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A Discrete Element Model of Ice Ridge Interaction with a Conical Structure

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ABSTRACT

A numerical model of ice ridge interaction with narrow sloped structure is being developed to examine possible failure scenarios and loads it may impart on the structure. In reality there is no dominant interaction scenario and the roles of the consolidated layer, keel rubble and rubble pile accumulation on the slope still remain uncertain. Bonded-particle discrete element models are capable of simulating both the failure of continuous layers of ice and the granular behaviour of ice rubble. The computational complexity of the model is high; therefore, the simulations are run on high-performance computers. Ice ridge interactions with a Confederation Bridge pier have been simulated and the results compared with analytical estimates. The results show that the rubble pile heights and load levels obtained in the simulations are in agreement with observations indicating that the model performs well. The model will be used to further study ridge-structure interactions and hopefully help reduce uncertainties related to ridge properties and load determinations.

KEYWORDS: Ice; Ridge; Rubble; DEM; Failure

INTRODUCTION

Mechanical interaction between an ice ridge and a sloping offshore structure is extremely complex. It involves failure of ice (mostly in bending; however, all modes are possible), formation and evolution of a rubble pile, interaction between the rubble pile and approaching ice, interaction between the ridge keel rubble and the structure, hydrodynamic effects, etc. In addition, the mechanical properties of the ice and geometry of ice ridges are highly variable. This makes the process very difficult to model mathematically. As a consequence, the overall uncertainty becomes the major challenge for design load determination.

The analytical estimate of the total load from an ice ridge on a sloping structure currently proposed by ISO 19906: 2010 (ISO, 2010) is the sum of the loads caused by the consolidated layer and the rubble keel. The first term is found by considering the breaking process of level ice of equivalent thickness on an elastic foundation with consequent interaction with a rubble pile on the cone (Croasdale & Cammaert 1994), and the second term is calculated assuming plug failure of cohesive Mohr-Coulomb rubble (Dolgopolov et al. 1975). This approach often overestimates the real load, and it is said to give an upper-bound load estimate. Recent study by Croasdale et al. (2016) improves the model by introducing secondary breaking of the ice and better rubble pile geometry representation. Worthy of note, is the model of Mayne (2007) that considers the geometry of rubble pile in more detail and calculates the total load using "slices" through the pile. While these methods are very robust, they do not provide transient solutions and do not provide an opportunity to examine the processes inside the ridge. In addition, the mutual effect of the rubble keel and the consolidated layer on their strength is unknown.

Recent numerical models enable time-domain analysis of ice motion and dynamics, i.e. evolution of ice loads. A variety of methods have been developed to address ridge-structure interaction: finite-element method (Heinonen 2004), finite-discrete element method (Paavilainen et al. 2011), discrete element method (Liu, J. et al., 2016), and particle-in-cell (Barker et al. 2014). For the discrete element method (DEM), the physical size of the problem often prohibits reaching the required resolution. Domain decomposition techniques may be used to effectively parallel the computations. Thus, the model may be run on a graphics processing unit (GPU) or on high-performance computers (HPC). This helps to overcome the limitation and accelerate the simulations.

This study presents a DEM-based model of ridge-sloping structure interaction, which is currently under development, and demonstrates its performance. Ice ridge-interactions with a Confederation Bridge pier are simulated because some data are available to help validating the numerical model. The influence keel depth has on the failure mechanics and simulated loads are investigated. In particular, the influence of the truncated cone on deep ridge keels is discussed. Simulated pile heights are compared with the work of Mayne (2007) and total loads with ISO analytical solutions.

NUMERICAL METHOD

Bonded-particle model for discrete element method (Potyondy and Cundall 2004) was used to simulate the ice in the model. As in conventional discrete element method, the material consisted of spherical particles that had visco-elastic frictional contacts. In addition, the particles were bonded through visco-elastic contacts, which produced tension. If the bond stresses exceed a certain critical value, the bonds would break and the applied tension force removed.

