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Discrete Element Modelling of Interaction between Level Ice and Ship Hull

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In this study, a discrete element method (DEM) is developed to calculate the ice load on ship hull in level ice. The sea ice is constructed with 3-D bonded spherical elements considering its breakage characteristics based on a failure criterion. Both of the buoyancy and drag force of current on ice elements are considered. The ship hull is modeled with triangle elements considering the geometric structure of icebreaker *Snow Dragon* of China. Two typical situations in navigations are simulated with DEM, i.e, straight shipping and turning. Global ice resistances and local load distributions are obtained with the DEM simulations. Additionally, the influences of sea ice thickness and shipping speed on ice load are also investigated.

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1. Introduction

The requirement of ship operations in ice-covered sea areas has a rapid increase in the last decades due to the navigation and scientific investigation in polar and sub-polar regions. More attentions have been paid on the structural design and maneuvering performance of icebreakers. In early design, it will give us a direct figure of ships if some valid simulations have been used for the calculation of ice resistance and ship propulsion (Mróz et al. 2008; Zhou et al. 2013).

Typical failure of crushing and bending occurs throughout the interaction between ship hull and level ice (Su et al. 2010; Kujala and Arughadhoss, 2012; Zhou et al. 2013). And the fracture mode has an intrinsic universality in the random ways apparently (Goldstein and Osipenko 1993). The representation of the failure accurately is necessary to approach the actual results. The finite element model (FEM) has been used, mainly in macro-scale, to model both ice pressure and global ice load on hull of level ice, ice ridge and iceberg (Aksnes, 2010; Su et al. 2011). Nevertheless, this approach is based on the assumption of continuum and homogeneous material, which does not entirely correctly present the ice freezing and fracture process. To represent an accurate interaction between sea ice and structure, studies begun to focus on the contact zone with other numerical methods (Izumiyama 1992; Su et al. 2010; Lubbad and Løset 2011). The discrete element method (DEM) has more powerful description of the rupture feature of sea ice on micro scale. To model the crack and fracture process of sea ice, the DEM presents instinctive advantages due to its reasonable and natural characteristic base on discrete structure (Shen et al. 1987; Leppäranta et al. 1990; Hopkins 1997; Ji and Di, 2013). As a typical ice condition, level ice presents strong impact loads on ship hull. The mechanical behavior of level ice is governed by the formation, freezing and fracture (Su et al. 2011; Zhou et al. 2013). The detailed information about initial defects and load-induced cracks are revealed by the microscopic observation of sea ice (Blair and Cook 1998).

To model the breakup of continuum materials, the approach with bonded-particles has been developed and applied in the rock mechanics (Jing, 2003; Potyondy and Cundall, 2004). In this paper, the level ice is modeled with bonded spheres to simulate the interaction between level ice and a running icebreaker. The ship hull is structured with triangular planes. The fracture mode in macroscopic is presented and the global ice load on hull is calculated. Furthermore, the influences of ice condition and maneuvering speed are also discussed.

2. Numerical Model Base on DEM

2.1 Construction of level ice

In the DEM simulation, the level ice is constructed with 3D parallel bonding particle which the buoyancy and gravity are also considered. To avoid complex computation, the sea ice model is confined in a limited boundary. A resistance is applied on the boundary ice cover, which can counteract effects of limited extension, as the shown in Fig 1(a). And the contact force model and the failure model of bonded particles are plotted in Fig 1(b).

