Discrete Element Modeling of Ice Loads on Ship and Offshore Structures

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Abstract In order to investigate ice loads on the ship and offshore structures, the discrete element method (DEM) is employed to construct ice model. In this method, the sea ice is modelled by the bonding-breaking spherical particles and dilated polyhedral element based on the Minkowski sums theory, respectively. Additionally, the size effect of spherical particle is discussed in the numerical tests of uniaxial compressive and three-point bending of sea ice. Considering different ice condition, the ice loads on these structures can be obtained by the ice DEM model. The numerical results show that the proposed ice DEM model can effectively simulate the interaction between sea ice and ship and platform structures.

1 Introduction

Marine structures in cold regions, especially offshore platform and ship often encounter sea ice, which is harmful for the safety of the structure. Therefore, it is important to well understand this process and properly estimate ice loads on structures.

To overcome ice loads on ship and platforms, some beneficial work including field tests, laboratory experiments and numerical simulations have been conducted. As field test and laboratory experiment are difficult and expensive, numerical simulation is a valid method to investigate ice loads on ship hull and platforms. Due to the discontinuity and frangibility of sea ice, discrete element methed (DEM) becomes an option. It can effectively simulate the failure process of sea ice transforming from continuum to bulk, and reasonably reflect the characteristics of ice load on different types of marine structures. The shapes of sea ice can be modeled by spheres [3, 4], polyhedra [5] and dilated disks [7]. Moreover, the

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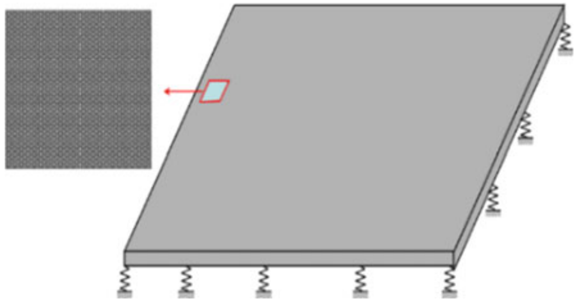


Fig. 1 Construction of discrete element of sea ice

relationship between the macro and micro parameters is investigated based on sphere DEM model [8].

In this paper, sea ice is constructed by the DEM including bonding-breaking spherical particles and dilated polyhedral elements. Moreover, the size effect of the spherical particle is studied by the numerical tests of uniaxial compressive and three-point bending of sea ice. Meanwhile, the ice loads on ship hull and platform are obtained by the ice DEM models. The results calculated by the spherical particle coincide with full-scale measurements from the JZ20-2 MUQ platform in Bohai Bay.

2 Ice DEM Modelling

2.1 Ice DEM Modelling with Spherical Particles

Bonding-Breaking Spherical Particles

To simulate the breakage characteristics of ice cover and the relative ice load on platform structure, the discrete element method (DEM) with the bonding-breaking parallel glue between boned particles, was applied in this paper and the discrete element model of the sea ice as shown in Fig. 1. The parallel-bond glue placing between the particles can transmit both force and moment, which in normal direction and shear direction associated with the parallel bond are denoted by F_n, F_s, M_n and M_s, as shown in Fig. 2. The maximum tensile and shear stresses acting on the bonding region are calculated based on the beam theory as [4]

$$\sigma_{\max} = \frac{F_n}{A} + \frac{M_s R}{I} \quad \tau_{\max} = \frac{F_s}{A} + \frac{M_n R}{J} \tag{1}$$

where the variable A, I and J, denotes the area, radius, polar inertia moment of bonding section, respectively.

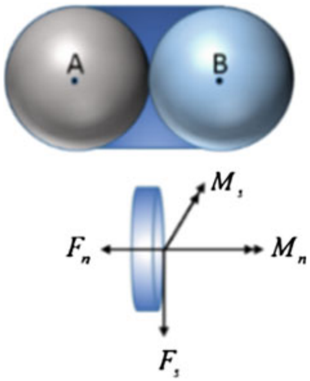


Fig. 2 Parallel bonding model

Particle Size Effect

To investigate the influence of spherical particle size on the mechanical properties of sea ice, the uniaxial compression and three-point bending tests are simulated with DEM using different specimens and particle sizes, as shown in Table 1.