The solid ice structure was produced using spherical particles that were the same size and arranged in hexagonal close packing (HCP). This arrangement of particles created anisotropy, which, is often observed in columnar ice. The relation between the normal and tangential stiffness and material properties was estimated by considering the dynamics of a particle in a unit HCP-cell. The normal stiffness was set to be equal to the tangential stiffness and was expressed as

$$K_n = K_\tau = \frac{1}{12}\pi E D \tag{1}$$

where E is the elastic modulus of ice and D is the particle diameter. The time step Δt in the simulations was chosen as a small fraction of a characteristic period of oscillation

$$\Delta t = \alpha D \sqrt{\frac{\rho_i}{E}} \qquad (2)$$

where ρ_i is the density of ice and $\alpha = 0.1$ is a constant maximizing time step that provides stability to the simulation.

The model was implemented using an open-source package for granular materials called LIGGGHTS (Kloss et al. 2012), which can be run on multi-core distributed systems. This is extremely advantageous in that it allows large numbers of particles to be simulated, which is needed to consider the three-dimensional geometry of ice ridges and the failure of solid ice blocks in the keel.

The numerical set-up consisted of a Confederation Bridge pier imported as a triangular mesh and an ice ridge embedded in level ice. The motion of the ridge was limited by a confining wall at one end, and the pier was displaced at a constant velocity of 0.4 m/s from the opposite end. The velocity magnitude was chosen as certain representative value for the ice floe velocities measured at the bridge (Brown et al., 2010). No confinement was applied on the sides to see if splitting was possible.

It was assumed that the hydrodynamic force caused by the water flow around the pier was significantly less than the total force produced by ice. Yet, the water flow may influence the clearing of the ice blocks in the vicinity of the structure. However, this hydrodynamic effect was not implemented in the current version of the model.

Generation of Ice Ridges

Ice ridges for the simulations were constructed in several stages. First, the keel was formed by emerging cuboid-shaped blocks under level ice with a consolidated layer using a rigid body engine. It was more efficient than emerging blocks consisting of large number of particles, obviously because of reduced number of bodies and much larger time steps used in rigid body dynamics. When the blocks had settled and total kinetic energy of the system became low, each block was filled with spherical particles forming a lattice oriented in accordance with the corresponding block orientation. The ridge sail was formed in similar way. Next, all the particles in the keel and sail were exported and joined with the level ice and consolidated layer made of latticed particles, and the block-block contacts added. The obtained structure was released into the water and simulated for a short period with no forces applied except the gravity force and buoyancy, to dissipate any remaining pre-stresses between the blocks.

The size of the generated ice rubble blocks was random. The ratio between the length and the thickness for the blocks was made to follow lognormal distribution with the mean equal to 1.06 and the standard deviation equal to 0.5 according to (Kulyakhtin, 2014). The blocks were rectangular in shape so that interlocking between blocks is possible, which as Liu et al. (2015) showed is important when considering any kind of compaction build up around a structure.

A newly created ice ridge is shown in Figure 1. For this particular ridge the height, width and length of the ridge were 9.7 m, 100 m and 200 m, respectively, where the length is perpendicular to the interaction direction. It consists of more than half a million particles. The shoulders of the ridge have slope angles of approximately 6° which is in accordance with (Wadhams & Doble 2014). All of the ridges in this study were embedded into a level ice of 0.6 m thickness with a 20-m-wide and 0.9-m-thick consolidated layer in the middle.

