POAC'23
Glasgow, United Kingdom

Proceedings of the 27th International Conference on
Port and Ocean Engineering under Arctic Conditions
12-16 June 2023, Glasgow, United Kingdom

Three-dimensional numerical model for ice-structure interaction process

Arttu Polojärvi
Aalto University School of Engineering, Department of Mechanical Engineering, Espoo, Finland
arttu.polojarvi@aalto.fi

ABSTRACT

This paper presents a three-dimensional combined finite-discrete element model capable of describing a process of an ice sheet failing against an offshore structure. The ice sheet is consists of polyhedral rigid discrete elements joined by a lattice of Timoshenko beam elements that undergo cohesive softening upon ice failure. Contact model for discrete elements considers inter-particle friction and local ice failure. A validation study, where an ice sheet is pushed against an inclined plane, is presented. Modelled and experimental failure processes show convincing agreement.

KEY WORDS: Discrete element method; Ice failure process; Ice-structure interaction; Numerical simulations.

INTRODUCTION

Ice sheets interacting with offshore structures, such as wind turbines or lighthouses, undergo a failure process resulting on structural loads due to ice. These processes are extremely complex, as in them, the ice sheet fails into ice blocks, which form an ice rubble pile in the vicinity of the structure. The rubble pile interacts with both, the structure and the still-intact ice sheet. Furthermore, the processes show a strong feedback loop, with earlier ice failure events affecting later ones. Simulation-based analysis offers detailed insight into ice-structure interaction processes, yet reliable numerical tools for modeling it are still scarce, necessitating new carefully validated developments.

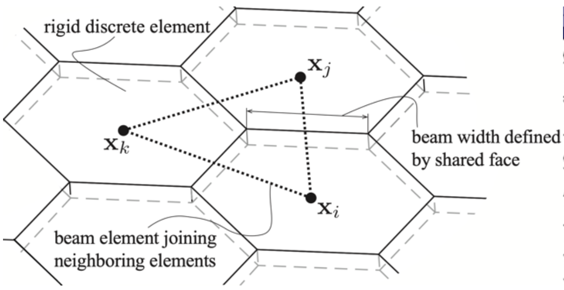
The numerical tools for ice engineering must account for the continuous failure process of an intact ice sheet, resulting broken ice, and contacts between the blocks of broken ice; it is crucial to model, not only the ice sheet failure, but also the ice blocks and their interaction, in order to realistically describe phenomena such as ride-up and pile-up of ice. In addition, ice engineering problems are often inherently three-dimensional, such as the process of an ice sheet failing against a cone, a common structural element of an offshore structure. A representative simulated failure process may need to last for minutes, or even tens of minutes, as different phases of the process must be modelled.

This paper describes a novel three-dimensional ice engineering simulation tool. The tool is based on combined finite-discrete element method (Cundall and Strack, 1979; Munjiza, 2004). Models using similar approach have become popular in ice engineering during the past few decades (Tuhkuri and Polojärvi, 2018). The strength of the model presented is that it is physics-based and able to account for all of the aforementioned features of the ice-structure interaction process. The paper briefly describes the main features of the model. Then it presents a validation study where simulations of the ice-inclined plane interaction process are compared to laboratory-scale experiments on the same problem. The results are also briefly analyzed and discussed. The work presented is described in detail by Polojärvi (2022).

MECHANICS

The sheets were discretized into discrete elements by using centroidal Voronoi tessellation and the intact ice sheet was modeled by using a lattice of rigid discrete elements connected by three-dimensional, elastic-viscous, Timoshenko beam elements (Figure 1). The model extends a two-dimensional ice sheet model introduced by Paavilainen et al. (2009). Lilja et al. (2019a, 2019b, 2021) verified that the model is able to predict the initial fracture and deformation of an intact ice sheet. The beam elements connect the centroids of pairs of discrete elements that share a face, and ice sheet deformation and failure result from the individual beams deforming and failing due to the relative motion of discrete elements. Beam failure is determined based on a mixed-mode failure criterion (Schreyer et al., 2006) similar to the Mohr-Coulomb failure criterion. To account for fracture energy dissipation, a cohesive softening model with linear softening is used (Hillerborg et al., 1976; Paavilainen et al. 2009). Cohesive elements are not used within the intact ice sheet in the elastic regime; instead, they are created on the fly upon beam failure, utilizing initially rigid cohesive elements. This approach avoids issues with artificial compliance (Sam et al., 2005).