In order to analyze the influence of size effect to the behavior of sea ice, we propose a relative particle size *D/L*, and set $L = a$ and b (or h) in the uniaxial compressive and three-point bending test. It is obvious that the Young's modulus E, the uniaxial compressive strength σ_c and the flexural strength σ_f linearly decrease with *D/L*.

As shown in Figs. 3, 4 and 5, it can be found that the mechanical properties of sea ice depend on the relative element size *D/L* rather than the specimen size. All of the E, σ_c and σ_f decrease perfectly linearly with the increase of *D/L*.

2.2 Ice Model with Dilated Polyhedral Elements

The dilated polyhedron element is constructed by Minkowski Sum of a sphere and a randomly-shaped polyhedron. The dilated polyhedron makes the contact detection of two elements become more efficient and simple, as a consequence, the vertices and edges turn are treated as spheres and cylinders. This method used in

Table 1 Specimen dimension matrix

Uniaxial compressive test ($a \times a \times H$) (mm^3)
70 × 70 × 175, 100 × 100 × 250, 150 × 150 × 375 200 × 200 × 500, 1000 × 1000 × 2500, 2000 × 2000 × 5000
Three-point bending test ($b \times h \times L_0$) (mm^3)
37.5 × 37.5 × 250, 75 × 75 × 500, 112.5 × 112.5 × 750, 150 × 150 × 1000

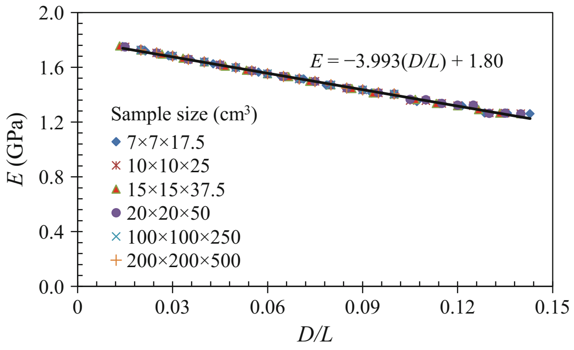


Fig. 3 Variation of the young's modulus E with the ratio of D/L simulated with DEM under various specimen sizes

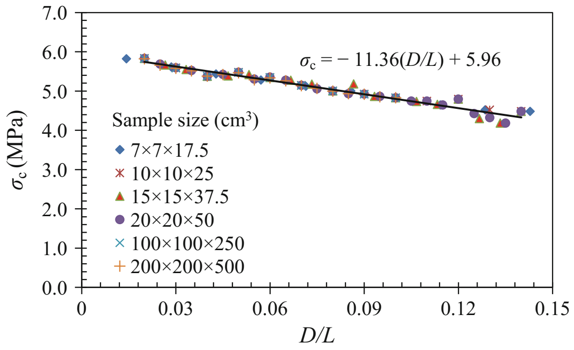


Fig. 4 Variation of the uniaxial compressive strength σ_c with the ratio of D/L simulated with DEM under various specimen sizes

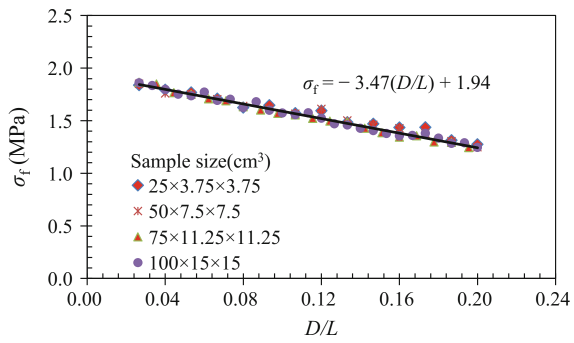
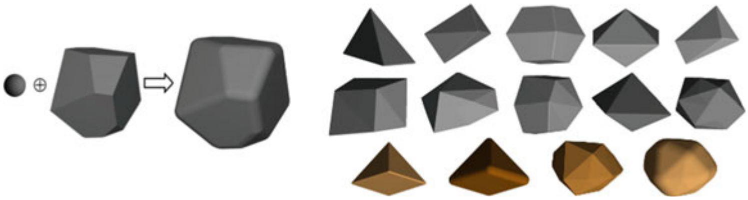