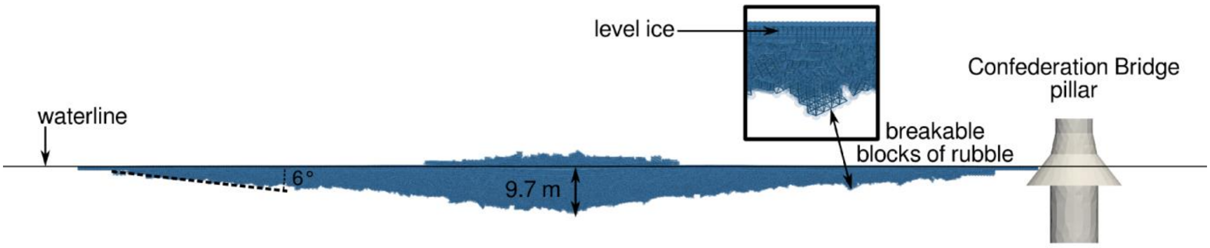

Figure 1. Side view of a generated ice ridge. The half-width is approximately 90 m and the slope angle is approximately 6°.

RESULTS

Ice Failure Behaviour

In the model the interaction with an advancing ice ridge started from level ice breaking on the slope of the cone. The particles contacting the cone experienced an upward contact force component. While the contact area was small, the bonds supporting these particles became broken and many small pieces of ice became free; this may be considered as crushing at the interface. When the interaction area expanded, the ice sheet could get radial cracks followed by flexural failures of newly formed wedges (Figure 2a).

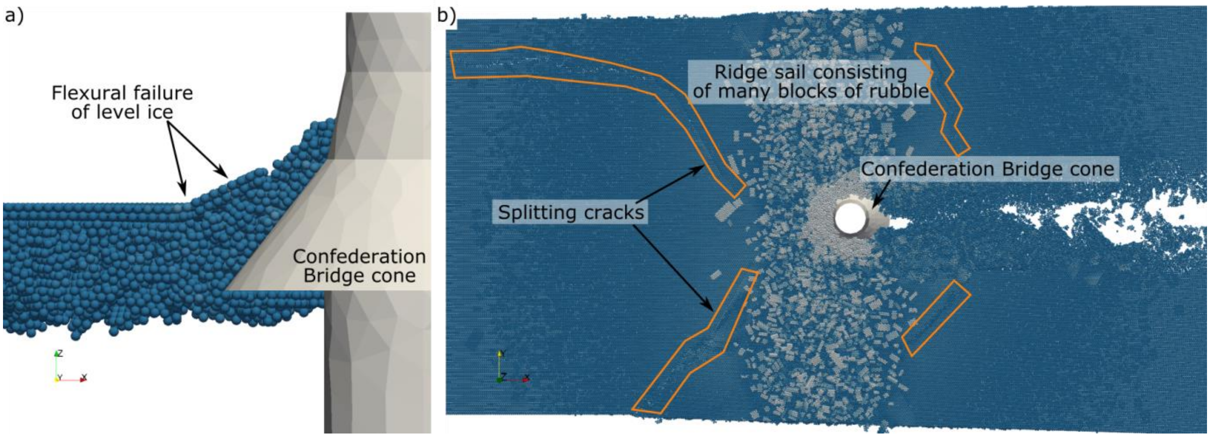

Figure 2. a) Cross-section of an ice ridge shoulder interacting with the Confederation Bridge cone; b) Top view snapshot showing formation of long splitting cracks occurring when the cone goes through a 100-m-wide section of an ice ridge.

The characteristic length of a 0.6-m-thick, quasi-infinite, ice sheet should be approximately 10.8 m; however, in our simulations the ice broke in smaller pieces. Similar behaviour has been observed by Mayne (2007); he reports the average of the maximum observed piece length of 4 m for 1-m-thick level ice. While being pushed through the pile, the blocks in the simulation were broken down to single particles. The blocks size observed in the reality was on the order of 0.5 m, which is the size of the spherical particles used in the simulations. The rubble blocks in the ridge keel often remained intact and emerged, once freeze bonds were broken.

Longitudinal cracks appeared later in the simulation, when the cone started to penetrate the consolidated layer (Figure 2b). The ice, however, continued to interact with the cone and no abrupt force reduction was observed. Interestingly, the longitudinal cracks occurred only for large ridges.

