-14, 2011
Montréal, Canada

POAC11-028

THE STUDY OF RELATIONSHIP BETWEEN ICE GEOMETRIC CHARACTERISTICS AND THEIR EFFECT ON ICE ACTION

Noorma Shrestha [1], Thomas G. Brown [1], Derek C. Mayne [1]
[1]University of Calgary, Calgary, CANADA

ABSTRACT
During the design of piers of the Confederation Bridge, various design parameters including ice velocity, ice thickness, rubble height, ride up and ridge keel properties were considered in the assessment of ice action. After the Bridge opened in 1997, various monitoring programs were initiated to monitor these and other design parameters. One of the major projects includes continuous measurement of ice forces on piers P31 and P32. In the span of thirteen years of monitoring, the relationship between design models and reality has been investigated using the full-scale data from the Bridge. As part of this study, this paper focuses on analyzing the relationship between various ice parameters including: ice thickness, ice velocity, keel depth, interaction height, presence of rubble or ride-up and their effect on ice actions. The relationships between these parameters and their effect on ice actions are derived using data available from the Confederation Bridge monitoring program. The results are also compared and verified with the existing models. The results have confirmed the importance of some parameters and have indicated that others do not have the expected influence. The particular shape of the Confederation Bridge Piers is considered in assessing the results.

INTRODUCTION
The effects of ice parameters such as ice velocity, ice thickness, keel depth and interaction heights are important topics in ice action research for offshore structures. Ice parameters have always been uncertain factors while estimating ice action on the structures. Various studies have been carried out to investigate the relationship between ice geometric parameters and their effects on ice load, individually or combined. However, the conclusions vary between different studies. Conical structures are more effective in reducing the forces associated with interactions with ice features. Still, the failure against the conical structures is a complicated process which involves a number of different parameters affecting ice load in the structure. In this paper, five such parameters are considered to study the relationship between each other and their effects on the total load on the structure. These parameters are: ice speed, ice thickness, pile-up height, rubble angle and keel depth.

The data from the Confederation Bridge Monitoring Program (CBMP) is used to investigate the relations between these parameters. The monitoring program has been in place since 1997. The program measures ice loads at two piers, P31 and P32, of the 12.9 km bridge that spans the Northumberland Strait. A total of 1950 events at pier P31 and 823 events at pier P32 are selected for the analysis. The data used for the analysis are for the years 2005 to 2010, but keel data is available for only two years, 2007 and 2008 for this period. The study has also examined the effect of several variables on ice action.

METHODOLOGY

The ice loads were processed for every ice season and ice events i.e., ice load greater than 0.75 MN were identified from the tiltmeter record after correcting the tilts for wind effects. For events that occurred in daylight hours, the required event specific parameters were determined from image analysis of the video imagery. These parameters include: ice speed, ice thickness, pileup or ride-up height, rubble angle and upper pile length. Figure 1 show some typical measurements obtained from the image analysis. The ice thickness was determined from ice pieces within the rubble pile or ride up ice. For each event, multiple ice thickness measurements were taken, if available. To define rubble geometry, pile up height, rubble angle, and upper pile length were measured. The ice sheet velocity was determined from two images taken approximately 10 sec apart and measuring the distance of a particular landmark on the moving ice sheet. Multiple landmarks on the ice sheet surface were identified in each set of pictures and velocity was averaged for a particular event time. The digital ice videos are available from year 2005 onwards only, so this study is limited to events after the year 2005. For the years 2007-2008, sonar data is used to derive the geometric properties of keel. Events occurring due to limit driving force have been excluded from the analysis. Detailed statistical analysis on data is then carried out to find the relation between the ice load and ice parameters.