Polojärvi (2022) describes the contact force model used in the simulations in detail. Simulations rely on a soft contact model, allowing the interacting ice blocks to overlap slightly, with the contact forces being determined based on the overlap volume. The contact force between a pair of ice blocks, $\mathbf{f}_c = \mathbf{f}_n + \mathbf{f}_t$, consists of a normal and a tangential component, $\mathbf{f}_n$ and $\mathbf{f}_t$, respectively. An elastic-viscous-plastic contact force model is used to calculate $\mathbf{f}_n$ (Hopkins, 1992). The elastic and viscous components of $\mathbf{f}_n$ are solved using the gradient of overlap volume and its rate of change, respectively (Feng, 2021). Plastic component of $\mathbf{f}_n$, describing local yielding or crushing of ice blocks, is based on area of contact. Tangential compliance and dynamic Coulomb friction between the contacting ice blocks yields $\mathbf{f}_t$ (Hopkins, 1992). Point of application for $\mathbf{f}_c$ is the centroid of the overlap volume allowing calculation of moment due to it. Importantly, the contact model can be parameterized by using material properties of ice.



(a)


(b)

Figure 1. Intact ice and ice fragments in the simulations: (a) discrete elements connected by beams and (b) ice floating in water. Figure (a) is reproduced from Polojärvi (2022).

VALIDATION

Figure 2 shows laboratory-scale experiments conducted by Saarinen (2000) and modelled for validation. The set-up involved a floating ice sheet being forced to move with constant velocity and fail against an inclined plane. In the simulations, the ice sheet was moved by translating its far end with a constant velocity towards the structure without allowing its rotation. No other boundary conditions were applied to the ice sheet, which was initially in a hydrostatic equilibrium. The experiments had a static ice cover surrounding the moving strip, simulated by using static rigid bodies. A gap of the thickness of the ice sheet separated the moving strip and the static ice cover. Table 1 lists the main simulation parameters.

Ice load records and load levels

Figure 3 shows the horizontal ice load applied on the inclined plane, *F*, plotted against the amount of ice that has failed against the structure, *L*, for both the simulations and the experiment. The general features of the *F-L* records from the simulations and the experiments compare well as they show a slowly increasing trend with consecutive peak ice load events. Although it is essential for the model to capture these features, an exact match between simulation and experiment results is not expected due to the non-linear and even stochastic nature of ice loading processes (Daley et al., 1998; Jordaan, 2001).

The *F-L* records remained similar when the mesh configuration or the element size changed as demonstrated by the envelope for *F-L* records from nine simulations where these properties were varied in Figure 3. Element sizes ranging from 1 to 5 times the ice thickness were tested and it was observed that while the details of the *F-L* records differed between the simulations with different element sizes, maximum and mean load showed only moderate variation; maximum and mean load values were within 25 % of that measured in the experiment. Notably, there was no trend observed in the load values with respect to the element size.

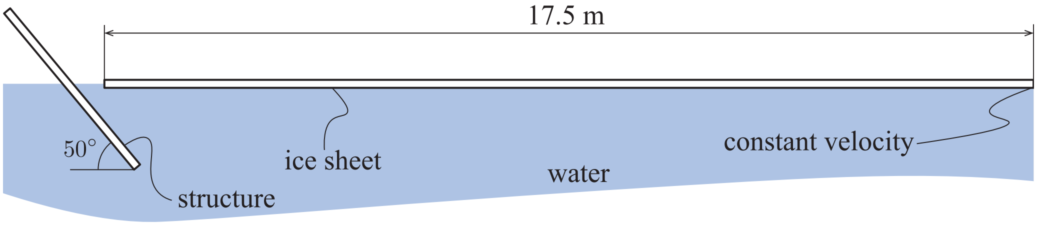


Figure 2. Set-up for the simulations on laboratory-scale experiments by Saarinen (2000). Figure is reproduced from Polojärvi (2022).

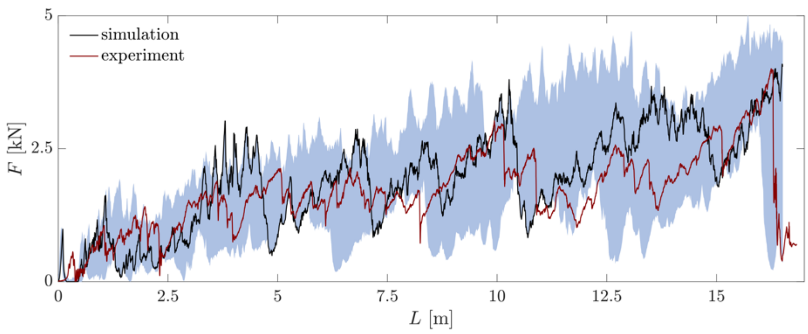


Figure 3. Horizontal load, *F,* on the inclined structure plotted against the amount of ice pushed against the structure, *L*, in the experiments by Saarinen (2000) and in the simulations presented here. Figure shows the envelope for *F-L* records from nine simulations with different ice sheet tessellations and element sizes. Figure is reproduced from Polojärvi (2022).