Rubble Pile Characteristics

During the simulated ridge-structure interaction, the ice formed a rubble pile on the cone. The pile was deforming, and its shape and height constantly varied. The shape of the pile cross-section on the cone can be described as linear mostly for level ice interactions, when ice accumulation is weak. The cross-section becomes parabolic when ice accumulates while interacting with sail of the ridge supported by consolidated layer and large keel. As expected, the highest point of the pile is usually located at the upstream surface of the cone, whereas rubble pile height is lower on the sides of the cone (Figure 2b).

The variation of rubble pile height with time is shown in Figure 3. It can be seen that after approximately 10 m of penetration into the ice floe (or after approximately 25 s) the pile height remains on the same level. No significant change in pile height was observed in the simulations when the pier interacted with the consolidated layer.

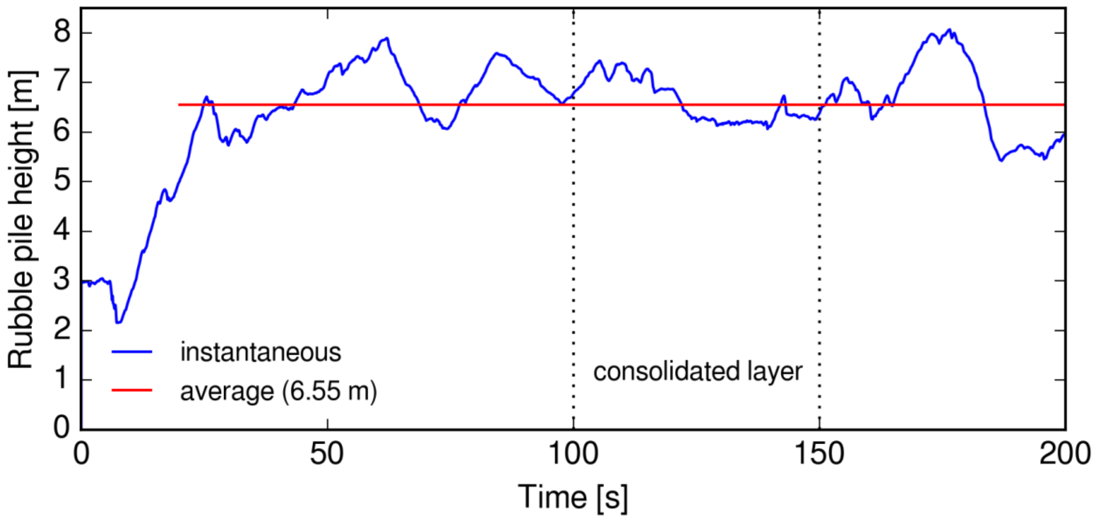

Figure 3. Evolution of a rubble pile height during interaction with a ridge having 7.9-m-thick keel. No significant changes in rubble pile height has been observed during the interaction with the consolidated layer.

Total Force

The evolution of the *x*-component of the total force acting on the structure is shown in Figure 4. The force generally follows the profile of the ridge with an additional increase when the consolidated layer is encountered. However, when the ridge splits, the force does not drop instantly. The remaining pieces of ice continue to break on the cone, but under less confinement.