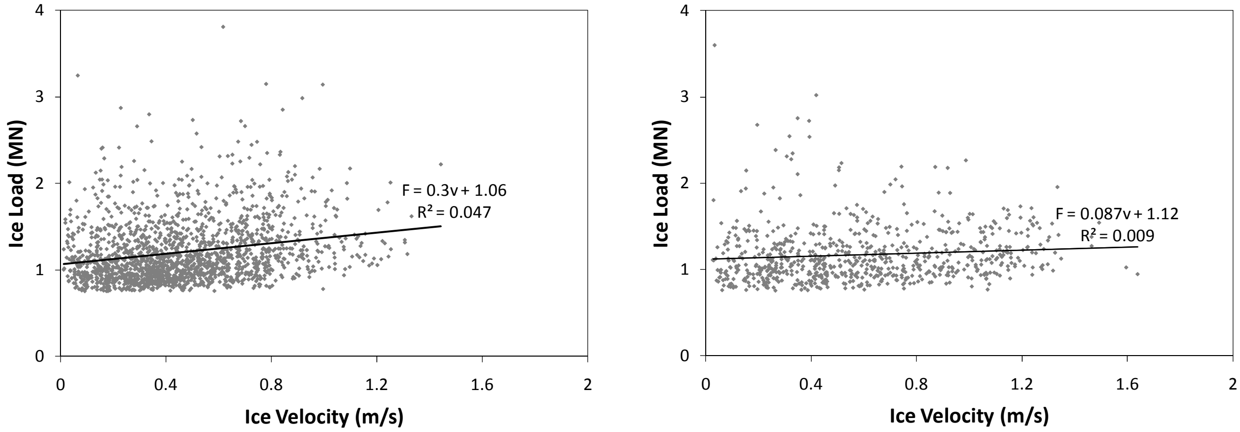
Figure 1: Typical example of image analysis for the measurements of rubble pile geometry (left), ride up (mid) and ice thickness (right)

OBSERVATIONS AND RESULTS

Ice velocity

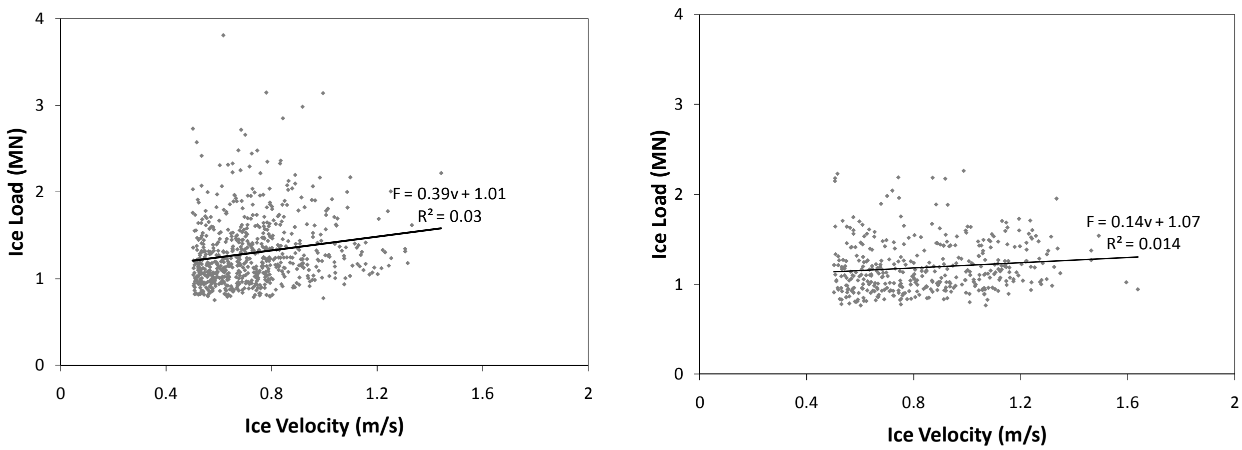
The momentum of the ice is related to the velocity of ice, which affects the load it can impart to a structure during an impact. Matskevitch (2002), in his study concludes that, for a mid-size conical structure, velocity effect is negligible for speed up to 0.5 m/s and after this point, the load will increase linearly with the velocity. Brown (2008) used the Confederation Bridge data from 1998 to 2000 to examine the relationship between ice velocity and ice load on the Bridge pier. But the relationship was weak between ice loads and velocity, thus suggesting that velocity is not a major factor when determining loads on this conical structure.

In this paper the ice velocity and ice load data from 2005 to 2010 is used to investigate the effect of velocity on load and other ice parameters. Figure 2 illustrates the relation between the measured load and speed of the interacting ice. Figure 3 shows a similar plot for ice velocity greater than 0.5 m/s. The data presented in these figures has weak relationship between the measured load and the velocity. But, in general, the ice load increases with the increase in velocity. The ice velocity measured for the selected events are in range of 0.01 to 1.44 m/s at pier P31 and 0.03 to 1.64 m/s at pier P32.



