CONICAL STRUCTURES IN ICE: RELEVANT RELATIONSHIPS FOR ISO 19906

Anne Barker, Denise Sudom, Mohamed Sayed
Ocean, Coastal and River Engineering
National Research Council of Canada, Ottawa, Ontario, Canada

ABSTRACT

Conical shapes are often chosen for structures that are exposed to floating ice, such as offshore drilling platforms, bridge piers and offshore wind turbine foundations. The flexural ice failure promoted by the shape of a cone can lead to lower forces on the structure than compressive failure, which would take place if ice is to encounter a vertical surface. In spite of the wide use of conical structures, many aspects of their performance in ice covered waters remain poorly understood. For example, the ISO 19906 Arctic Offshore Structures standard does not provide guidance with respect to ridge keel loading on cones, or the height to which ice could ride up on a conical structure. With the planned revision of that document presently beginning, it is important to address the guidance gaps in order to include new insights in the revised standard.

Previous work by the authors employed a numerical model of ice dynamics in order to predict ice failure patterns and forces on various conical structures. The present work extends those studies and predicts the extent of ice ride-up on the structures; the roles of the waterline width of the structure and ice thickness are discussed. The resulting ice force estimates are comparable to those predicted by an approach recommended in ISO 19906.

Both the plastic and elastic beam-bending methods recommended by ISO 19906 for determining ice actions on conical structures require an initial assumption of the maximum height of accumulated rubble. Little guidance is given in ISO 19906, except to note that this height depends on the structure geometry and ice regime. For the present calculations, the chosen rubble height for each ice load calculation is based on the results of the corresponding numerical model run. Previous numerical studies by the authors have also been reviewed and the estimates of ice ride-up heights summarized. Numerical simulations could be expanded to produce a comprehensive range of ride-up values to support users of ISO 19906.

INTRODUCTION

Conical structures have long been recognized to efficiently resist ice action. Their tendency to create bending failure of the ice can result in lower global loads than those induced by crushing failure, which commonly occurs on a vertical-sided structure. The cone can be oriented to break the ice either upward or downward, or both as in the case of a double cone structure which narrows inward at both the top and bottom of the structure. Designs vary for the angle of the cone and waterline diameter, and the structure may be faceted or have a smooth "true" cone shape. A number of bridge piers, lighthouses and offshore wind turbine towers have adopted conical shapes to reduce ice forces. Cones have also been employed in offshore structure designs, either in the shape of the hull itself or on the legs of jacket structures. Examples of these types of structures include the drill barge Kulluk, which had a conical hull designed to break ice downwards; the Confederation Bridge piers, with collars to induce upward-breaking of ice; the lighthouse Kemi-I with an upward-breaking conical foundation; and the jacket structures in the Bohai Sea. Only a few of these field structures have been instrumented to measure ice loads (see, e.g., Brown and Määttänen, 2009; Yue et al., 2007; Xu et al., 2011).

A relatively large number of physical tests have been carried out to understand ice loads on conical structures, and in recent years some numerical studies have been done. Wessels and Kato (1988) made a comprehensive review of literature published from 1978 to 1988 on ice forces on fixed cones, including analytical, model test and full scale results. Further examples of past tests and simulations have been listed in Brown and Määttänen (2009), Huang (2010) and Barker et al. (2014).

Several theoretical models have been developed over the years which are supported by scaled model results as well as the limited field data. Estimating ice forces on conical structures is traditionally based on formulas that account for idealized scenarios of the flexural failure of ice and friction forces between the resulting ice rubble accumulation and the cone. Such formulas have also been adopted in the new recommendations of ISO 19906 Arctic Offshore Structures standard. ISO 19906 (2010) gives two methods of calculating the load on a cone: (1) plastic method based on Ralston (1978); and (2) elastic beam bending method based on Croasdale (1980 and 1994).

Reliability of the input needed to use the formulas recommended by ISO 19906 is crucial for obtaining realistic estimates of ice forces. A major challenge for estimating ice forces is the choice of the appropriate ice ride-up height. Previous work (Barker et al., 2015) has shown that estimates of ice forces are very sensitive to the value of ice ride-up height.