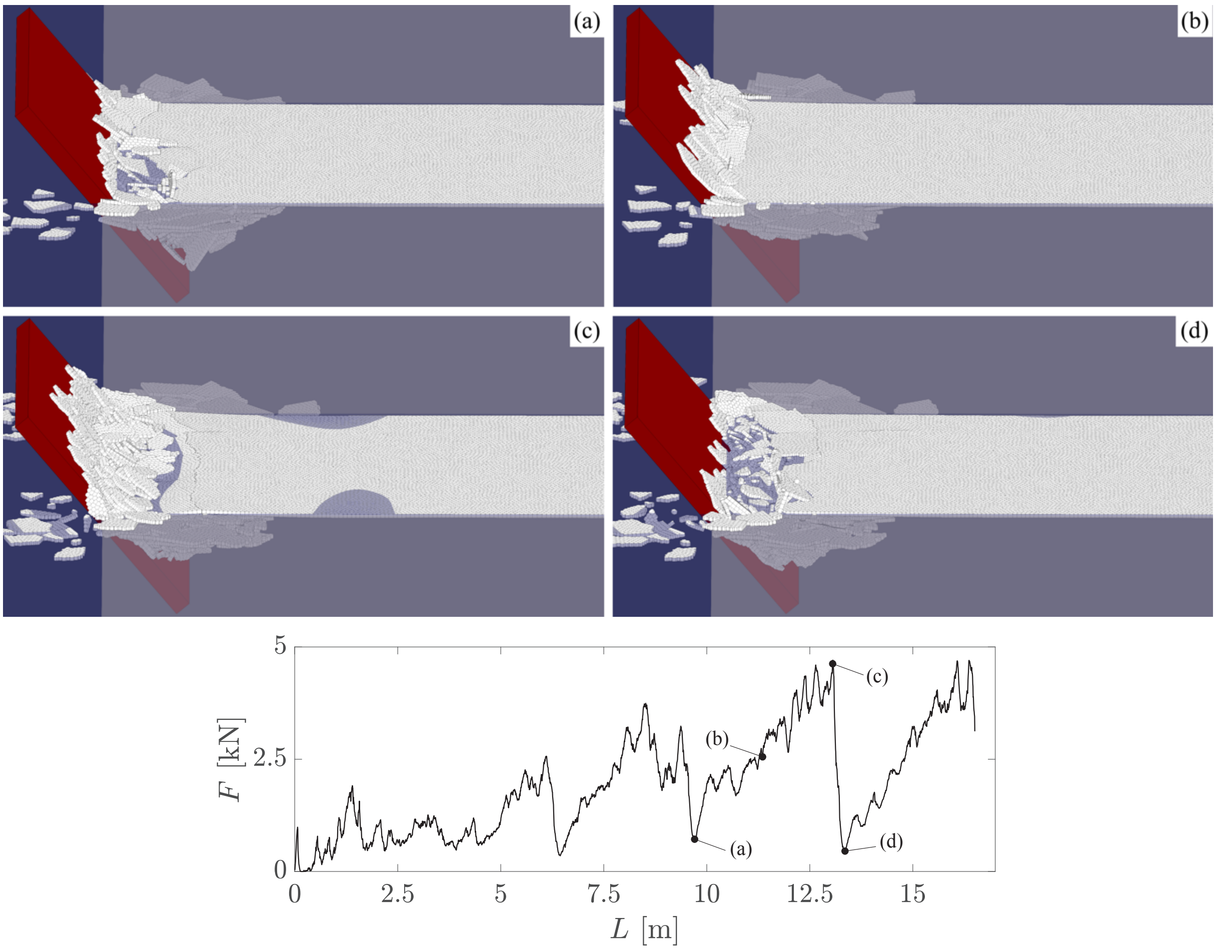
Table 1. Main simulation parameters. The parameters were chosen after the laboratory-scale experiments by Saarinen (2000) and Paavilainen et al. (2009) when applicable. Contact parameters were defined based on material parameters as described by Polojärvi (2022).