(a) (b)

Figure 2: Plot of load against ice velocity (a) P31 and (b) P32

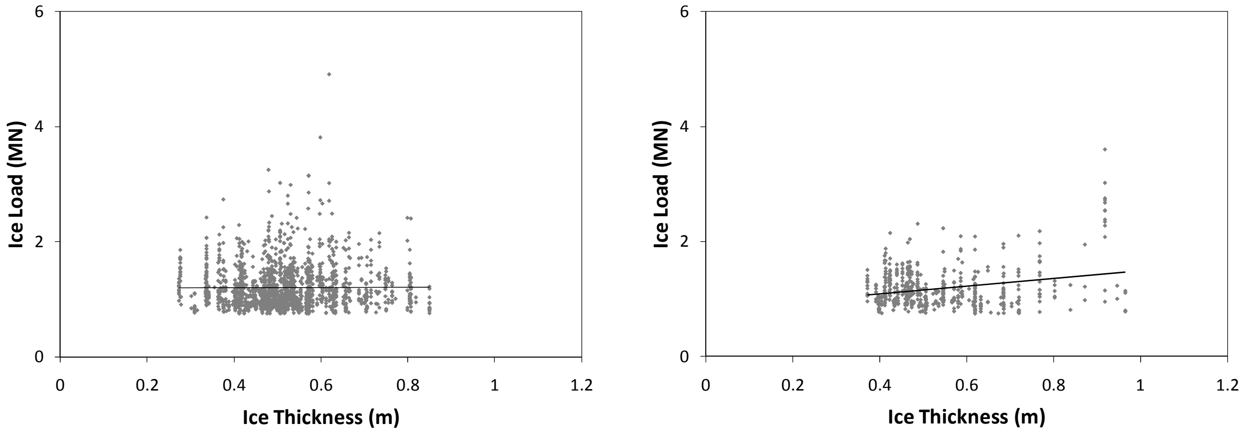


(a) (b)

Figure 3: Plot of load against velocity for ice velocity > 0.5 m/s (a) P31 and (b) P32

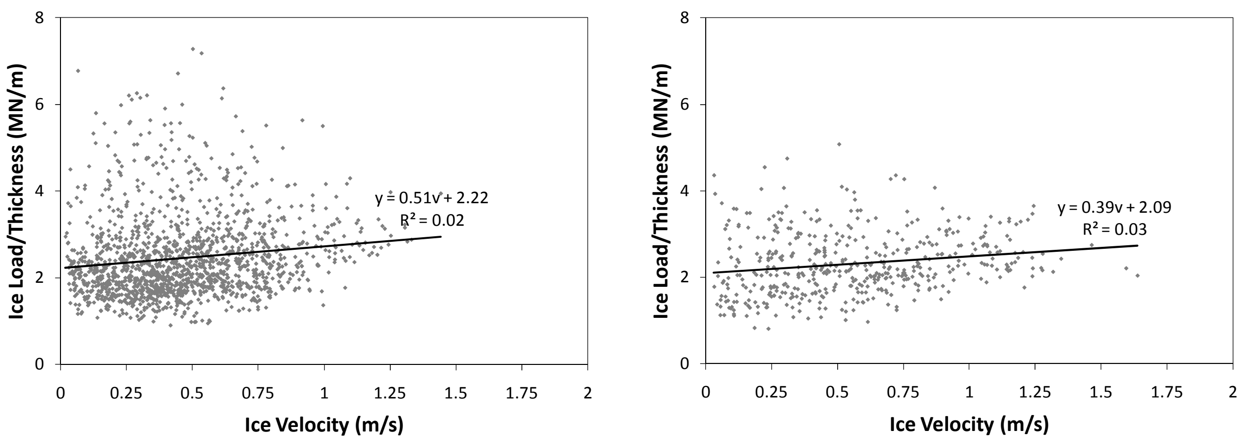
Ice thickness

Ice thickness is one of most important parameters in flexural failure model (Croasdale et.al., 1994; Nevel, 1992; Ralston, 1977). The theoretical flexural failure term depends on the thickness squared; rideup and rubble terms are related to ice thickness. All flexural failure models (Crosdale, Ralston, Nevel, and Mayne models) report an increase in load for an increasing ice thickness (Tibbo, 2010). In the Northumberland Strait, thickness of ice varies throughout the winter; ice sheets can reach thickness of up to 1m. The ice thickness measured for selected events varied from 0.17 to 1.6 m at P31 and 0.2 to 1.37 m at P32. Figure 4 illustrates the plot between ice thickness and measured load. The data shows very weak relationship between measured load and ice thickness. The ice thickness term can be more of an influence on rubble and ride up terms while estimating ice load on structure. Figure 5 plots the ratio of load and thickness against ice velocity. This shows that the effect of thickness can be incorporated in model by factoring load by some function of the thickness.