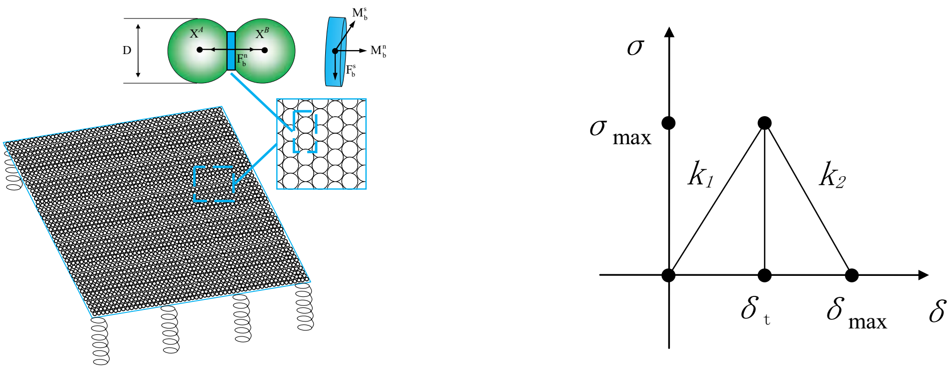
The maximum normal and shear stresses within the bonding section are determined with the inter-particle force and moment as

$$\sigma_{\max} = \frac{|\mathbf{F}_b^n|}{A} + \frac{|\mathbf{M}_b^s|}{I} R \quad [1]$$

$$\tau_{\max} = \frac{|\mathbf{F}_b^s|}{A} + \frac{|\mathbf{M}_b^n|}{J} R \quad [2]$$

where A, R, J and I are the area, radius, polar inertia moment, and inertia moment of the bonding disk, respectively. Here we have $A=\pi R^2$, $J=\pi R^4/2$, $I=\pi R^4/4$, where R is the radius of the bonding section, and is set as the bonded particle diameter.

The fracture of frozen particles is determined by the relative displacement δ between the bonding position, and the fracture mechanism is shown in Fig.3. Here, δ_t is tensile displacement and δ_{max} is the displacement when the bonded particles break up. k_1 is the slope of loading curve and k_2 is that of unloading curve. When the normal stress reaches the maximum normal stress, the parallel-bond glue is not invalid suddenly. The damage emerges and accumulates with time until the relative displacement δ reaches δ_{max}. This failure model had been applied in the breakage of rock material with DEM simulation under uniaxial compression (Ji and Di, 2013b).



(a). Parallel bonding mode (b). Invalid mechanism of a parallel-bond

Figure.1 Bonding model of level ice base on DEM

The interaction between free ice particles is calculated with an elastic-viscous contact model based on the Mohr-Coulomb shear friction law, as shown in Fig.2, where M_A and M_B are the mass of ice particle A and B, K_n and K_s are the normal and tangential stiffness, C_n and C_s are the normal and tangential damping coefficients, μ is the inter-particle friction coefficient.

The normal and the tangential force are calculated as

$$\mathbf{F}_n = K_n \mathbf{x}_n - C_n \dot{\mathbf{x}}_n \quad [3]$$

$$\mathbf{F}_s = \min(|K_s \mathbf{x}_s - C_s \dot{\mathbf{x}}_s|, \mu |\mathbf{F}_n|) \cdot \mathbf{n}_s \quad [4]$$

here

$$C_n = \zeta_n \sqrt{2MK_n} \quad [5]$$

$$\zeta_n = -\ln e \big/ \sqrt{\pi^2 + \ln^2 e} \quad [6]$$

where x_n, $\dot{x}_n$ and x_s, $\dot{x}_s$ are the relative displacement and velocity of the two contacting particles in normal and tangential directions, respectively. n_s is the unit vector in tangential direction. C_n is the damping coefficient, ζ_n is the dimensionless normal damping coefficient, e is the coefficient of restitution. The normal and tangential stiffness have the relationship of $K_s=0.5K_n$ and $C_s=0.5C_n$.

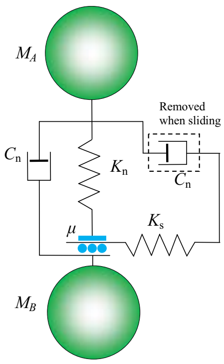


Figure.2 Contact force model

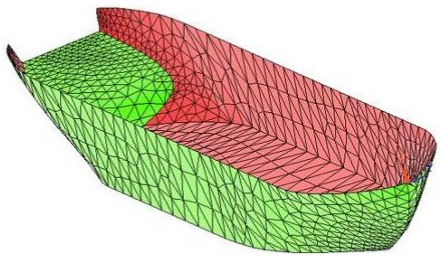


Figure.3 Ship hull of Snowdragon ice breaker

2.2 Contact between ice cover and ship hull

The geometric structure of ship hull, such as the bow angle, plays an important role on the ice load (Zhou et al. 2013). The model of ship hull in this DEM simulation is constructed with the icebreaker *Snow dragon* of China. The ship hull is discretized by a number of triangle elements, as shown in Fig.3. The main geometric parameters of ship hull are listed in Table 1.

