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Ice block breakage within deforming ice rubble

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ABSTRACT

This paper studies ice block breakage during shearing of ice rubble by using discrete element method simulations with a block breakage model. In the case of ice rubble, breakage is the tendency of ice blocks failing due to loads acting on them. Block breakage often plays an important role in force transmission through granular materials, yet it has not been thoroughly studied in the context of ice rubble. In this research, direct shear box experiments on ice rubble were simulated with and without the block breakage model and the simulation results were compared with experiments. Our results indicate that accounting for breakage improves the accuracy of the DEM simulations. Moreover, in our case, shear strength of the ice rubble decreased about 15% when the blocks are allowed to break in the simulations.

KEY WORDS: Ice block breakage; Discrete element method; Ice rubble

INTRODUCTION

Understanding of the mechanical behavior of ice rubble is important in modeling ice-structure interaction processes. Ice rubble is a granular material, thus, force transmission through an ice rubble pile occurs predominantly through force chains, which comprise of ice blocks under high compressive contact forces. Force chains in ice rubble are known to collapse due to their buckling. Force chain buckling and its effect on mechanical properties of ice rubble has been studied previously by Paavilainen and Tuhkuri (2013) and Ranta et al. (2018) by using discrete element method (DEM) simulations. Ice block breakage was observed in the direct shear box experiments on ice rubble by Pustogvar et al. (2014), nevertheless, the effect of block breakage on ice rubble behavior has not been thoroughly studied. Hopkins and Hibler (1991) presented a DEM model with bending failure-based block breakage model and simulated the direct shear box experiment on ice rubble. Their results suggest that the dilatancy of ice rubble in direct shear box experiments decreases when the particles are allowed to break. Moreover, Kulyakhtin (2019) presented a continuum ice rubble model with a breakage parameter and simulated a structure pushed through an ice rubble field. Their results suggest that ice loads were governed by the accumulation of rubble but not breakage. However, continuum models are not capable of capturing force chains within. Therefore, there exists a research gap related to the effect of ice block breakage on rubble behavior. The present study focuses on investigating the effect of block breakage on mechanical behavior of ice rubble by numerically modeling direct shear box experiments on ice rubble. A DEM code with a block breakage model was used and simulations with the breakage model and without it were performed to study the effect of breakage on simulation results.

METHODS

DEM model

Research described in this study was performed by using the in-house DEM code of Aalto university ice mechanics research group. The code is described in detail by Polojärvi (2022). In brief, the code models arbitrary shaped ice blocks by using three-dimensional polyhedral elements. Interaction between blocks is modeled by using a pairwise soft contact model, that is contact force between two interacting blocks is calculated based on a small overlap between them. Central difference scheme is used for explicit time stepping. The code is fully parallelized and usually run on a cluster. For the work presented here, a breakage model was integrated into the DEM code. The breakage model is described in detail by Prasanna and Polojärvi (2023) and it is based on experimental data and high-resolution bonded particle modeling by Prasanna et al. (2021, 2022). The breakage model assumes that an ice block can fail by shear failure governed by the Mohr-Coulomb failure criterion. Failure of a block is calculated by using quasi-static equilibrium of contact forces acting on the block.

Shear box experiments

Fig. 1 presents an illustration of the direct shear box experiment setup simulated. The physical experiments were performed by Pustogvar et al. (2014). In the simulations, the ice rubble specimens modeled had dimensions of 600 mm × 400 mm × 40 mm (length × width × thickness) and consisted of ice blocks of size 60 mm × 40 mm × 40 mm. The setup can be considered pseudo two-dimensional, since the thickness of the ice blocks and the rubble specimen were equal to that of the shear box. Shear box was filled by using gravitational deposition. Vertical confining pressure, P, was applied through the cover of the shear box and four P values, covering range 5.75...22.06 kPa, were used. Velocity of the shear box cover was 0.02 ms^{-1}, thus, the simulations were quasi-static. From the simulations, shear force exerted on the cover by ice rubble, S, was obtained as a function of the displacement, d, of the upper half of the box. Then the shear stress within the rubble was calculated by dividing S by the area of the shear plane. The mean shear resistance, $\bar{\tau}$, and the maximum shear strength, τ^m, of the ice rubble were then derived by taking the average and the maximum of shear stress, respectively, for a given interval of d.