(a) (b)

Figure 4: Plot of load against ice thickness (a) P31 and (b) P32



(a) (b)

Figure 5: Load/Thickness vs. Ice Velocity (a) P31 and (b) P32

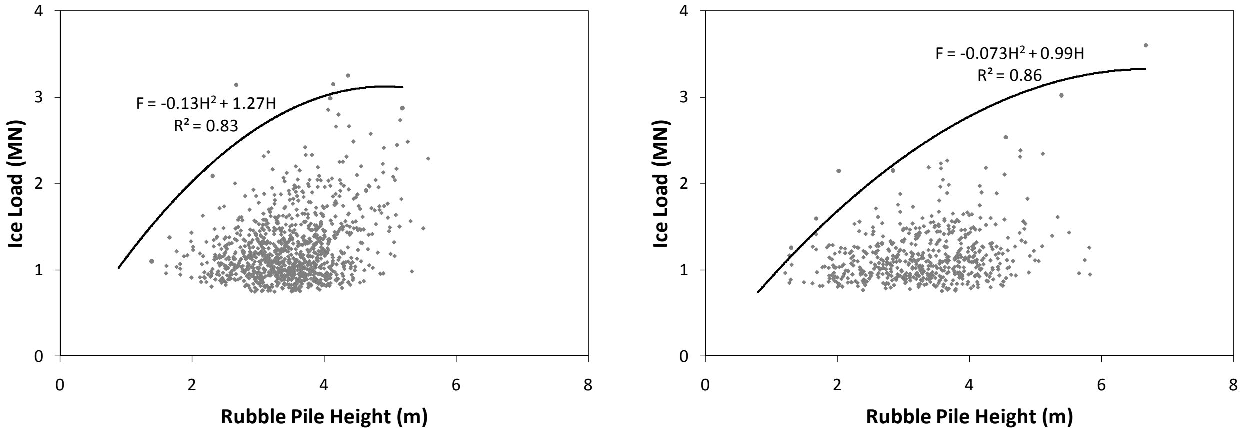
Pile up height

Rubble pile load contribution is the most significant in flexural failure of ice on the conical structures. The shape and size of rubble pile depend on the surface conditions, ice thickness, ice velocity and piece size (Mayne and Brown, 2000). The rubble pile height observed ranged from 1.39 to 5.58 m at P31 and 1.69 to 6.67 m at P32 from water level. Since keel data is not available for all ice seasons, keel effect on the behaviour of rubble has not been considered. Figure 6 plots the ice load against rubble pile height. Clearly, load increase with increase in rubble pile height. However, all rubble piles do not have full confinement around the pier. The relation between pile up and load can be improved by grouping pile up height according to rubble pile confinement or pile volume. Considering only the maxima, the best-fit trend line shown is the second order polynomial, where equation (1) is for P31 and equation (2) is for P32. The trend lines are specified with an intercept of zero.

$$F = -0.13H^2 + 1.27H \text{ , with } R^2 \text{ value of } 0.83 \quad (1)$$

$$F = -0.073H^2 + 0.99H \text{ , with } R^2 \text{ value of } 0.86 \quad (2)$$

where, F = ice load and H = rubble pile height.



(a) (b)

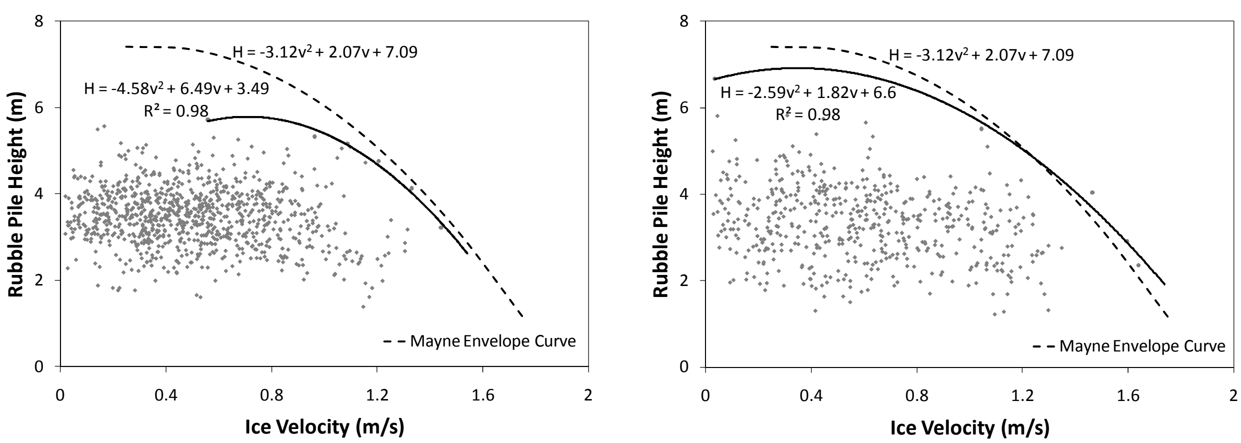
Figure 6: Ice Load vs. Rubble Pile Height (a) P31 and (b) P32