The approach in this study is to use an ice dynamics model to simulate the three-dimensional deformation and failure of ice against a conical structure. The simulations predict the evolution of ice deformation, rubble accumulation geometries, stress distributions, and the resulting ice forces on the structure. The present work was motivated by the need to provide reliable information to support the use of ISO 19906 recommendations for conical structures. In this paper, we focus on evaluating ice ride-up heights along with keel depths, and ice forces. The paper also addresses the roles played by ice thickness and the waterline width of the cone.

Previous work includes model validation tests by Barker and Sayed (2012), a comparison between upward-breaking and downward-breaking cones by Barker et al. (2014), and a larger parametric study by Barker et al. (2015). These studies are reviewed in this paper and the numerical predictions of ride-up heights (or depths, for downward-breaking cones) are summarized. It is anticipated that such results could be used as inputs to the equations recommended by ISO 19906 for calculating ice loads on conical structures.

NUMERICAL SIMULATIONS OF ICE INTERACTION WITH CONICAL STRUCTURES

Approach and Test Set-Up

The numerical simulations are based on solving the equations that account for conservation of mass and linear momentum, as well as equations describing an extended von Mises failure criterion for the ice cover. The failure criterion accounts for the compressive, shear and tensile strengths of the ice cover. The solution of the governing equations adopts an implicit finite-difference method and a Lagrangian advection Particle-In-Cell scheme. Details of the model formulation and solution approach were discussed in previous papers (e.g., Barker and Sayed, 2012) and are not repeated here.

The simulations aimed at examining a relatively wide range for waterline width of the cone (henceforth referred to as *width*), and ice thickness. The width values are: 10 m, 15 m, 20 m, and 30 m. These widths are representative of typical conical structures existing in the field. The ice thickness values tested are: 1.0 m, 1.4 m, 1.6 m, and 2.0 m. A 45° slope of the cone was used in most simulations but a few cases examined a 55° slope. An ice-structure friction coefficient of 0.15 was used in all simulations. The velocity of the ice cover was 0.5 m/s.

Base Case

The Base Case examined the interaction of a 1.0 m thick ice cover with a cone of 45° slope and a width of 15 m. The grid covered an area of 108 m length along the direction of ice movement and 50 m width. Water depth was taken as 6 m, which was sufficient to avoid grounding of ice rubble accumulation.

The ice cover was driven upstream at a constant velocity of 0.5 m/s. Ice that reached the downstream boundary of the grid was removed to maintain a stress-free condition. The initial ice cover is uniform and intact. It breaks ahead of the cone upon contact. It appears that 3D buckling takes place. As a result, some rough ice (rubble) forms. The force builds up during the loading phase that ends with the broken ice cover in front of the cone. The force then decreases after reaching the peak as the advancing ice pushed the broken ice cover against the cone. This loading event repeats once new intact ice reaches the cone.

Snapshots showing the geometry of ice accumulation against the cone are shown in Figure 1. As the ice cover impinges on the cone, ice rubble accumulates over the cone. A keel also forms below the water level. As ice continues to move against the cone, the ice accumulation reaches limiting height and depth. Clearing of the ice rubble takes place as the accumulation flows around the cone.

Ice forces were calculated by integrating the stresses over the surface of the cone. The resulting horizontal and vertical forces are plotted versus time in Figure 2. Choice of the peak force may be somewhat subjective. We opt to ignore two very brief spikes in the data that appear early in the simulation, as it is unclear what caused these. Such spikes would be unlikely to have an effect on the structure. Future analysis may experiment with using different filters. Therefore, we consider the peak horizontal force to be 2.0 MN, and the peak vertical force to be 1.5 MN (acting downwards).

