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Discrete Element Simulation of Sea Ice Loads on Narrow Conical Structures

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Discrete element method (DEM) is used to simulate the interaction between level ice and narrow conical structures in this paper. The level ice is modelled by spherical particles with a parallel-bonding approach. The effect of particle size on flexural strength is researched to confirm the micro parameters in DEM. A relationship between them is calibrated by simulating three-points bending physical experiments and applied to study the ice loads and failure patterns on conical structures in DEM. A comparison with HSVA experiments is necessary to validate the accuracy of the calibrated DEM model. The background and modeling parameters in HSVA are described. The force records and failure patterns from the experiments and numerical simulations are in agreement. Moreover the frequency and distribution of ice force are also analyzed to compare with experiments data. More discussions on the contact force model and its input parameters are recommended for improving the DEM application in the dynamic ice load simulations of offshore structures.

Keywords: discrete element method (DEM), sea ice, particle size, narrow conical structure, ice load

1. Introduction

Currently the conical offshore structure is widely used in ocean engineering, such as the Finnish Kemi-I lighthouse in the Gulf of Bothnia [Määttänen and Hoikkanen, 1990], the Confederation Bridge in the Southern Gulf of Lawrence [Brown et al., 2010], and the conical jacket platforms in the Bohai Sea of China [Qu et al., 2006; Yue et al., 2007]. A well-designed cone can reduce the ice load and change the ice failure mode from crushing to bending comparing with the cylindrical structure. Field measurements, model tests and numerical simulations are the primary methods to obtain the ice loads during the interaction between sea ice cover and conical structures [Xu et al., 2015]. The results of full scale field measurements are structure-specific, but still insufficient for general design purpose. Model tests also cannot be applied directly in engineering because of scaling issues. Therefore a general numerical approach such as discrete element method (DEM) with the advantages of low cost and highly efficient may provide a better alternative method for engineering applications.

DEM has obvious advantages in modeling the ice breakup and obtaining the ice load process in detail [Paavilainen and Tuhkuri, 2013]. The 2-D block DEM has been adopted to study the plane strain problem of the interaction between a moving ice sheet and a stationary structure [Selvadurai et al., 1999]. The 3-D block DEM code (DECICE) was used to model the interaction of an ice sheet with a conical bridge pier [Lau et al., 2011]. In the broken ice field, the DEM is propitious to describe dynamic behaviors of ice floes and its action on offshore structures. During the interaction between ice cover and offshore structures, the ice cover is broken into small fragments within a process of discrete failure events to generate random impulse ice loads [Ji and Di, 2015]. The DEM with bonded spheres can model the cracking feature of ice cover with a rational failure criterion. In the DEM simulations, ice loads are sensitive to the microcosmic parameters such as particle size, bonding strength and friction coefficient. Many scholars discuss how these DEM parameters effect on the mechanical property of sea ice by simulating mechanical experiments [Tian and Huang, 2013]. Both compressive strength and flexural strength of sea ice are related to particle size. However the selection of computational parameters also needs to validate by comparing with the results of model tests or field measurements.

This paper focuses on simulating the interaction between sea ice and conical structure by DEM with bonded-particles approach. Considering particle size effect, the relationship between computational parameters and flexural strength of ice is validated by comparing the ice load and fracture mode with HSVA tests.

2. Parallel-bonding model

To simulate the mechanical properties of sea ice by DEM, the spherical particles are glued together with parallel-bonding model [Potyondy and Cundall, 2004], as shown in figure 1. The parallel-bonding can be envisioned as a set of elastic springs with constant normal and shear stiffness, uniformly distributed over a circular disk lying on the contact plane and centered at the contact point. Comparing with the contact-bonding model, the parallel-bonding model can not only transfer forces also moments which is more suitable for the simulation of sea ice breaking.

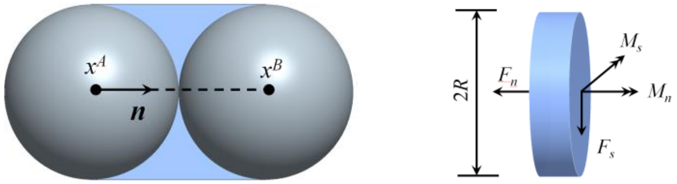


Figure 1. Bonding model between two spherical particles

The force and moment in normal direction and shear direction associated with the parallel bond are denoted by F_{n}, F_{s}, M_{n} and M_{s}. The maxiumum tensile and shear stresses acting on the bonding disk are calculated based on the beam theory as

$$\sigma_{\max} = \frac{-|F_{\mathrm{n}}|}{A} + \frac{|M_{\mathrm{s}}|}{I} R, \ \tau_{\max} = \frac{|F_{\mathrm{s}}|}{A} + \frac{|M_{\mathrm{n}}|}{J} R \qquad \textbf{[1]}$$

where the variables *A*, *I* and *J* are given by

$$A = \pi R^2, \ J = \frac{1}{2}\pi R^4, \ I = \frac{1}{4}\pi R^4 \qquad \textbf{[2]}$$

If tensile stress esceeds the normal strength, or shear stress exceeds the shear strength, then the parallel bonding relationship breaks.