Figure 7 shows the relation between rubble height and ice velocity for all observations at piers P31 and P32. As speed increases, the maximum rubble pile height is reduced as a result of improved clearing of the rubble. Considering only maxima, the relationship between decreasing pile height (H) as velocity (v) increases, fitting second order polynomial trend line is:

$$H = -4.58v^2 + 6.49v + 3.49 \text{ , with } R^2 \text{ value of } 0.98 \quad (3)$$

$$H = -2.59v^2 + 1.82v + 6.6 \text{ , with } R^2 \text{ value of } 0.98 \quad (4)$$

where equation (3) represents pier P31 and equation (4) represents pier P32. Figure 7 also shows the upper envelope curve developed by Mayne and Brown (2000) using data from the Confederation Bride for years 1998-2000, indicating similar trends.



(a) (b)

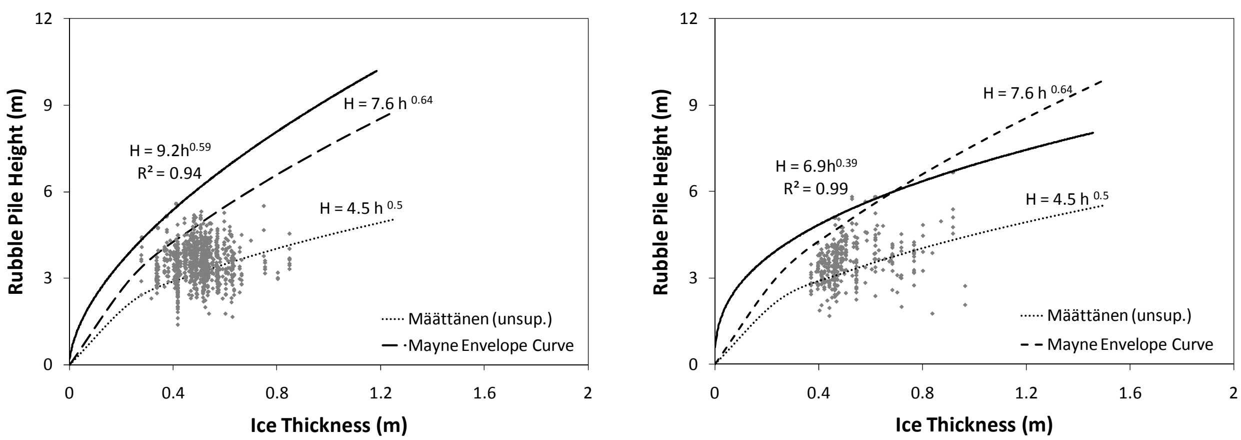
Figure 7: Rubble Pile Height vs. Ice velocity (a) P31 and (b) P32

The rubble pile height versus ice thickness plot for both piers is shown in Figure 8. Considering only maxima, the relationship between pile height (*H*) and ice thickness (*h*), fitting power relation is:

$$H = 9.2\,h^{0.59} \text{ , with R}^2 \text{ value of } 0.94 \qquad (5)$$

$$H = 6.9\,h^{0.39} \text{ , with R}^2 \text{ value of } 0.99 \qquad (6)$$

where, equation (5) represents pier P31 and equation (6) represents pier P32. Figure 8 also shows the upper envelope curve developed by Mayne and Brown (2000) using data from the Confederation Bride for years 1998-2000 and Määttänen and Hoikkanen (1990) theory based on field observations made from light piers in the Gulf of Bothnia.



(a) (b)

Figure 8: Rubble Pile Height vs. Ice Thickness (a) P31 and (b) P32

Though, the thickness and velocity have been considered separately, their effects are related and should be considered together. Applying linear and second order polynomial multi-regression analysis for all events with rubble piles, the relationship between pile up height (*H*), ice velocity (*v*) and ice thickness (*h*) is given in equations (7) to (10). However, the R^2 value is weak in all relations. Equation (7) and equation (8) represents linear and second order polynomial for pier P31 and equation (9) and equation (10) represent the same relations for pier P32.

$$H = 0.41\,h - 0.52\,v + 3.56 \text{ , with R}^2 \text{ value of } 0.05 \qquad (7)$$

$$H = -3.02\,h^2 + 3.55\,h - 0.63\,v^2 + 0.2\,v + 2.62 \text{ , with R}^2 \text{ value of } 0.06 \qquad (8)$$

$$H = 1.52\,h - 0.37v + 2.99 \text{ , with R}^2 \text{ value of } 0.112 \qquad (9)$$

$$H = -6.66h^2 + 9.64\,h + 0.24\,v^2 - 0.69\,v + 0.75 \text{, with R}^2 \text{ value of } 0.143 \qquad (10)$$