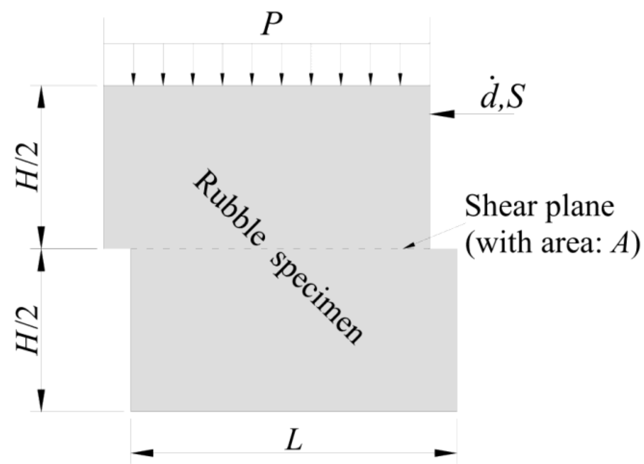


Figure 1: An illustration of the direct shear box experiment setup.

RESULTS

Shear force results

Fig. 2 presents typical force-displacement, *S-d*, results from direct shear box experiment simulations with and without the breakage model. The confining pressure, *P*, was 5.75 kPa in both simulations and the internal cohesion of the ice blocks, c_i, a measure of the strength of the ice blocks, was 250 kPa in the simulation with the breakage model. The figure further shows experimental *S-d* results obtained by Pustogvar et al. (2014) for the same confining pressure. As the figure demonstrates, *S-d* records have several distinct peaks, referred here to as peak load events. The simulation with the breakage model produces peak load events having their magnitude closer to those in the experiments than the simulation without the breakage model. Thus, breakage model seems to improve the simulation results. In the figure, *S-d* record from the simulation with the breakage model follows that from the simulation without the breakage model until the first peak load event. Then the two records deviate from each other suggesting that breakage effects the mechanical phenomena governing the peak load event. This is reflected further in the *S-d* records, where the magnitudes of the peak loads are in general smaller in the simulation with the breakage model than to that without it.

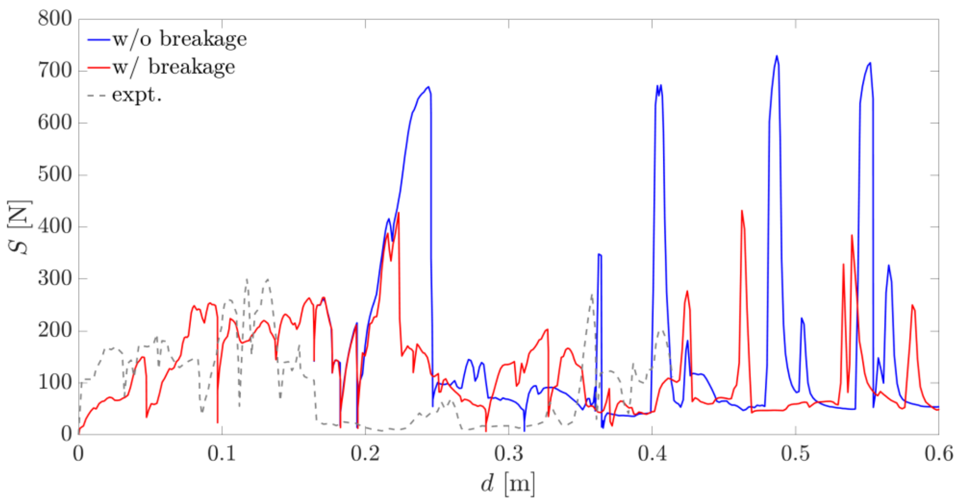


Figure 2: Typical shear force-displacement, *S-d*, records from simulations compared with the same from experiments of Pustogvar et al. (2014).