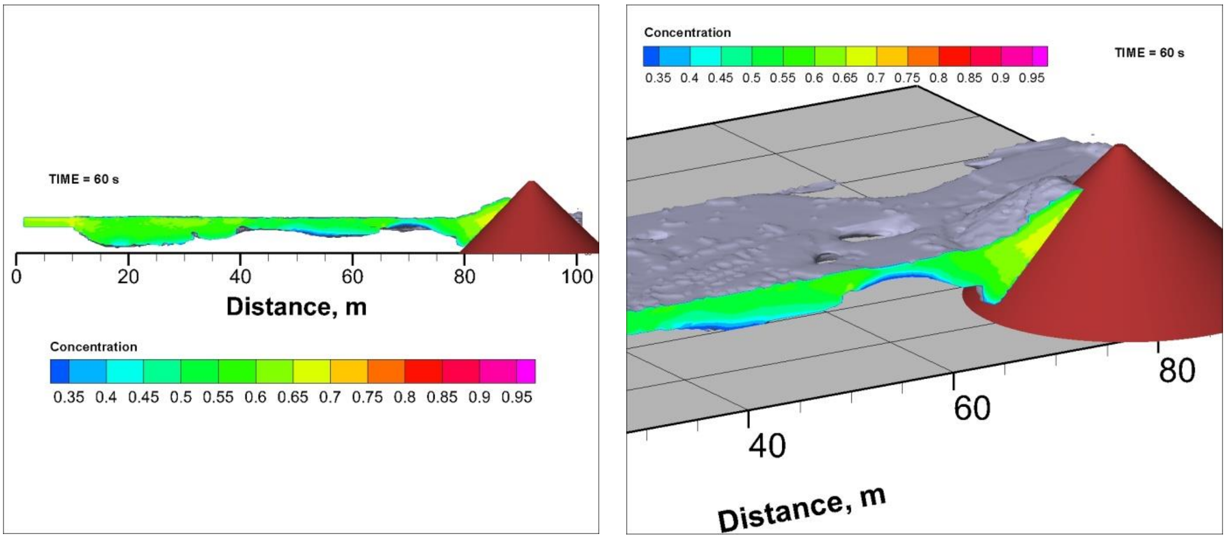


Figure 1: Cross-section and oblique views of ice accumulation against the cone for the Base Case after 60 s.

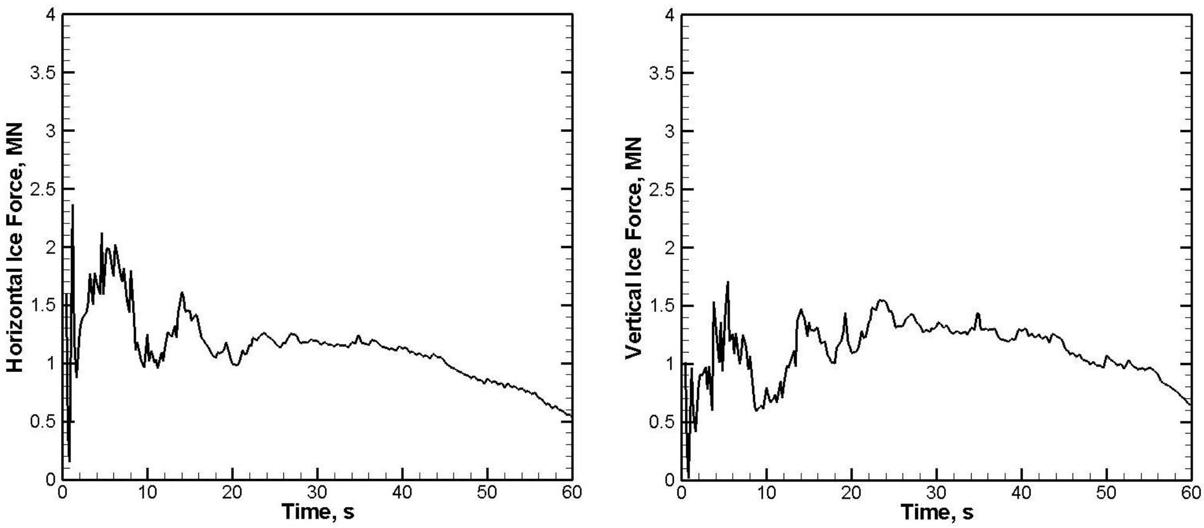


Figure 2: Horizontal and vertical ice forces versus time for the Base Case. The width of the cone is 15 m, and ice thickness is 1.0 m.

Effects of Ice Thickness, Structure Width and Structure Slope

The resulting maximum ride-up height and maximum keel depth values are combined from all simulations here. The maximum ride-up height and keel depth are plotted versus ice thickness for cones of various widths in Figure 3. Both the maximum ride-up height and maximum keel depth values clearly increase with increasing ice thickness. The role of the width of the cone is not as obvious. Evidently complex mechanisms influence the ride-up height and keel depth. Further analysis of the results of the simulations is needed to explain the observed role of structure's width. Compared with the results from Brown and Määttänen (2009) values, ride-up heights from these simulations are less than the empirical formula for maximum ride-up height presented in that paper. It should be noted that snow effects are not included implicitly in the simulations. This could be a factor in this difference.