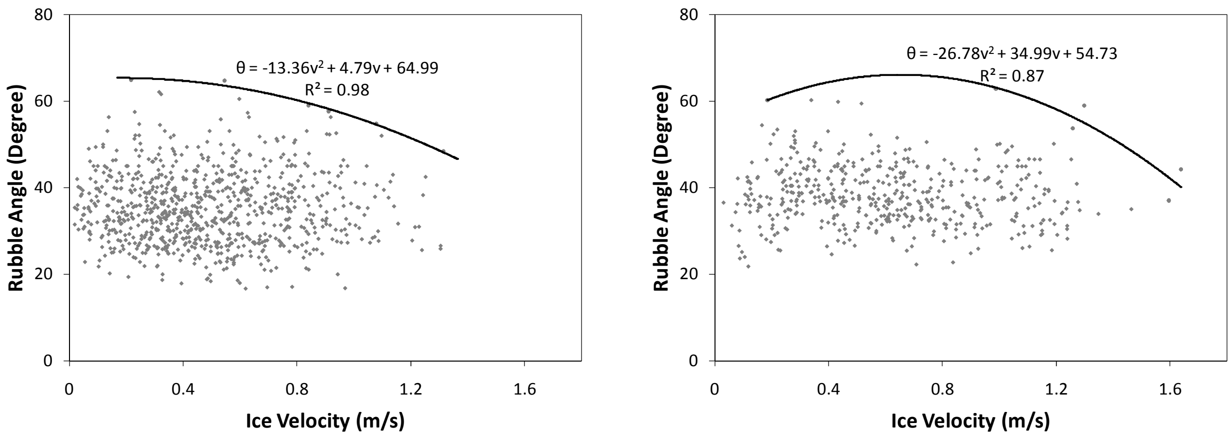
Rubble angle

Due to the unique shape of the Confederation Bridge piers, the typical rubble pile at the pier is bilinear. Table 1 shows the maximum and minimum rubble angles for a bilinear rubble profile measured at the piers, P31 and P32, of the Confederation Bridge. Figure 9 plot rubble angle against ice velocity. For bilinear rubble profile, the rubble angle is the average of the two slopes, lower angle and upper angle. As a result, this slope cannot be used to calculate rubble pile volume in load calculation, but can be used to understand the general trend between rubble angle and ice velocity. Considering only maxima, there is a decrease in the rubble pile angle (θ) as velocity increases. The upper envelope curve shown is second order polynomial:

$$\theta = -13.36v^2 + 4.97v + 64.99 \text{ , with } R^2 \text{ value of } 0.98 \tag{11}$$

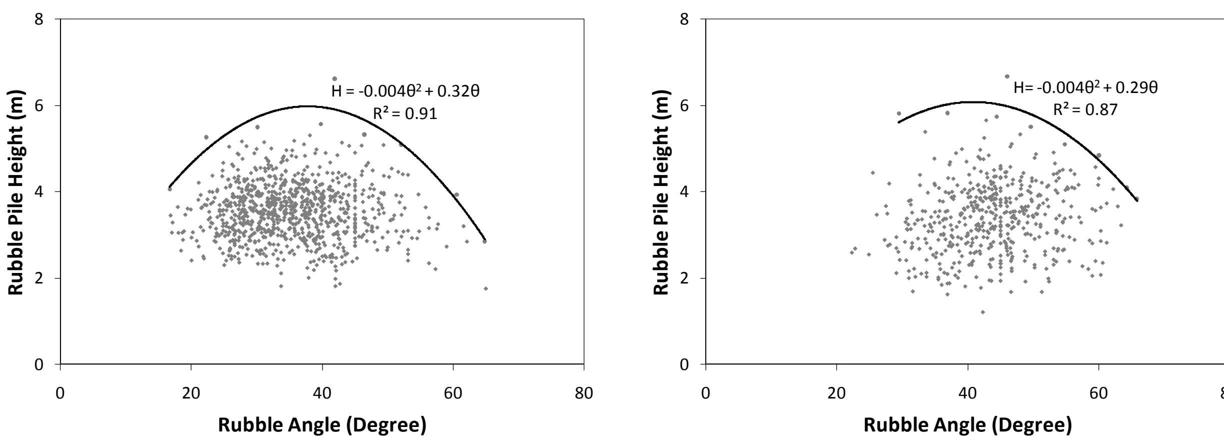
$$\theta = -26.78v^2 + 34.99v + 54.73 \text{ , with } R^2 \text{ value of } 0.87 \tag{12}$$