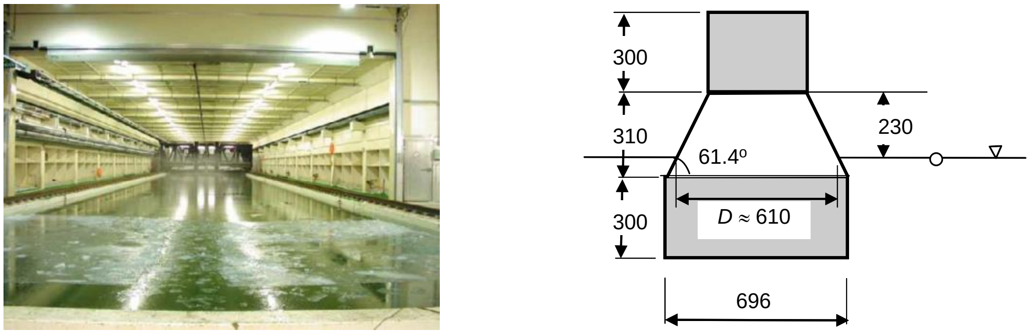
$$\sigma_{\max} > \sigma_n^c, \ \tau_{\max} > \tau_s^c \qquad \textbf{[3]}$$

where σ_n^c and τ_s^c are respectively preinstall normal and shear strength, and both of them are related to bonding strength between particles (σ_{b}).

3. HSVA model and DEM parameters

The model was tested in the ice tank of The Hamburg Ship Model Basin (HSVA), shown as figure 2(a). The tank, which is 78m long by 10m wide by 2.5m deep (the end of tank with 12m long by 10m wide by 5m deep), is housed in a large insulated cold room that can be chilled to temperature of -28℃. The shape of the model cone is identical to that of the full scale cone; According to the scaling factors, the narrow cone was erected narrow cone to larger scaling factor of 6, with cone diameter at waterline 610mm shown in figure 2(b).

The thickness of ice was adjusted by selecting an appropriate freezing time to produce the desired thickness. This produced an ice sheet with an average thickness of 30mm.The strength of the ice was adjusted by altering the time allowed for warming up the ice. The speed of the ice-structure interaction was accomplished by adjusting the speed of the carriage. Some ice parameters are list in table 1, and σ_{fice} is flexural strength of sea ice in the tests.



(a) (b)

Figure 2. (a) HSVA's ice basin: 78m long, 10 m wide and 2.5m deep (b)Test structure schematics characteristics

Table 1. Ice factors of HSVA tests

Test No.	Cone type	Velocity (mm/s)	Thickness (mm)	σ_{fice} (kPa)
1010	Narrow	200	32.03	60.6

The size effect has a significant meaning to DEM simulation. The relationship between particle size and flexural strength (σ_f) is acquired by simulating three-point bending experiment in figure 3 and formula 4 where the computational bonding strength of particles (σ_b^0) is 0.6 MPa. σ_f is decreased with increasing related particle size ($\overline{D}$) as Eq.(5).

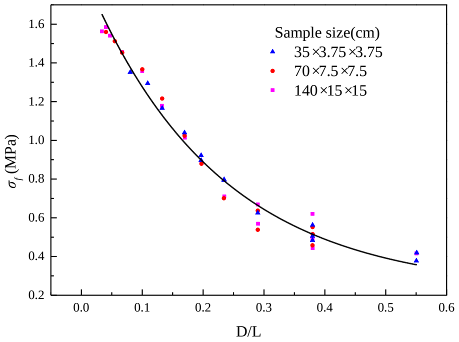


Figure 3. Relationship between particle size and flexural strength

$$\sigma_f = 1.67e^{-\overline{D}/0.2} + 0.23 \qquad \textbf{[4]}$$

$$\overline{D} = D/L \qquad \textbf{[5]}$$

where D is particle diameter and L is ice sample size. The flexural strength of sea ice decreases with the increasing particle size when the sample size is a constant. This relationship does not change with three different sample sizes. Therefore the macro mechanical property of sea ice is related to micro computational parameters such as particle size. So the bonding strength in DEM of this case can be calculated by particle size and flexural strength as formula 4 and formula 6 where $\overline{D} = 1.0$.