Table 1. The main geometric parameters of the icebreaker *Snow dragon*

Definition	Symbol	Values
Length	L	160m
Height	H	14m
Waterline	H_{wl}	9m
Width	B	27m

In the DEM simulation of contacts between ice elements and triangular plane of ship hull, the contact patters can be sphere-surface, sphere-edge and sphere-vertex, as shown in Fig. 4. To reduce the simulation dimensionally, a contact detection scheme is presented for triangles and spheres based on the vector projections.

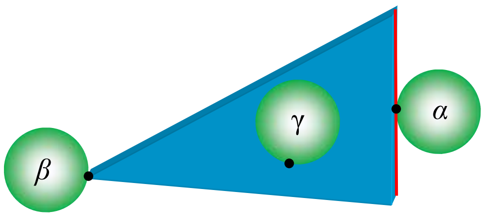


Figure.4 Interaction mode between triangular plane and spherical element

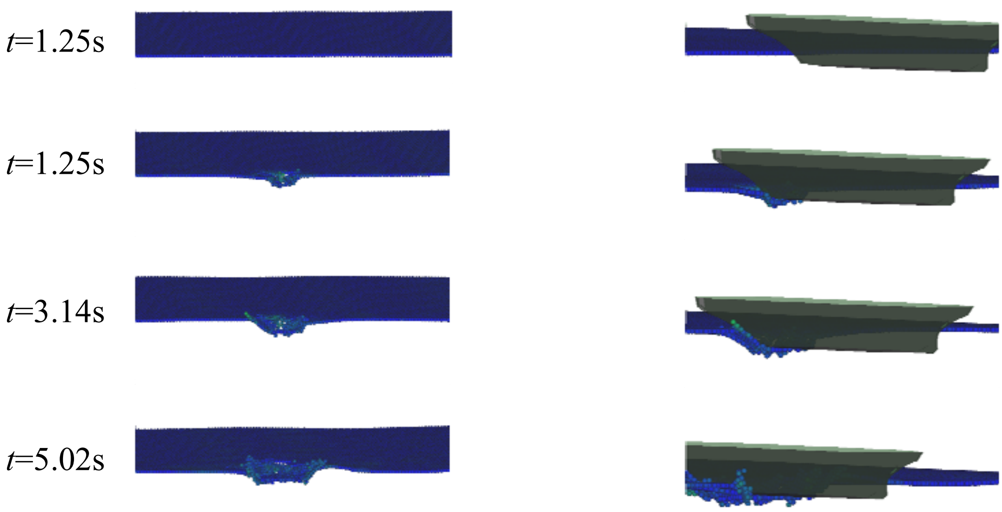
3. Fracture of Ice Cover under Action of Ship Hull

The contact primarily occurs around the stem and slides during the running of ship in a level ice. The main fracture modes are crushing and bending (Su et al. 2010). The failure of level ice is represented explicitly with breakage of bonded-elements while the ice cover is broken into small fragments.

In this DEM simulation, some computational parameters are listed in Table 2. Based on the simulated results, the transformation of a level ice is presented to observe the failure process. To obtain a more directly observation, a single layer particles with different times are plotted in Fig.5. An apparent bending failure appears at t=1.25s. The level ice has a greater strain with the contact force increase and broke when t=2.51s. Then a totally fracture is presented as the rest figures. At the same time, the fracture and contact between icebreaker and level-ice are also presented in this figure.