The resulting horizontal and vertical peak ice forces on the conical structures are plotted versus ice thickness in Figure 4. The peak forces increase with increasing thickness. There is also a trend of higher forces for the larger cone widths.

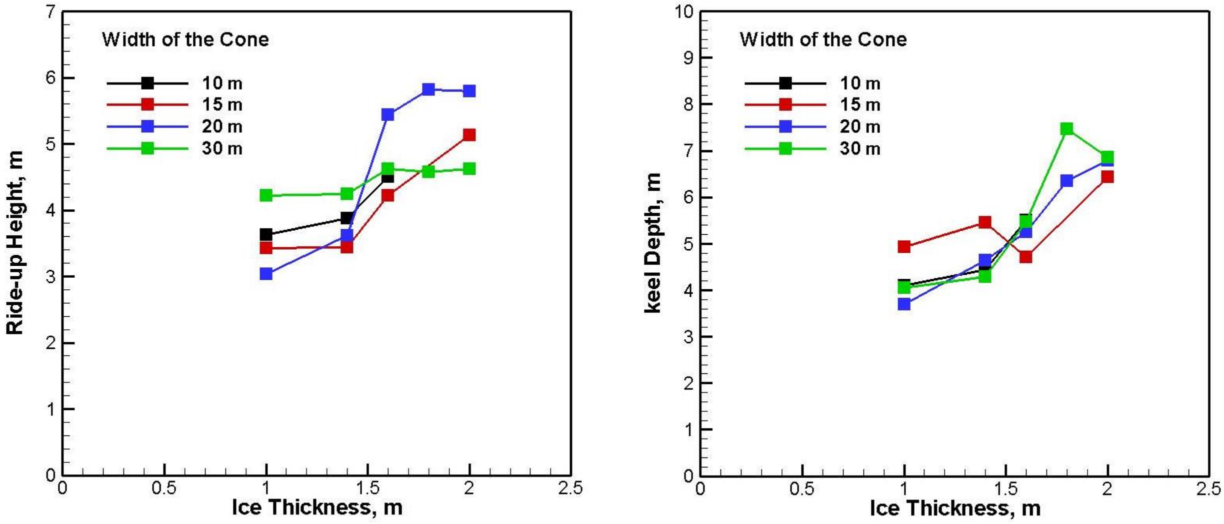


Figure 3: Maximum ride-up height (left) and keel depth (right) versus ice thickness for cones of various widths and a slope of 45°.