Table 1 compares the experimental results against results from the simulations with the breakage model and without it by reporting mean and maximum shear force, $\bar{S}$ and S^m, respectively, for each. For each experiment and simulation, $\bar{S}$ and S^m were calculated by taking the average and the maximum of the *S* record, respectively. The table also presents the error in $\bar{S}$ and S^m results from the simulations with respect to the experiments. For each case, the results of the table were calculated from five repeated simulations with different initial rubble arrangements. The relative error of $\bar{S}$ and S^m results are on average 13% and 10%, respectively, in the simulations with the breakage model, whereas in the simulations without the breakage model the corresponding errors were 30% and 33%. This means the simulations with the breakage model yielded $\bar{S}$ and S^m results closer to those from the experiments. Thus, accounting for the breakage appears to improve the accuracy of the simulations. Moreover, it is worth noting that $\bar{S}$ and S^m results from the simulations with the breakage model are 15% lower in general compared to the same from the simulations without the breakage model.

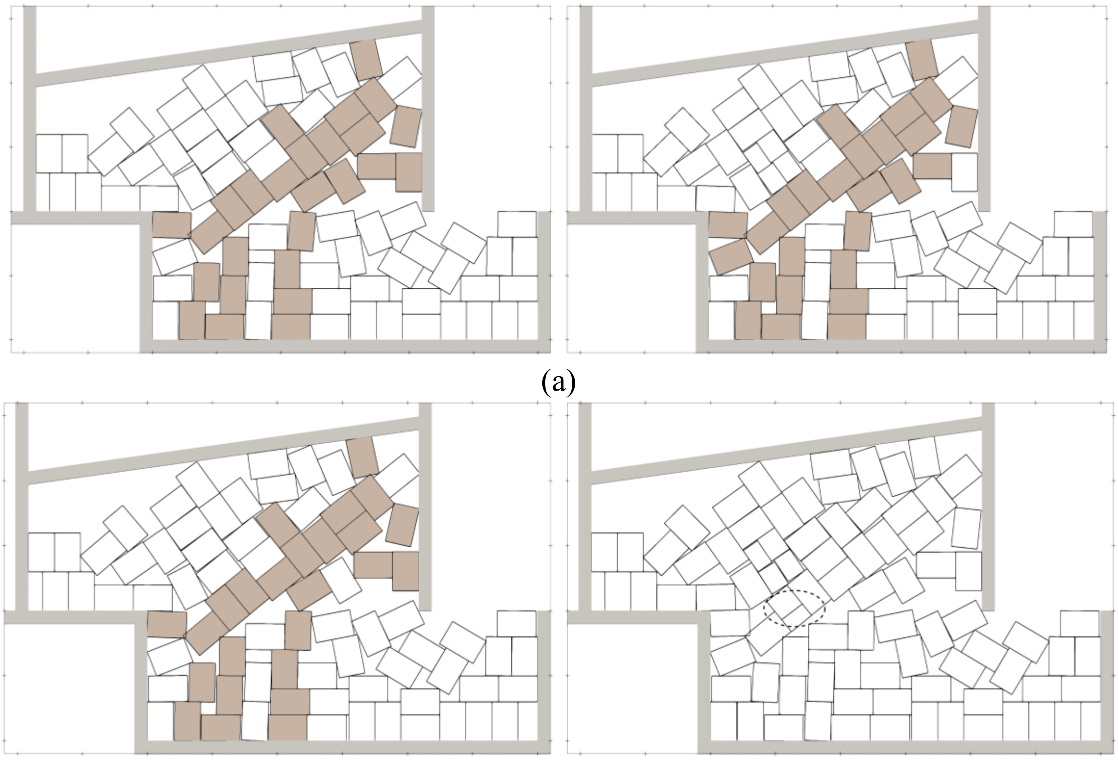
Table 1: Mean shear force, $\bar{S}$, and maximum shear force, S^m, from the simulations and corresponding experiments. Results were calculated from five repeated simulations and experiments for each case

	P [kPa]	Experiment [N]		DEM with breakage [N]		DEM without breakage [N]	
		Mean	Std. deviation	Mean (error)	Std. deviation	Mean (error)	Std. deviation
$\bar{S}$	5.75	179.6	43.1	182.6 (1.7%)	38.7	209.9 (16.9%)	38.5
	11.03	220.2	102.9	272.6 (23.8%)	47.2	313.1 (42.2%)	28.7
S^m	5.75	415.7	150.1	446.7 (7.4%)	123.9	562.8 (35.4%)	244.4
	11.03	549.6	98.4	615.5 (12.0%)	90.0	714.3 (30.0%)	98.2