$$\sigma_{\mathrm{b}} = \frac{\sigma_{\mathrm{b}}^{0}}{\sigma_{f}} \times \sigma_{fice} = \frac{0.6}{0.23} \times 0.606MPa = 0.16MPa \qquad \textbf{[6]}$$

For comparing with HSVA tests, the parameters of structure and model ice reach an agreement with experimental conditions. Both size and flexural strength of ice cover are set according to the tests. The main parameters of DEM model are list in table 2.

Table 2. DEM parameters to compare with HSVA

Definition	Symbol	unit	value
Sea ice Density	ρ	kg/m^3	920
Initial ice cover area	$a \times b$	m^2	8×5
Particle diameter	D	mm	32.03
Normal stiffness	K_{n}	N/m	2.5×10^6
Shear Stiffness	K_{s}	N/m	2.5×10^5
Bonding strength	σ_{b}	MPa	0.16
Particle friction	μ_{p}		0.2
Particle restitution	e_{p}		0.3
Wall-particle friction	μ_{w}		0.15
Wall-particle restitution	e_{w}		0.3

4. DEM results compared with HSVA

The structure in test 1010 is narrow cone. The failure processes of level ice interacted on narrow cone from three angles are similar with each other and shown in figure 4 (DEM result) and figure 5 (HSVA test) respectively. From the failure process, the failure model of sea ice interacted with conical structure is mainly flexural failure. When internal cracks run through the ice sheet, circumferential and radical cracks were observed. The broken ice can be removed by the two sides of structure in time, and it will not produce the accumulation of floe ice obviously, then the subsequent ice can be directly acting on the structure and generate larger ice load.

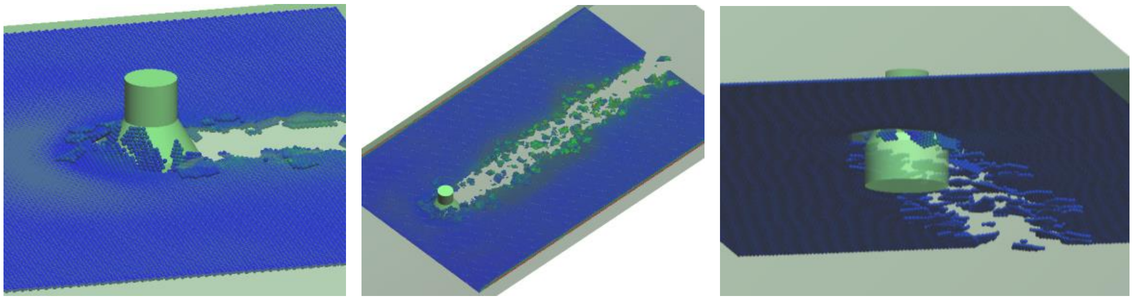


Figure 4. Broken process of ice cover in DEM result

The ice forces in level direction are shown in figure 6 including HSVA data and DEM result which are selected peak force and compared with each other. The force results' comparisons are listed in table 3. The DEM result is similar to test one according to maximum ice load and the mean value of selected peak forces. Therefore from the ice load and failure pattern, the selecting method of micro parameters in DEM is accepted for comparison of HSVA tests.

Obviously ice force-time curves of both experiment and simulation in figure 6 are includes two parts: loading and unloading. In loading process, the ice cover is interacted with structure directly and broken by the impact force; while in unloading process, the broken ice climbs along structure and follows into water. Hence the ice load curves are periodic and discrete with the movement of ice cover. The periodicity and energy of ice load also has a positive influence on the vibration and damage of structure. The distributions of peak forces are analyzed for a better understanding of ice load.