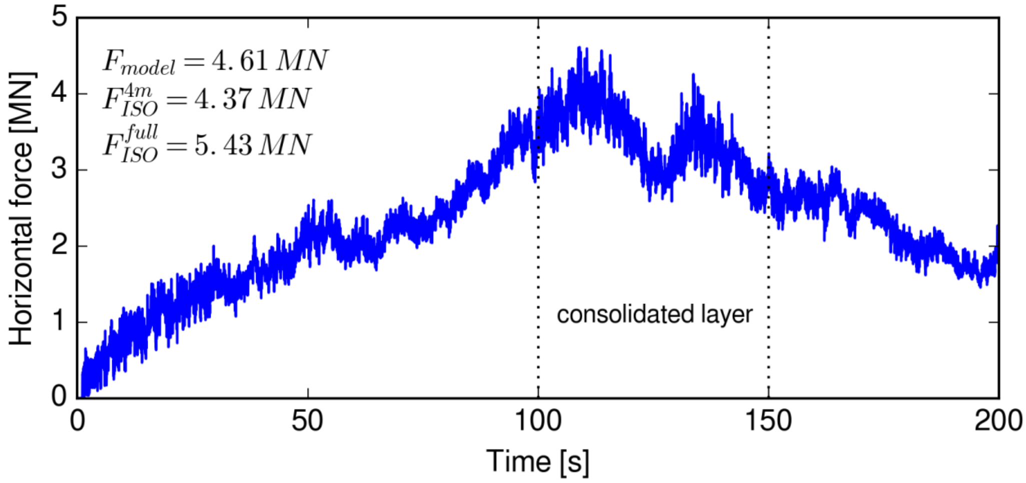

Figure 4. Evolution of the *x*-component of the total force obtained for an ice ridge with 7.9-m-deep keel. Estimates according to ISO are given for a 4-m-deep keel equivalent and full keel depth.

DISCUSSION

A scenario when an embedded ice ridge interacts with a Confederation Bridge pier has been simulated numerically. The numerical model employs strong assumptions regarding ridge geometry, mechanical properties and hydrodynamics, while the real environment has more natural variability particularly in ridge profile geometry. Nevertheless, the numerical model provides control over the parameters and helps to capture the ice behaviour which may be hard to observe in reality.

Simulations showed that the rubble pile geometry varied constantly, but the pile height remained approximately on the same level. The rubble accumulates due to incoming ice sheet breaking on the cone, and it is eventually spread on both sides of the cone. The rubble pile also collapses downwards, from time to time, if the pileup becomes too heavy. Both linear (as in Figure 2a) and more complex (Figure 5a) pile cross-sections were observed. The thickest profiles were observed when crossing the crest of the ridge and the keel was at its maximum depth. This is as expected as there would have been the greatest buoyancy forces preventing the rubble pile from collapsing. Therefore, more rubble was able to accumulate and consequently impart higher loads on the structure.

The rubble pile heights obtained from the model and measured in reality (Mayne, 2007) are compared in Figure 6. The numerical model slightly overestimates the pile height, because the simulated pile porosity is higher than the real one. This occurs due to equal-sized spherical particles representing the material. The minimum porosity that an assembly of these particles may have is 26%, if they are closely packed in a lattice. Assuming the packing in the pile is random during the rubbling process, the porosity is likely to be on the order of 40%, while the porosity values between 10% and 30% are often assumed when using ISO. This discrepancy in porosity calculations will likely not have much effect on the simulations, as the breaking of the incoming ice sheet is determined from the mass of the rubble pile. It is the mass that has to overcome the bearing capacity of the ice sheet in order to collapse the pile. More simulations are planned for the range of velocities to find the upper bound pile height and compare it with the results of Mayne (2007).