Force chains

The *S-d* plots demonstrate that breakage limits the magnitudes of peak load events. Peak load events in the simulations without the breakage model are caused by formation and subsequent buckling of force chains within the rubble. However, when blocks are allowed to break, force chains can collapse due to block breakage before the load transmitted by them reach the load required for their buckling. This behavior is demonstrated in Fig. 3, which shows two sequences of images from the first peak load event in simulations with the *S-d* records presented in Fig. 2. In the figure, left and right columns show the ice rubble in simulations without and with the breakage model, respectively. Force chains within the rubble are illustrated by coloring the ice blocks whose normalized first principal stresses of their particle stress tensor exceed the threshold of 0.1. Principal stresses here are normalized by its maximum value during the peak load event in the simulation without the breakage model.

Fig. 3a shows how a force chain is forming at the beginning of the peak load event in both simulations. As the load increases, some of the ice blocks within the force chain break in the simulation with the breakage model, which in turn causes the force chain to collapse (Fig. 3b). Whereas, in the other simulation, force chain gets compressed further and eventually collapses due to buckling. This confirms that block breakage is one of the failure modes of force chains. The *S-d* records of Fig. 2 reflect this behavior as the magnitude of the first peak load event is significantly smaller in the simulation with the breakage model compared to the stimulation without it. It is important to note that some of the force chains in the simulations with the breakage model also failed by buckling, thus, block breakage is not the only failure mode in them.



(a)

(b)

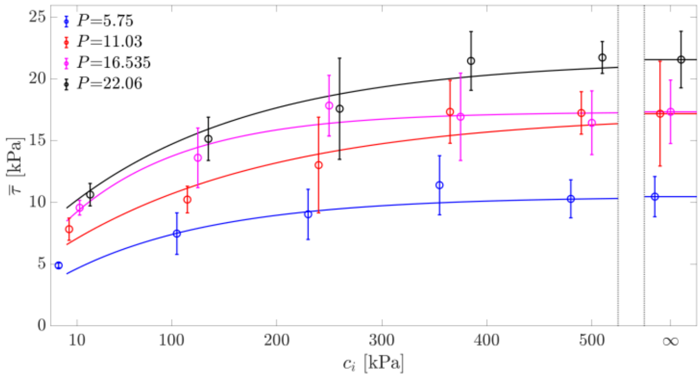
Figure 3: Snapshots from the simulations comparing force chain formation. Left column shows figures from a simulation without the breakage model while those in the right column are from a simulation with the breakage model. Force chain is (a) first forming near the shear plane in both simulations, and then (b) force chain in the simulation with the breakage model collapses due to block breakage.

Shear strength of ice rubble

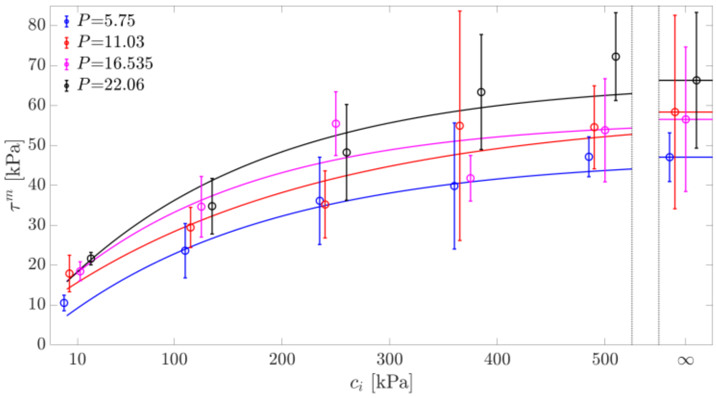
The results above show that the shear force measured in direct shear box experiments is affected by block breakage, which in turn effects the measured shear strength of the rubble. The effect of ice block strength on measured shear strength of rubble was, thus, further investigated by varying the internal cohesion, c_i, of the ice in simulations. As described in Prasanna and Polojärvi (2023), c_i is a central parameter when describing the strength of the ice blocks in the breakage model. Fig. 4 presents the data for mean shear resistance and the maximum shear strength, $\bar{\tau}$ and τ^m, respectively, from the simulations plotted against c_i. Results presented are from simulations with confining pressures, P = 5.75, 11.03, 16.54 and 22.06 kPa. Further, the data presented are the mean values and standard deviations of $\bar{\tau}$ and τ^m from five repeated simulations, only differing by the initial arrangement of the blocks, for each case. The figure further shows an asymptotic function fitted on the data. The asymptotic function was of form $y = a' - (a' - b')\ exp^{-x/c}$, where a', b' and c′ are the parameters defined during fitting. The fits were forced to pass through the respective mean values of the simulations without the breakage model, indicated by the data at $c_i = \infty$ kPa in the figure.