Fig. 5 Variation of the flexural strength σ_f with the ratio of D/L simulated with DEM under various specimen sizes

polyhedron/polygon element of DEM was initially adopted by [6], and then developed by [1, 2]

Given a polyhedron A in 3D spaces and a sphere B, their Minkowski Sum is defined by (Fig. 6)



(a) Dilated polyhedron (b) Different basic polyhedron and dilated radius

Fig. 6 Dilated polyhedron

$$A \oplus B = \{\bar{x} + \bar{y} \,|\, \bar{x} \in A, \; \bar{y} \in B\} \tag{2}$$

The 2D-Voronoi tessellation algorithm is employed to divide a domain into random shape of polygons called 2D-Voronoi diagram. The ice floes are generated via stretching polygons from 2D-Voronoi diagram in vertical direction. Figure 7 shows 200 Voronoi points and the result of Voronoi tessellation, in which the rectangle boundary is concerned.

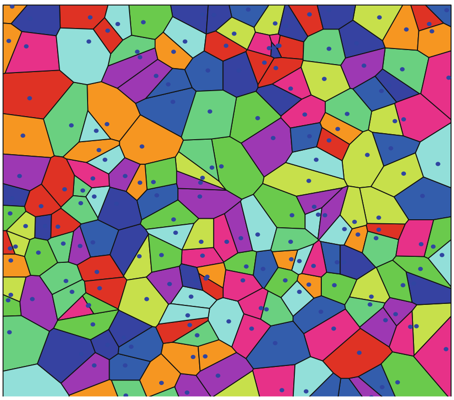
3 DEM Simulation of Ice Loads

3.1 Ice Load on Conical Offshore and Ship with Spherical Particle

Ice Load on Conical Offshore

Dynamic ice loads on the cone are obtained by accumulating the impact load on the cone surface. A 90 s duration of the ice cover and Jacket interaction was simulated,

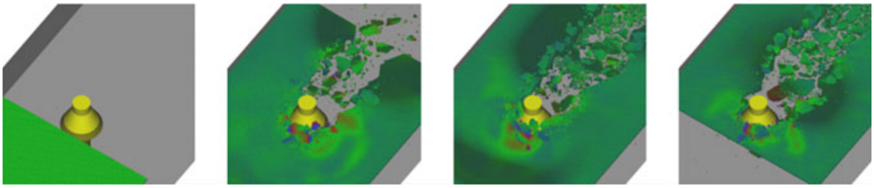
Fig. 7 Voronoi cell for broken ice field



requiring 27 h running time on the K40 GPU Card workstation. And the failure mode of the level ice against a narrow conical structure is simulated with DEM model as shown in Fig. 8.

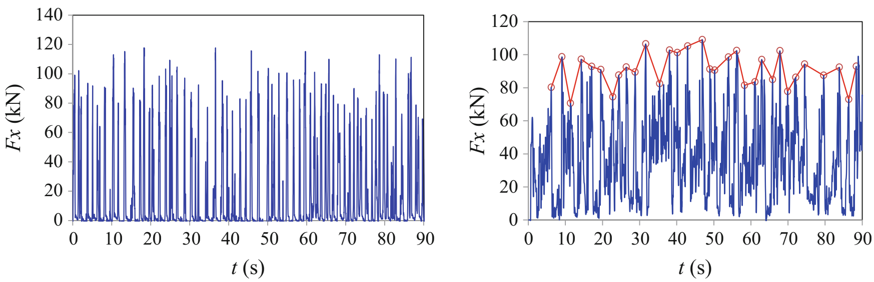
Figure 9 presents the comparisons of the simulation result and field measurements on ice loads time histories. It can be seen that the simulation results agree quite well with the measurements across several ice load amplitudes and frequencies.