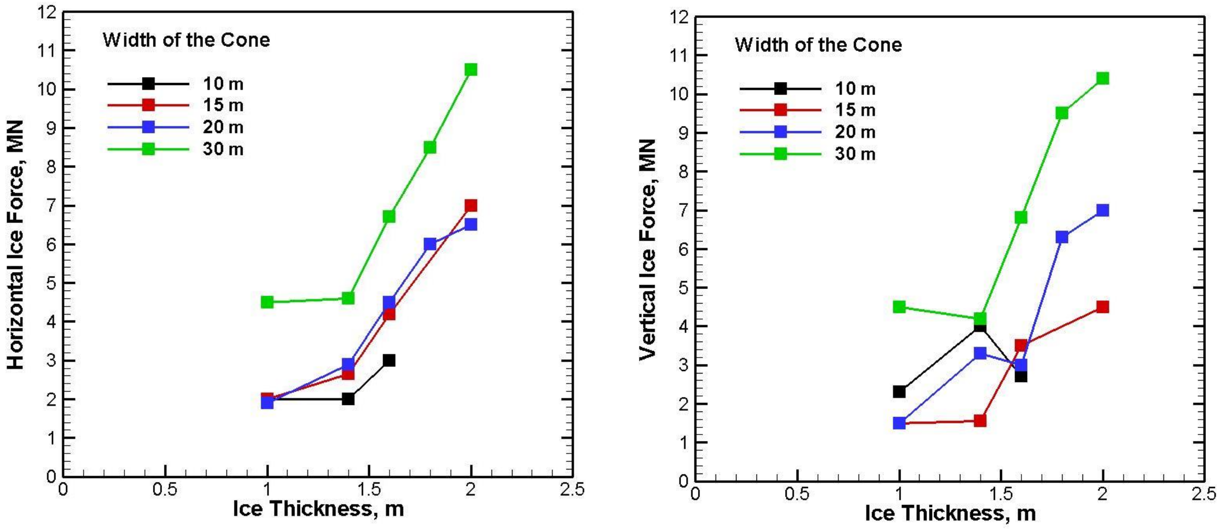


Figure 4: Peak horizontal and vertical ice forces versus ice thickness for various values of the width. Slope of the cones is 45°.

A few simulations examined ice interaction with a cone of 55° slope. Figure 5 (left) compares the resulting maximum ride-up heights with those obtained for a 45° slope; the results are very close for both slopes. Figure 5 (right) shows the horizontal ice forces for the 45° and 55° slopes, for varying ice thicknesses. Horizontal forces are generally higher on the steeper, 55° cone.

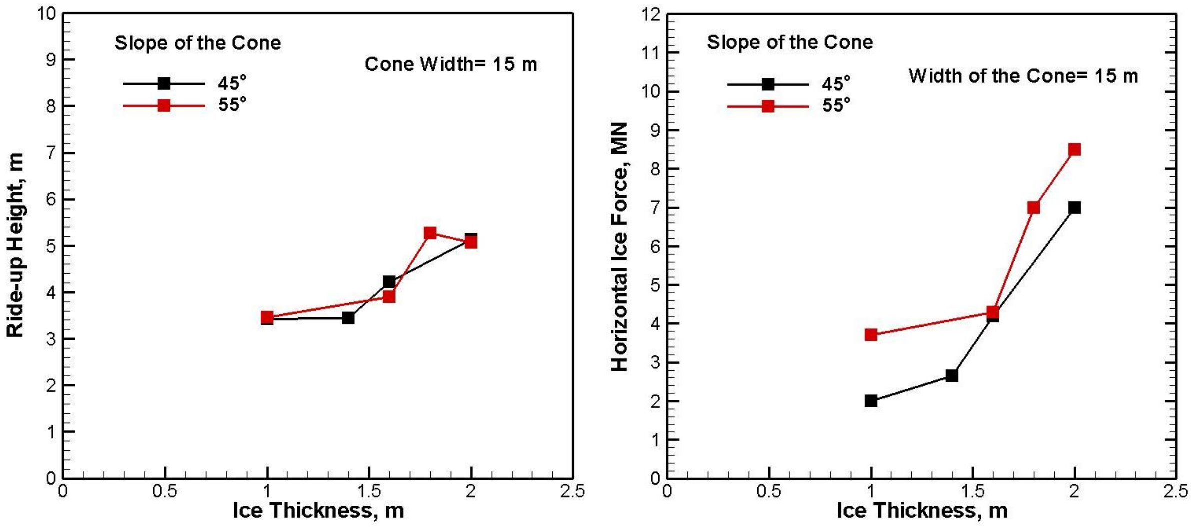


Figure 5: Maximum ride-up height (left) and horizontal ice force (right) versus ice thickness for cones of 45° and 55° slopes. The width is 15 m.

COMPARISON OF NUMERICAL RESULTS WITH CALCULATIONS BASED ON ISO 19906 STANDARD

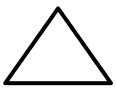
The peak global ice forces for all numerical tests are listed in Table 1. The forces calculated using ISO 19906 (2010) are also included for comparison. These calculations are based on the elastic beam bending method in Croasdale (1980) and Croasdale et al. (1994).

In order to use the Croasdale approach in the ISO 19906 Arctic Offshore Structures Standard, conservative estimates were made of a number of parameters, using guidance from the Standard where available. Assumptions were made on ice-to-ice friction coefficient (0.4), ice elastic modulus (10 GPa), ice rubble porosity (0.3), rubble cohesion (50 Pa), friction angle of rubble (45°), and angle of repose of rubble (cone slope minus 5°). All other parameters were set at the same values used in the numerical model tests.