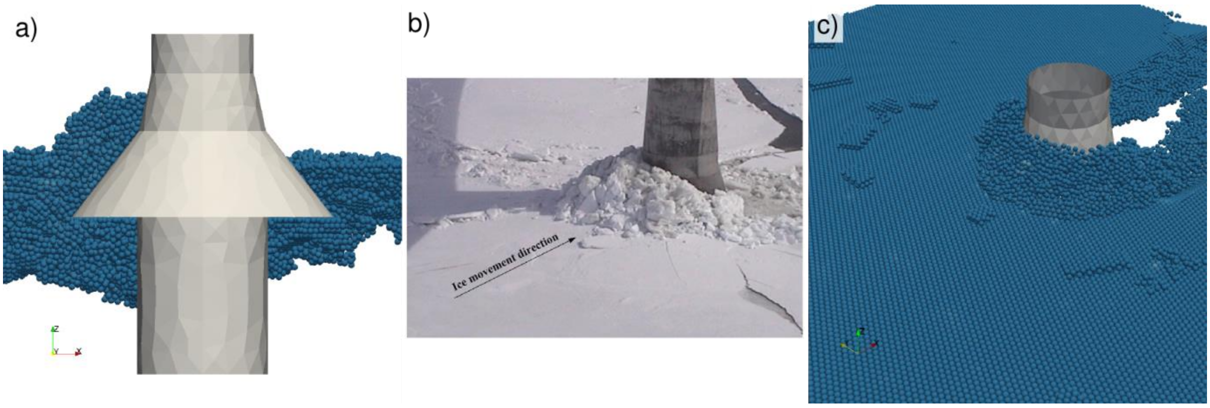

Figure 5. a) Parabolic rubble pile profile; b) observed rubble pile from Brown et al. (2010); c) snapshot from the simulation with similar geometry.

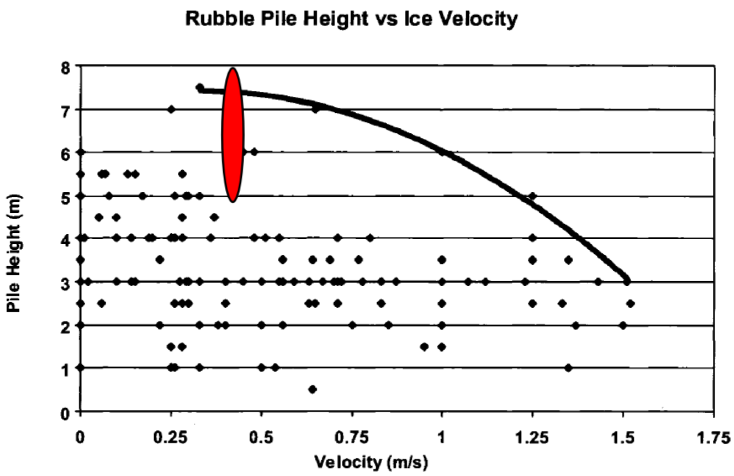

Figure 6. The rubble pile heights measured by Mayne (2007) compared to those obtained during the simulations which were done at 0.4 m/s (the set is denoted by red circle).

The simulations have been performed for several ridges of different keel depths. In one test only the consolidated layer was considered (i.e. zero keel depth). Overall, the ice loads in the simulations approximately followed the ridge cross-section profiles. Peak ice loads obtained in the simulations are compared with estimates provided by ISO 19906: 2010 (Figure 7). Rubble pile heights and porosity from the numerical simulations have been used in the analytical equations.

The peak load for only the consolidated layer is very close to that of Croasdale and Cammaert (1994). Once the keel is considered, the analytical solutions used in ISO are systematically higher than those simulated by the numerical model. This may be because they are upper bound solutions, but also there are other sources of error in the model. Firstly, the ice ridge in the simulation was not confined laterally which could have caused a load reduction. Longitudinal splitting was only observed in one simulation, when the ice ridge was 8 m deep and it took place at the moment the pier was crossing the consolidated layer. Secondly, for unconsolidated ice ridges, the cohesion of the rubble keel may be too low. A cohesion of 3 kPa and friction angle of 30° have been used to give the estimates shown in Figure 7.

Although, the blocks in the keel were frozen in the simulation, they may not have been sufficiently bonded to simulate the correct behavior. The effects of freeze bond strength will be studied in the future.