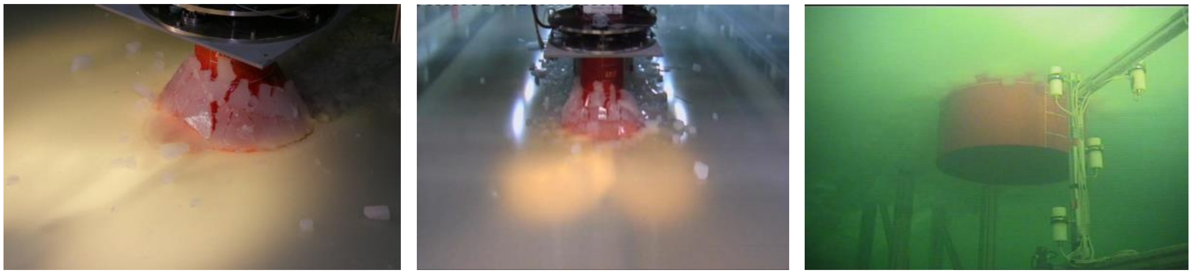
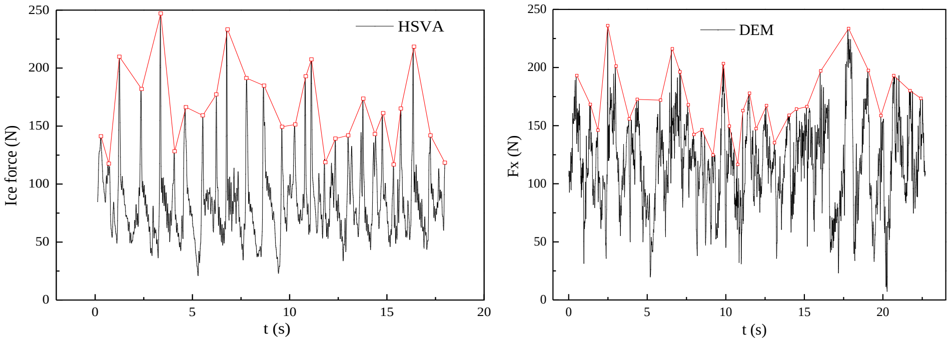


Figure 5. Broken process of ice cover in HSVA test 1010



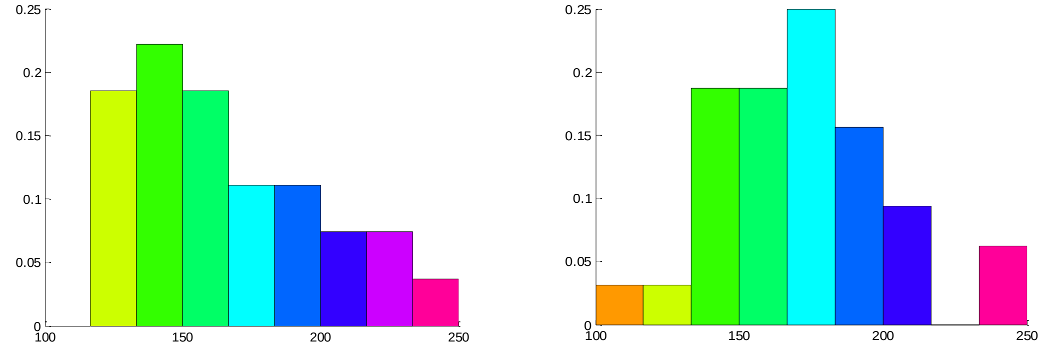
(a) HSVA test (b) Numerical calculation

Figure 6. Ice loads of narrow conical

Table 3. Comparison of maximum and mean ice load

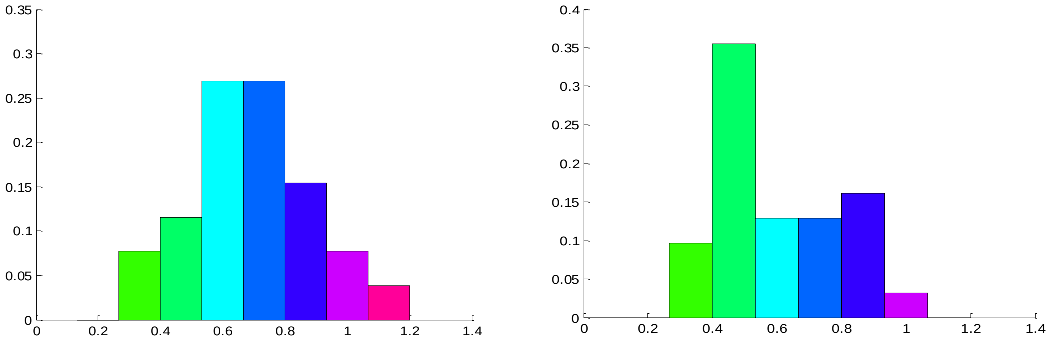
	Max force (N)	Mean peak force (N)
Test 1010	247.06	165.86
DEM result	236.71	172.56

The results in figure 7 to 9 analyzed by the peak forces selected in figure 6 are respectively probability distribution of peak forces, probability distribution of peak forces’ time intervals and power spectral density of ice load. The peak ice force of both test and simulation results are distributed at about 100~200N. The peak forces’ time intervals of them are mostly distributed at 0.4~1.0s. The power spectral densities for ice load of them are mostly distributed at about 0~10.0s, and the maximum values of frequency are about 1.0s in both two figures which illustrates that the frequency of high energy is similar. The numerical results have an agreement with HSVA experiment in peak force, periodicity and energy of ice load.