As shown by Fig. 4, both $\bar{\tau}$ and τ^m increase with the block strength towards the results from the simulations without the breakage model. This would be expected, but the fits further imply that the effect of block breakage on the shear strength of ice rubble decreases with increasing block strength fairly fast; The effect of breakage on $\bar{\tau}$ disappears for c_i>400 MPa as the $\bar{\tau}$ values are then about 90% of those from the simulations without the breakage model, whereas, for τ^m

breakage affects the results still at c_i=500 MPa with the effect being more pronounced with higher P.



a)



b)

Figure 4: Effect of shear strength of ice on the shear strength of ice rubble. The mean shear resistance, $\bar{\tau}$, and maximum shear strength, τ^m,of ice rubble against the internal cohesion , c_i, of ice. Figure shows means and standard deviations of five repeated simulations for each case.

DISCUSSION

In DEM simulations of ice rubble, or ice in general, local contact failure of the ice blocks is usually modeled by setting a plastic limit for the contact force based on the compressive strength of ice (Hopkins, 1992; Paavilainen et al., 2009; Ranta et al., 2018). However, the simulation results of the present paper with and without a block breakage model suggests that the previously used approach is not always sufficient, but breakage has to be modeled as well. This is because breakage often limits the forces transmitted by force chains. Moreover, smaller fragments generated by block breakage may fill the voids within the rubble during rubble deformation, which in turn may locally reduce the porosity of the rubble. Nevertheless, block breakage models in DEM simulations of ice are scarce. Hopkins and Hibler (1991) presents a bending failure-based block breakage model, yet its applicability to ice blocks with low aspect ratio is questionable, since shear failure appears to often be the governing block failure mode in such case (Prasanna et al., 2021).

Our results on peak load magnitudes show that the force chain failure due to block breakage often occurs at lower force level compared to force chain buckling. Thus, the force transmission capacity of the simulated ice rubble is lower when the blocks are allowed to break. This reduces the mean shear resistance, $\bar{\tau}$, and the maximum instantaneous shear strength, τ^m, of the ice rubble. Here the $\bar{\tau}$ and τ^m results show about 15% decrease (Fig. 5) for internal cohesion of ice c_i=250 kPa, chosen following the experimental results of Prasanna et al. (2021). With different blocks sizes this result could have changed. Nevertheless, the results here indicate that the ice load estimates obtained from DEM simulations without any block breakage model may be overly conservative and their values should be used with this in mind when studying, for example, ice-structure interaction processes.

CONCLUSIONS

The present paper investigated the effect of block breakage on mechanical behavior of ice rubble. Direct shear box experiments on ice rubble were simulated by using a discrete element method code with an embedded block breakage model. The block breakage model in the DEM code was based on experimental observations and assumed that the blocks fail due to shearing. Simulations with and without the breakage model were performed and compared with experimental data. Simulation results show that accounting for breakage improves the accuracy of DEM simulations. In the simulations with breakage, force chains within ice rubble often fail due to block breakage, which in turn limits the force transmission capacity of the rubble. Moreover, the mean shear resistance and the maximum shear strength of the simulated rubble showed about 15% decrease in the simulation with the block breakage model. Therefore, modeling block breakage in DEM simulations of ice rubble seems to be essential for material modeling of ice rubble.

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