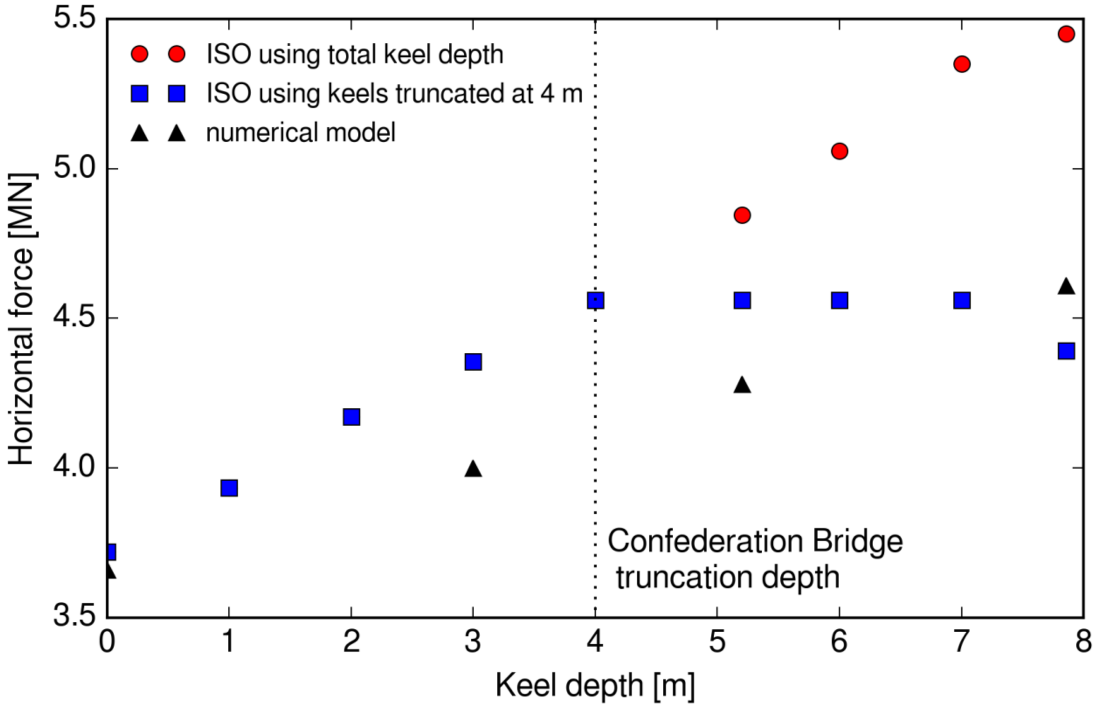

Figure 7. Results of the simulations compared with ISO 19906: 2010.

The effects of the truncated cone are also depicted in Figure 7. It has been reported previously, that marine life was present on a pier shaft under the cone (Lemee and Brown, 2005) meaning that ice interaction from the rubble keel is minimal if not absent at all. In addition, data provided by ElSeify and Brown (2006) confirm that the variation in keel depth appeared to have no effect on the peak loads. In the numerical model, the keel rubble interacts with the leading side of the shaft. It can be seen in Figure 7 that the loads from the model are growing monotonously with increasing keel depth. The ISO estimates using load levels "frozen" at 4 m keel depth are shown in the same figure. The numerical model lacking accurate hydrodynamics may cause some overestimate of the keel forces. The flow of water around the shaft likely facilitates the rubble transport and prevents violent interaction between the blocks and the shaft. On the other hand, the data presented by ElSeify and Brown (2006) has considerable variability and given for various velocities, confinements and level ice thicknesses. Further investigation is warranted to clarify the effect of the truncated cone.

CONCLUSIONS

The preliminary results of the numerical model testing clearly demonstrate that it is capable to simulate ice failure in different modes on a conical surface, and it captures some features of rubble behaviour, both on the slope of the cone and in the keel. The model is planned to be applied to simulate interaction using actual ice ridge profiles obtained by sonars and implementing limit momentum scenarios to improve reliability. This will hopefully result in improved accuracy for the design values for sloped structures. It is also worth noting that the model may be potentially applied to simulate ridge-ship interactions during station-keeping operations, which is likely to be the next phase of modelling.

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