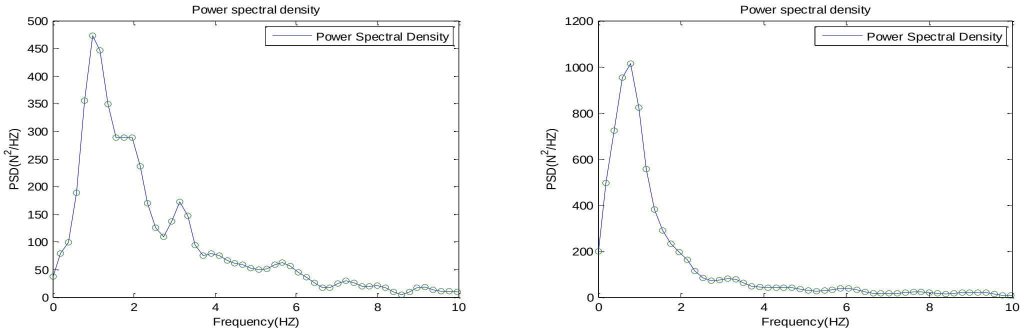
(a) HSVA test (b) Numerical calculation

Figure 7. Probability distribution of peak ice force



(a) HSVA test (b) Numerical calculation

Figure 8. Probability distribution of peak force interval



(a) HSVA test (b) Numerical calculation

Figure 9. Analysis of power spectral density for ice load

6. Conclusions

The discrete element method was applied to study the effect of particle size on the macro-mechanical properties of sea ice. The sea ice sample was constructed with bonded particles in regular packing pattern. It was found that macro flexural strength of sea ice is in general a function of both the specimen and particle sizes from three-point bending tests. The flexural strength of sea ice increases with the increase of dimensionless partilce size ($\overline{D}$). The DEM parameters calculated by this relationship are used to simulate the interaction between ice and narrow conical structures and compare with HSVA tests. Both the maximum and mean value of ice load approach to the tests data in the comparison. Meanwhile the broken process of ice cover is compared and a satisfactory agreement between tests and DEM results is achieved. In this way the method of selecting micro parameters in DEM is accepted and validated by HSVA tests.

Acknowledgments

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References

Määttänen, M., Hoikkanen, J., 1990. The effect of ice pile–up on the ice force of a conical structure. Proc. IAHR Symposium on Ice 1990, Helsinki University of Technology, Espoo, Finland, pp. 1010-1021.

Brown, T.G, Tibbo, J.S., Tripathi, D., Obert, K., Shrestha, N., 2010. Extreme ice load events on the Confederation Bridge. Cold Regions Science and Technology 60, 1-14.

Qu, Y., Yue, Q., Bi, X., Karna T., 2006. A random ice force model for narrow conical structures. Cold Regions Science and Technology 45, 148-157.

Yue, Q., Qu, Y., Bi, X., Karna T., 2007. Ice force spectrum on narrow conical structures, Cold Regions Science and Technology 49, 161-169.

Ning, X., Yue, Q, 2015. Experimental study of dynamic conical ice force, Cold Regions Science and Technology 120, 21-29.

Paavilainen, J., Tuhkuri, J., 2013. Pressure distributions and force chains during simulated ice rubbling against sloped structures. Cold Regions Science and Technology 85, 157–174

Ji, S., Di, S., 2015. Analysis of ice load on conical structure with discrete element method. Engineering Computations 32(4), 1121-1134.

Selvadurai, A.P.S., Sepehr, K., 1999. Two dimensional discrete element simulations of ice_structure interaction. International Journal of Solids and Structures 36, 4919–4940.

Lau, M., Lawrence, K.P., Rothenburg, L., 2011. Discrete element analysis of ice loads on ships and structures. Ships and Offshore Structures 6(3), 211–221.

Tian, Y., Huang, Y., 2013. The dynamic ice loads on conical structures. Ocean Engineering 59, 37-46.

Potyondy D.O., Cundall P.A., 2004. A Bonded-Particle Model for Rock[J]. International Journal of Rock Mechanics & Mining Sciences, 41(8):1329-1364.