Description		Unit	Value
General	Gravitational acceleration	m s^{-2}	9.81
	Ice sheet velocity	m s^{-1}	0.05
	Drag coefficient	-	1.0
	Time step	s	$1.0 \cdot 10^{-4}$
	Duration of simulation	s	330
	Number of discrete elements		1422...36709
	Number of beam elements		4072...109013
Ice	Sheet thickness (h)	m	0.045
	Sheet width	m	4.6
	Initial sheet length	m	17.5
	Density	kg m^{-3}	930
Beams	Young's modulus	Mpa	70
	Damping ratio	-	0.75
	Poisson's ratio	-	0.3
	Tensile strength	kPa	40
	Shear strength	kPa	40
	Fracture energy	J m^{-2}	18
	Mean length	m	$1h...5h$
Contact	Normal contact stiffness	Pa m^{-3}	see Polojärvi (2022)
	Normal damping constant	Pa $s^{-1}m^{-3}$	see Polojärvi (2022)
	Tangential contact stiffness	N m^{-1}	see Polojärvi (2022)
	Tangential damping constant	N $s^{-1}m^{-1}$	see Polojärvi (2022)
	Damping ratio	-	0.75
	Plastic limit	kPa	40
	Ice-ice friction coefficient	-	0.34
	Ice-structure friction coefficient	-	0.07
Water	Density	kg m^{-3}	1000
Structure	Inclination angle	deg	50
	Structure width	m	4.6

Mechanics of the ice loading process

In addition to producing *F-L* records similar to those obtained in the experiments, the simulations must also depict the mechanical phenomena observed in the experiments correctly. Figures 4a-d show four snapshots from a peak load event in a simulation with the accompanying *F-L* record given in Figure 4e. The event begins with the intact ice sheet moving over a floating rubble pile of ice, formed of the ice that has previously failed during the interaction process (Figure 4a). During the period of increasing *F*, the ice locally fails against the structure and broken ice pieces ride up along the structure (Figure 4b). The ice load increases as long as the weight of the ice riding up the structure is supported by the ice sheet and the floating rubble pile. The load drop occurs immediately after a global downward bending failure of the ice sheet (Figure 4c). This leads to the ice on the structure to slide backwards and submerge in the water in front of the structure. The load drop is abrupt as it only takes a few seconds until the peak ice load event comes to an end (Figure 4d).

The above-described mechanical phenomena during the peak load events are virtually identical to that observed in the experiments by Saarinen (2000). When the ice rides up the structure, the load increases, until a downward bending failure of the ice sheet occurs. Polojärvi (2022) analyzed the peak load events in detail, revealing a strong correlation between the volume of ice riding up the structure and F; weight of the ice supported by the structure governs F. The reason for slowly increasing trend in the F-L records is a fairly straightforward. During the continuous failure process, the amount of broken ice in front of the structure increases, leading to an increasing support for the ice sheet and ice riding up the structure, thus restricting the downward bending failure of the ice sheet.



(e)

Figure 4. Snapshots from a peak ice load: (a) start of the event, (b) load, F, increases due to ice ride-up, (c) maximum F followed by global ice sheet failure, and (d) end of the event. F-L record indicating the instances of the snapshots is given in (e). Figure is reproduced from Polojärvi (2022).

DISCUSSION

The example above involved a three-dimensional simulation being applied on a problem that is, in principle, two-dimensional. This is because the structure modeled could be considered wide, since the structure width to ice thickness ratio was about 1:100. The same experiment was earlier modeled by Paavilainen et al. (2009) by using two-dimensional combined finite-discrete element simulations. Their simulations yielded satisfactory results. For instance, the maximum line load in their simulations was about 1.15 kN m^{-1}, close to the value 1.05 kN m^{-1} obtained from the nine simulations here on average. The two-dimensional simulations, however, also yielded different features from those observed here, such as a drop in F to zero after the peak load events, more distinct and frequent peak load events, and a failure to capture the increasing trend in the F-L record. In summary, the results reveal that three-dimensional modelling of a two-dimensional ice-structure interaction process can be advantageous in providing new insight on ice loading processes.

The results presented further demonstrate that long enough failure process needs to be modelled in order to estimate ice loads, since the F-L record shows consecutive peak load events with the peak loads increasing in magnitude. Modelling only the initial stages of ice loading process does not suffice. This was further exemplified by the simulations conducted on a full-scale ice-conical structure interaction process in Polojärvi (2022). Computational time is often the limiting factor when modelling interaction processes, but this limitation was avoided here by parallelization. Typical running times for the simulations here were about 8 h as the simulations were run parallel on some tens of processors. Wall clock times for the simulations here depended on the tessellation with the shortest ones being about 3 h. Related to this, it is worth noting that even the coarsest mesh yielded satisfactory results and that the load levels in the simulations did not depend on the element size.