Field measurements and DEM simulation results of the ice loads have been analyzed in the frequency domain. The power spectrum density curves of the ice loads obtained from the field data and DEM simulation are plotted in Fig. 10. The



(a) $t = 0.0$s (b) $t = 31.5$s (c) $t = 67.5$s (d) $t = 90.0$s

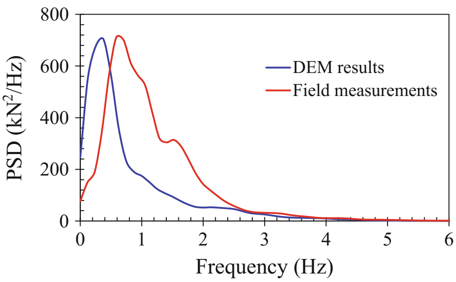
Fig. 8 Interaction between ice cover and conical structure simulated with DEM



(a) Ice load measured in field (b) Ice loads in simulation

Fig. 9 Dynamic ice load on conical structure simulated with DEM and measured in field

Fig. 10 Comparison of power spectral density of ice loads from field measurements and DEM simulation

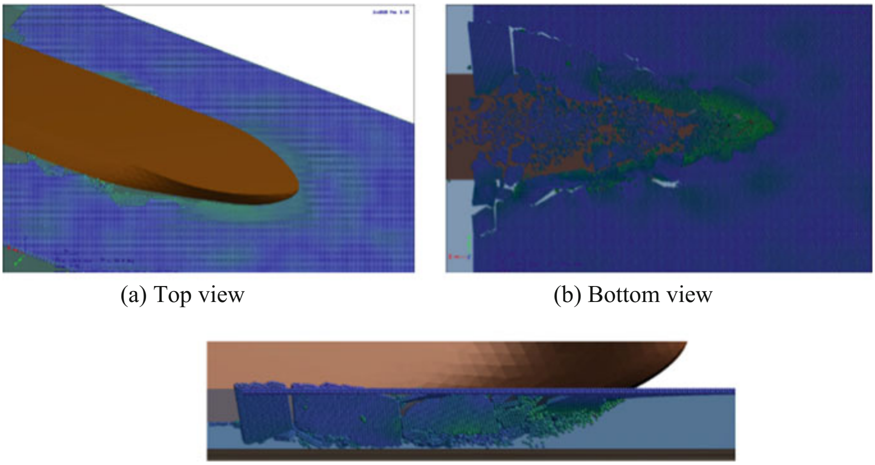


simulation results agrees well with the field test data in terms of the peak value and the frequency of power spectrum density.

Ice Load on Ship Hull

In the DEM simulation of interaction between level ice and ship hull, the ship speed is constant. Here we ignore the ice-induced vibration and deformation of hull structures, and the ice cover is static. Based on the previous investigation, we set the inter-element bonding strength of sea ice $\sigma_{max} = 1.2\,\text{Mpa}$. Figure 11 shows the simulated ice-hull interaction process from different perspectives respectively, captured from the IceDEM1.0 software. We can find the ice cover is crushed at the front of the bow area and piled up at the shoulder area. The inter-element contact force is displayed in different colors. It can be found that the high pressure zone appears in front of the bow, and the level ice breaks into blocks around the ship hull.