The Croasdale approach also requires that the user input the maximum height of the accumulated rubble. Little guidance is given in ISO 19906, except to note that this height depends on the structure geometry and ice regime. For the present calculations, the chosen rubble height for each scenario was based on the results of the corresponding numerical model run. The peak rubble heights are given in Table 1. In this way, the numerical model provides information on rubble pile ups which may be very useful in the initial design stages of a structure when performing calculations to estimate the peak global force.

As can be seen in Table 1, horizontal and vertical ice forces predicted by the numerical model and by the ISO Croasdale approach calculations are very similar in most cases.

Table 1.Summary of predicted ride-up heights and ice forces on upward-breaking cones.

Cone slope	**Waterline width (m)**	**Ice thickness (m)**	**Numerical model peak rubble height from waterline (m)**	**Numerical model peak force (MN)**		**ISO 19906 (Croasdale approach) peak force (MN)**	
				Horizontal	**Vertical**	**Horizontal**	**Vertical**
45° 	10	1.0	3.6	2.0	2.3	2.0	1.5
		1.4	3.9	2.0	4.0	3.3	2.5
		1.6	4.5	3.0	2.8	4.3	3.2
	15	1.0	3.4	2.0	1.5	2.5	1.8
		1.4	3.4	2.7	1.6	2.1	1.6
		1.6	4.2	4.2	3.5	2.8	2.1
		2.0	5.2	7.0	4.5	4.2	3.1
	20	1.0	3.0	1.9	1.5	1.3	1.0
		1.4	3.6	2.9	3.3	4.9	3.6
		1.6	5.4	4.5	3.0	7.5	5.6
		1.8	5.8	6.0	6.3	9.2	6.8
		2.0	5.8	6.5	7.0	10.5	7.8
	30	1.0	4.2	4.5	4.5	5.0	3.7
		1.4	4.2	4.6	4.2	7.3	5.4
		1.6	4.6	6.7	6.8	9.2	6.8
		1.8	4.6	8.5	9.5	10.6	7.9
		2.0	4.6	10.5	10.4	12.2	9.0
55° 	15	1.0	3.5	3.7	1.7	3.3	1.7
		1.6	3.9	4.3	1.6	6.7	3.4
		1.8	5.3	7.0	4.6	9.3	4.7
		2.0	5.1	8.5	2.4	10.6	5.3

REVIEW AND APPLICATION OF NUMERICAL RESULTS FROM PRESENT AND PREVIOUS TEST SERIES

The work reported here and in the previous, related test series is part of a project that aims to provide guidance on the nature of ice interaction with conical structures. The outcome will provide support for existing design codes such as ISO 19906 Arctic Offshore Structures Standard (ISO, 2010).

Barker and Sayed (2012) compared the numerical method against a test from the Esso Resources laboratory test series of a conical structure in a basin (Metge and Tucker, 1990), as well as an event from the Confederation Bridge field measurements. Then, ice forces were assessed for several conical shapes (ice rubble ride-up height and keel depth values were not published). It was shown that reducing the cone slope from 52° to 40°, while maintaining a waterline diameter of 16 m, reduced the horizontal ice load by nearly half.

Barker et al. (2014) further examined the difference in ice forces on upward- and downward-breaking cones for slopes of 52° and 40°, while testing the effect of ice-structure friction values. The use of downward-breaking cones reduced ice loads by 40 to 50%. Rubble heights or keel depths were determined in each case. The effect of ice ridging on forces was also examined.

Barker et al. (2015) performed a larger test series focusing on the roles of cone slope, waterline width, ice thickness and ice-structure friction. Rubble ride-up heights were determined and their effect on force on the structure examined. The assumed rubble height was shown to play an important role in determining the global force using the Croasdale approach in ISO 19906.

The Croasdale approach, as well as the Ralston (1980) method that is also recommended by ISO 19906, requires an initial assumption of the maximum height of accumulated rubble. This value can be difficult to estimate for a new structure design, and little guidance is given in ISO 19906 other than general notes that this height depends on the structure geometry and ice regime. For the calculations in publications by Barker et al. described above, the chosen rubble heights for the ISO ice load calculations were based on results of the corresponding numerical model run. Numerical simulations could be expanded to produce a comprehensive set of ride-up values to support users of ISO 19906. As an example, all values of the peak rubble ride-up height (or depth, for the case of downward-breaking cones) are given in Table 2 for the work done to date by Barker and colleagues.