where, equation (11) represents pier P31 and equation (12) represents pier P32. Similarly, Figure 10 plots rubble pile height against rubble angle. The second order polynomial trend line is fit to describe an upper envelope curve. The trend line is set to intercept at zero. The envelope curve shows that there is a range of rubble angles for which pile-ups attain maximum height. There is an upper limit value for slope angle and this value of slope angle is compatible with the maximum mathematical value of the slope of a rubble pile having 7m height and supported on the bridge cone.



(a) (b)

Figure 9: Rubble Angle vs. Ice velocity (a) P31 and (b) P32

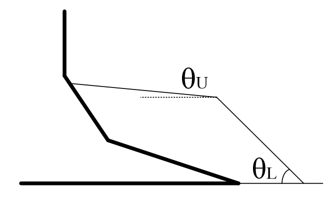


(a) (b)

Figure 10: Rubble Pile Height vs. Rubble Angle (a) P31 and (b) P32

Table 1. The maximum and minimum angles for a bilinear rubble profile

Pier#	Upper Angle (θ_U, deg)		Lower Angle (θ_L, deg)	
	min	max	min	max
P31	4	40.8	21.1	71.6
P32	7.1	42	34	65.8



Keel depth

The keel geometric parameters and their effect have been extensively studied for the Confederation Bridge data by Lemée (2003) and Obert (2010). The most recent ridge study for the area have measured maximum keel depths of 7.85 m and 8.49 m for the 2007 and 2008 ice seasons respectively (Obert, 2010). Keel depths up to 16m have been observed since bridge monitoring started. Obert (2010) study has shown that there is no apparent relationship between load and keel depth. Figure 11 shows the plot of load against keel depth and the relationship is very weak. Due to the unique shape of the Bridge pier, no relationship exists between ice load and keel depth as the bottom edge of the ice shield breaks up the keels greater than 4 m, thus reducing the load effect.

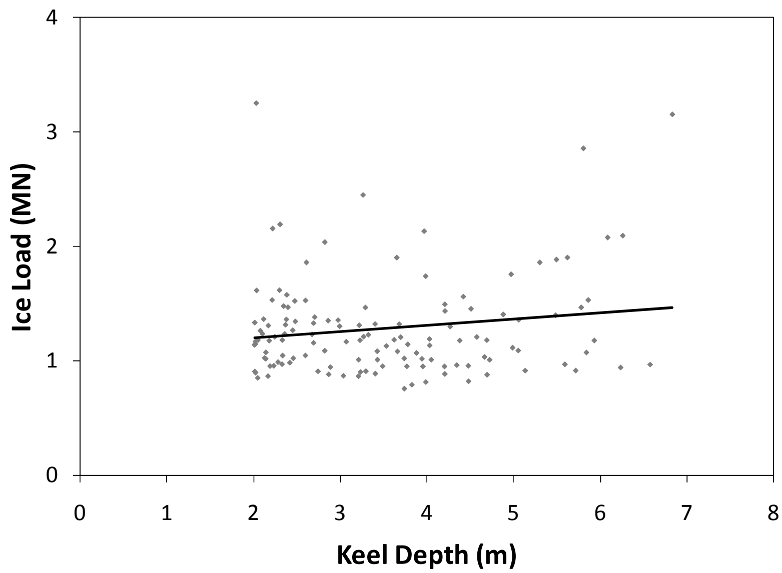


Figure 11: Plot of load against keel depth for P31

DISCUSSION

The analyses in this paper have been carried out on the basis of setting best-fit lines to the relation between load and the geometric and kinematics parameters. The analysis of the effect of ice velocity on the failure of ice features against a conical structure has a weak relation. From the results obtained we can conclude that the effect of ice velocity on the ice action on a conical structure in an ice regime as in the Northumberland Strait is not significant.

The ice thickness and rubble pile height are the most significant parameters in ice load calculation for conical structures. The pile up term in flexural failure model is related to ice thickness. Similar relations used for comparison in this paper were developed by Määttänen and Hoikkanen (1990) and Mayne and Brown (2000). Both relations had been developed for rubble piles resulting from interaction of level ice with conical structures. Määttänen and Hoikkanen (1990) model is based on field observations made from light piers in the Gulf of Bothnia. The rubble pile is supported by the face of the cone and the advancing ice sheet, if the ice sheet is in contact with the face of cone. Using the observations from the Gulf of Bothnia, a relationship derived between height of rubble pile (*H*) and ice thickness (h_i) is:

$$H = A.(h_i)^{0.5} \quad (13)$$

where, the constant (*A*) is assumed to be 4.5 when pile is unsupported and 6 when the pile is fully supported by ice sheet.