The parameterization of beam lattice-based models accurately is challenging (Lilja, 2019a, 2019b, 2021). Here the material properties for the beam elements were simply chosen after the material properties measured for the ice sheet in the experiment. Lilja et al. (2019b) show that this choice may lead to an error in the initial ice sheet stiffness. This error depends on the ice sheet dimensions and the ratio of the beam element length to ice sheet dimensions. This ratio was here varied by using fairly large range of element sizes. These were not picked after microstructure of ice. Error in the stiffness of broken ice fragments is difficult to estimate, but their deformation can be justifiably assumed to be negligible compared to their rigid body motion. Nonetheless, the simulations presented here demonstrate a convincing agreement with the experiment. This suggests that either the error in the material properties was not significant or that the simulated case is not sensitive to sheet stiffness.

CONCLUSIONS

This paper presented a study that validates a three-dimensional FEM-DEM simulation tool for ice-structure interaction. The study focused on simulations on laboratory-scale experiments on a case where an ice sheet interacts with an inclined structure. The ice sheet was modelled by connecting rigid discrete elements with beam elements that undergo cohesive softening upon failure. The model accounts for friction and ice failure in contacts due to local ice crushing. The validation of the model was successful. The study investigated the ice loading process in detail and found a strong correlation between the ice load and the volume of broken ice mass supported by the structure. The results demonstrate that three-dimensional simulations provide new insight even into apparently two-dimensional ice loading scenarios.

ACKNOWLEDGEMENTS

The author would like to acknowledge the financial support from the Academy of Finland research project (348586) WindySea - Modelling engine to design, assess environmental impacts, and operate wind farms for ice-covered waters. CSC–IT Center for Science (Finland) is acknowledged for computational resources under the project (2000971) Mechanics and Fracture of Ice.

REFERENCES

Cundall P., Strack O. (1979) A discrete numerical model for granular assemblies. *Géotechnique*, 29(1):47–65.

Daley C., Tuhkuri J., Riska K. (1998) The role of discrete failures in local ice loads. *Cold Regions Science and Technology*, 27(3):197–211.

Feng YT. (2021) An energy-conserving contact theory for discrete element modelling of arbitrarily shaped particles: Basic framework and general contact model. *Computer Methods in Applied Mechanics and Engineering*, 373:113454.

Hillerborg A., Modéer M., Petersson P.E. (1976) Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. *Cement and Concrete Research*, 6:773–82.

Hopkins M. (1992) *Numerical simulation of systems of multitudinous polygonal blocks.* Technical Report 92-22. Cold Regions Research and Engineering Laboratory (CRREL), 69 p.

Jordaan I. (2001) Mechanics of ice-structure interaction. *Engineering Fracture Mechanics*, 68:1923–60.

Munjiza A. (2004) *The combined finite-discrete element method.* Chichester, England: John Wiley & Sons Ltd.

Paavilainen, J., Tuhkuri, J., and Polojärvi, A. (2009). 2D combined finite–discrete element method to model multi-fracture of beam structures. *Engineering Computations*, 26(6):578–598.

Polojärvi, A. (2022). Numerical model for a failure process of an ice sheet. *Computers and Structures*, 269, 106828.

Lilja, V.-P., Polojärvi, A., Tuhkuri, J., and Paavilainen, J. (2019a). Effective material properties of a finite element-discrete element model of an ice sheet. *Computers and Structures*, 224, 106107.

Lilja, V.-P., Polojärvi, A., Tuhkuri, J., and Paavilainen, J. (2019b). A free, square, point-loaded ice sheet: A finite element-discrete element approach. *Marine Structures*, 68, 102644.

Lilja, V. P., Polojärvi, A., Tuhkuri, J., and Paavilainen, J. (2021). Finite-discrete element modelling of sea ice sheet fracture. *International Journal of Solids and Structures*, 217-218:228–258.

Sam C.H., Papoulia K.D., Vavasisc S.A. (2005) Obtaining initially rigid cohesive finite element models that are temporally convergent. *Engineering Fracture Mechanics*, 72(14):2247–67.

Saarinen S. (2000) *Description of the pile-up process of an ice sheet against an inclined plate*. Master's thesis. Helsinki University of Technology.

Schreyer H., Sulsky D., Munday L., Coon M., Kwok R. (2006) Elastic-decohesive constitutive model for sea ice. *Journal of Geophysical Research: Oceans*, 111(11).

Tuhkuri, J. and Polojärvi, A. (2018). A review of discrete element simulation of ice-structure interaction. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376(2129).