Note that all tests, aside from those in the present study, used a cone with a near-vertical "neck" section beginning at the narrow part of the cone. This neck can allow further ice ride-up and an increase in horizontal forces on the structure. Most designs would include some sort of neck or change in slope of the cone in part of the structure.

Table 2. Summary of past numerical simulations for level ice interaction with conical structures. Estimates are given for peak rubble accumulation height (for upward-breaking cones) or depth (for down-breaking).

Source	**Upward or downward breaking cone**	**Waterline width (m)**	**Cone slope (degrees)**	**Ice-structure friction**	**Ice thickness (m)**	**Numerical model peak rubble height or depth from waterline (m)**
Barker & Sayed, 2012	Upward	16	52	0.15	1	3
Barker et al., 2014	Upward	16	40	0.15	1	4.5
Barker et al., 2014	Upward	16	40	0.4	1	4
Barker et al., 2014	Upward	16	52	0.15	1	4
Barker et al., 2014	Upward	16	52	0.4	1	3.5
Barker et al., 2014	Downward	16	40	0.15	1	8.5
Barker et al., 2014	Downward	16	40	0.4	1	1
Barker et al., 2014	Downward	16	52	0.15	1	8
Barker et al., 2014	Downward	16	52	0.4	1	7
Barker et al., 2015	Upward	10	45	0.15	1	3.8
Barker et al., 2015	Upward	10	55	0.15	1	3.6
Barker et al., 2015	Upward	15	45	0.05	1	3.2
Barker et al., 2015	Upward	15	45	0.15	1	4
Barker et al., 2015	Upward	15	45	0.15	1.4	4.2
Barker et al., 2015	Upward	15	45	0.15	1.6	4.8
Barker et al., 2015	Upward	15	45	0.15	1.8	6.4
Barker et al., 2015	Upward	15	45	0.15	2	5.8

Barker et al., 2015	Upward	15	45	0.25	1	3.4
Barker et al., 2015	Upward	15	45	0.4	1	2.8
Barker et al., 2015	Upward	15	55	0.05	1	2
Barker et al., 2015	Upward	15	55	0.15	1	3.8
Barker et al., 2015	Upward	15	55	0.15	1.4	4.4
Barker et al., 2015	Upward	15	55	0.15	1.6	5.4
Barker et al., 2015	Upward	15	55	0.15	1.8	4.4
Barker et al., 2015	Upward	15	55	0.15	2	5.8
Barker et al., 2015	Upward	15	55	0.25	1	4.2
Barker et al., 2015	Upward	15	55	0.4	1	4.2
Barker et al., 2015	Upward	20	45	0.15	1	3.8
Barker et al., 2015	Upward	20	55	0.15	1	3.6
Barker et al., 2015	Upward	30	45	0.15	1	5
Barker et al., 2015	Upward	30	55	0.15	1	4.8
Present work	Upward	10	45	0.15	1	3.6
Present work	Upward	10	45	0.15	1.4	3.9
Present work	Upward	10	45	0.15	1.6	4.5
Present work	Upward	15	45	0.15	1	3.4
Present work	Upward	15	45	0.15	1.4	3.4
Present work	Upward	15	45	0.15	1.6	4.2
Present work	Upward	15	45	0.15	2	5.2
Present work	Upward	15	55	0.15	1	3.5
Present work	Upward	15	55	0.15	1.6	3.9
Present work	Upward	15	55	0.15	1.8	5.3
Present work	Upward	15	55	0.15	2	5.1
Present work	Upward	20	45	0.15	1	3
Present work	Upward	20	45	0.15	1.4	3.6
Present work	Upward	20	45	0.15	1.6	5.4
Present work	Upward	20	45	0.15	1.8	5.8
Present work	Upward	20	45	0.15	2	5.8
Present work	Upward	30	45	0.15	1	4.2
Present work	Upward	30	45	0.15	1.4	4.2
Present work	Upward	30	45	0.15	1.6	4.6
Present work	Upward	30	45	0.15	1.8	4.6
Present work	Upward	30	45	0.15	2	4.6

CONCLUSION

Numerical simulation of ice behaviour has several advantages over other prediction methods. The model allows for the viewing of a detailed ice force-time trace. Although not examined in detail in this paper, the geometry of the rubble (heights and horizontal extents) can be viewed as it builds up. The ice failure modes during the interaction can also be assessed. In addition, the rubble keel accumulation below waterline can be assessed, which is of interest for upward-breaking cones.