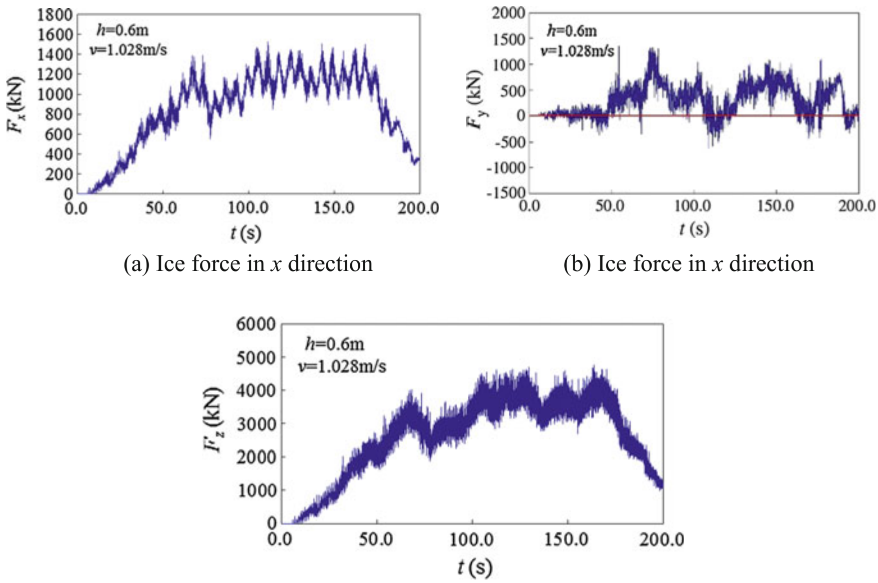
The global resistance acted on the ship hull is determined by summing the contact forces between ice element and hull element. From the Fig. 12, during the process of navigating, the ice loads in x and z directions increase from zero, then reach steady state with a certain fluctuation accompanying the breakage of ice cover. When the running length approaches 70 m (the longitudinal length of the bow), the global resistance is in a steady state relatively. When the ship runs out the ice field (after 160 m), ice loads on the bow disappear and frictions on the broadsides decrease rapidly.



(a) Top view (b) Bottom view

(c) Lateral view

Fig. 11 Snapshots of a sailing vessel in the level ice zone



(a) Ice force in x direction

(b) Ice force in x direction

(c) Ice force in x direction

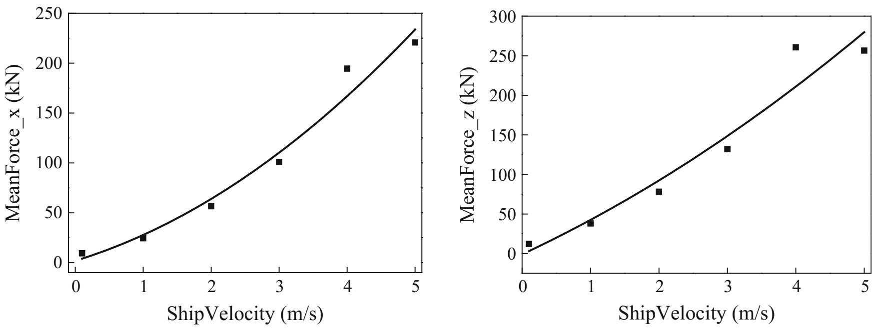
Fig. 12 Dynamic ice loads on the ship hull in various directions

3.2 Ice Load on Ship with Dilated Polyhedral Elements

In this section the ice load on ship hull in floe ice region is simulated by dilated polyhedral DEM. The whole hydrodynamic of ice and ship in sea water included buoyancy and the moment caused by buoyancy, and drag force and moment. Contrary to the ship velocity, a constant boundary velocity equalled to water velocity is set after the ice domain. Figure 13 is a snapshot of the simulation animation. It is clear that a water channel exists after the ship puts over. The channel shaped like a taper which is sharp at the bow of the ship.

In different ship velocity condition, the mean parameters of ice load on ship hull are analyzed. The ship velocity and the mean force are bigger as shown in Fig. 14. The pattern of mean values is nearly square relation.

Fig. 13 The ship navigation in broken ice field by DEM simulation



(a) x direction (b) z direction

Fig. 14 Mean value of Ice load in x and z direction on ship hull

4 Conclusion

The ice DEM model constructed by spherical particle and dilated polyhedral element based on the Minkowski sums theory is developed to evaluate the ice loads on the ship hull and the offshore platform. For the size effect of spherical particle, some liner relationships between macro-mechanical properties of sea ice and relative element size (D/L) are obtained from the DEM numerical result. In addition, the ice loads on the conical structure are verified through comparisons with field data, which show high consistency in amplitude and frequency. It demonstrates that the DEM can provide an effective way to analysis the ice loads on ship hull and offshore platform.

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