The Mayne and Brown (2000) envelope curve was based on the full-scale P31 data from the Confederation Bridge Monitoring Program. The relationship between height of rubble pile (*H*) and ice thickness (h_i) is:

$$H = 7.6(h_i)^{0.64} \quad (14)$$

The envelope curve plotted in Figure 8 indicates that Määttänen and Hoikkanen model underestimates the height of rubble pile for the ice regime in the Northumberland Strait.

Similarly, the relationship between the height of rubble pile (*H*) and ice velocity (*v*) described by Mayne and Brown (2000) is:

$$H = -3.12v^2 + 2.07v + 7.09 \quad (15)$$

The upper bound curve developed in this paper for both piers P31 and P32 is consistent with the Mayne and Brown (2000) model. It can be noted from Figure 7 and Figure 8 that, for any given velocity or ice thickness there are many pile heights below the maximum. Based on this, it can be concluded that there are other conditions for a rubble pileup to attain its maximum height, given the ice thickness and velocity.

The polynomial relationship proposed to describe the maximum rubble height against approaching ice sheet velocity indicates that no rubble pile is possible when the ice velocity attain certain value. Similarly, there is an upper limit to the thickness for which the upper bound relationship is no longer valid. Otherwise, the relationship indicates an increase in pile height as ice thickness increases. The envelope curves can be further improved by providing the upper and lower limits for the envelope equation. However, the limiting conditions have not yet been determined.

CONCLUSION

This paper presents a statistical study that has been done based on the results of the Confederation Bridge Monitoring Program. Ice video is used to confirm the events and extract event specific parameters. A significant range of ice velocity, ice thickness, rubble pile height and rubble angle are measured among the selected events. The observation shows weak correlations between the ice parameters and between load and ice parameters when all events are considered. This suggests that there are many uncertainties involved between ice load and ice parameters. However, a clear relationship exists when only the upper bound data set is considered. These data and equations would be important for input into probabilistic analysis for future work.

ACKNOWLEDGEMENT

The authors would like to acknowledge the support of Strait Crossing Bridge Ltd., Public Works and Government Services Canada, the National Science and Engineering Research Council (NSERC) and NRC-Canadian Hydraulics Centre.

REFERENCES

Brown, T., G., 2008. Ice Failure on Conical Structures – Effects of Speed, Proceeding of the 19th International Symposium on Ice (IAHR), 2008, Vancouver, Canada, Vol. II, pp 887-896

Croasdale, K. R., Cammaert, A. B., 1994. An Improved Method for the Calculation of Ice Loads on Sloping Structures in First-Year Ice, Hydrotechnical Construction, Vol 28, No. 3, pp 174-179

Lemée, E. M., 2003. Pressure Ridge Interaction with the Confederation Bridge Piers. MSc. Thesis, Department of Civil Engineering, University of Calgary, Calgary, Alberta, Canada

Määttänen, M., and Hoikkanen, J., 1990. The Effects of Ice Pile Up on the Ice Force of a Conical Structure, Proceeding 10th International Symposium on Ice, Vol. II, Espoo, Finland, pp 1010-1021

Matskevitch, D. G., 2002. Velocity Effects on Conical Structure Ice Loads, Proceeding OMAE 2002, 21st International Conference on Offshore Mechanics and Arctic Engineering, Oslo, Norway, June, pp 635-643

Mayne, D. C., and Brown, T. G., 2000. Rubble Pile Observations, Proceeding 10th International Offshore and Polar Engineering Conference, Seattle, USA, pp 596-599

Nevel, D., 1992. Ice Forces on Cone from Floes, Proceeding IAHR Symposium on Ice 1992, Vol. 3, Banff Canada, 1391-1404

Obert, K. M., 2010. Ridge Keel Geometry and Interaction with the Confederation Bridge, MSc. Thesis, Department of Civil Engineering, University of Calgary, Calgary, Alberta, Canada

Ralston, T., 1977. Ice Force Design Considerations for Conical Offshore Structures. Proc POAC 1977, Vol. II, Memorial University of Newfoundland, St. John’s Newfoundland, Canada, pp 741-752

Tibbo, J. S., 2010. Flexural Failure of Sea Ice, MSc. Thesis, Department of Civil Engineering, University of Calgary, Calgary, Alberta, Canada