In the present numerical test series, both the maximum ride-up height and maximum keel depth values clearly increase with increasing ice thickness for a cone of 45° slope and a given waterline width. The role of the width of the cone is not as obvious, as complex mechanisms (such as failure patterns and ability of ice to clear around the cone) influence the ride-up height and keel depth. Further analysis of the simulation results is needed to explain the rubble accumulation observations related to structure width. The peak horizontal and vertical forces on the conical structure increase with increasing ice thickness. There is also a trend of higher global forces for the larger widths. A few simulations examined ice interaction with a cone of 55° slope. The resulting maximum ride-up heights are very similar to those obtained for a 45° slope. Horizontal forces are generally higher on the steeper, 55° cone.

The ice loads predicted by the numerical model were compared with those calculated using the elastic bending method in ISO 19906 (ISO, 2010), which has been adapted from work by Croasdale and colleagues (1980 and 1994). The peak horizontal and vertical ice loads for both approaches are similar, which gives confidence in the numerical methods. The Croasdale approach also requires the assumption of a maximum rubble ride-up height in order to calculate the ice force. These values cannot be determined easily at the design stage, and no quantitative guidance is given in ISO 19906 (ISO, 2010) on the maximum rubble heights for different structures. The numerical model work is very useful in this regard and can give an initial estimate of the peak rubble accumulation.

ACKNOWLEDGMENTS

This study was funded by the Program of Energy Research and Development (PERD), Offshore Environmental Factors programme, and was also supported by the National Research Council Canada's Arctic Program.

REFERENCES

Barker, A. and Sayed, M. 2012. Upward- or downward-breaking cones in ice: which one should you use? Proceedings of the Cold Regions Engineering 2012 Conference, Quebec, Canada, pp.715-724.

Barker, A., et al., 2014. Conical structures in ice: the roles friction, slope and shape play. Proceedings of Arctic Technology Conference (ATC), Houston, USA, paper OTC 24566.

Barker, A., et al., 2015. Conical Structures in Ice: Ride-Up, Radius and Results. Proceedings of Arctic Technology Conference (ATC), Copenhagen, Denmark, paper OTC 22534.

Brown, T.G., and Määttänen, M., 2009. Comparison of Kemi-I and Confederation Bridge cone ice load measurement results. Cold Regions Science and Technology 55, pp. 3-13.

Croasdale, K. R. 1980. Ice forces on fixed rigid structures. Special Report 80-26, US Army CRREL, Hanover, USA.

Croasdale, K.R., Cammaert, A.B., and Metge, M., 1994. A method for the calculation of sheet ice loads on sloping structures. Proceedings of the 12th IAHR Ice Symposium, Trondheim, Norway, Vol. 2, pp.874-885.

Huang, Y., 2010. Model test study of the nonsimultaneous failure of ice before wide conical structures. Cold Regions Science and Technology 63, pp. 87-96.

ISO (International Organization for Standardization), 2010. ISO 19906:2010 Petroleum and natural gas industries – Arctic offshore structures. 465 pp.

Metge, M. and Tucker, J.R. 1990. Multifaceted Cone Tests Year Two 1989-1990. Esso Resources Canada Limited Proprietary Report ERCL.R.S.90.11. Calgary, Canada

Ralston, T.D., 1978. Ice force design considerations for conical offshore structures. Proceedings of the 4th International Conference on Port and Ocean Eng. under Arctic Conditions (POAC), St. John's, Newfoundland, Vol. 2, pp.741-752.

Wessels, E., and Kato, K., 1988. Ice forces on fixed and floating conical structures. Proceedings of 9th IAHR Ice Symposium, Sapporo, Japan, Vol. 1, pp. 666-691.

Xu, N., et al., 2011. Results of Field Monitoring on Ice Actions on Conical Structures. Journal of Offshore Mechanics and Arctic Engineering 133 (4).

Yue, Q., et al., 2007. Ice force spectrum on narrow conical structures. Journal of Cold Regions Science and Technology 49, pp. 161–169.