Table 2 Computational parameters in the DEM simulation

Definition	Symbol	Values
Sea ice density	P	970 kg/m^3
Ice cover size	$L\times B$	150m×50m
Ice thickness	h_i	0.6m
Ship speed	V_i	1.0m/s
Normal stiffness of ice particle	K_n	3.8 ×10^7 N/m
Shear stiffness of ice particle	K_s	1.9 ×10^{7}N/m
Particle-particle friction	μ_{pp}	0.3
Particle-particle restitution	e_{pp}	0.4
Wall-particle friction	μ_{wp}	0.1
Wall-particle restitution	e_{wp}	0.3
Maximum bonding strength	σ_b^{max}	1.2 MPa



(b) Ice-hull interaction (c) Ice-hull interaction

Figure.5 The fracture mode during the interaction between level ice and ship hull.

4. Global Ice Force on Ship Hull

The global ice resistance on the ship hull plays an important role to evaluate a ship maneuvering ability in level ice. In this study, the simulated ice force versus time is plotted in Fig. 6. There are three stages in this simulation. For the first stage, the ice force increased with time when the icebreaker navigates into the ice-cover water; For the second stage when t > 4s, the global ice force has a obvious fluctuation around a constant mean value; For the last state, the force decreases when the icebreaker runs out ice field. Of course, we have more interesting on the second stage when the icebreaker runs in the ice field with less boundary effect.

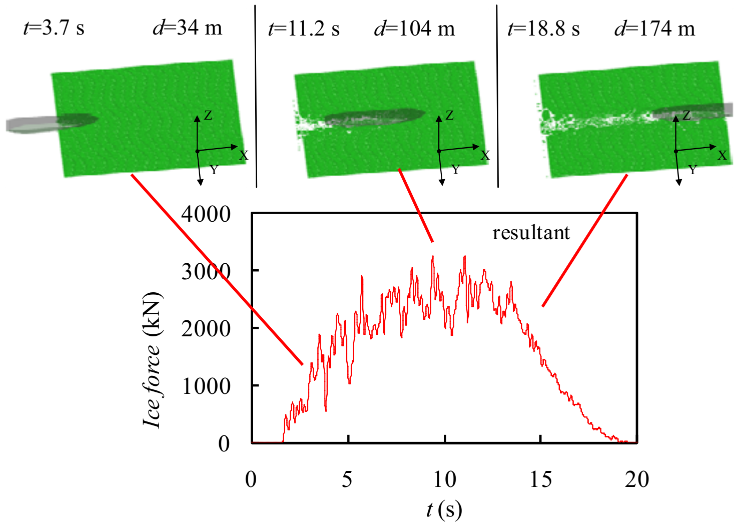


Figure.6 The simulated global ice force on ship hull versus time curve with DEM

To analyze the influence of ice thickness on ice load, we set the ice thickness varies from 0.5m to 1.1m while the speed of ship is 9.26m/s (5 knots). The simulated ice loads are plotted in Fig.7 with different ice thicknesses. The maximum and mean ice loads are plotted in Fig.9 when the whole ship runs in the ice field. It shows that the ice resistance increases linearly with increasing ice thickness.

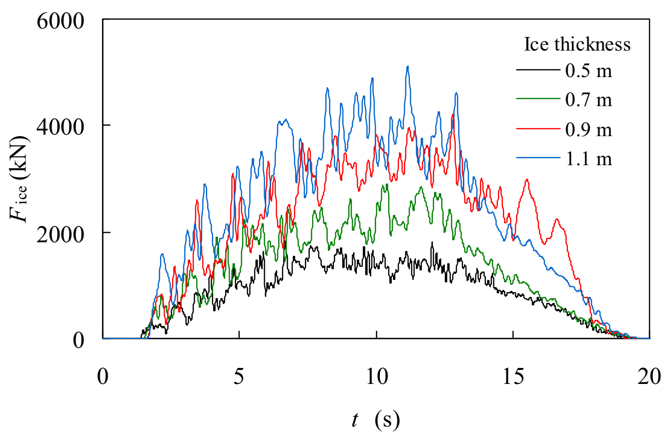


Figure.7 Time series of ice loads on ship hull with different ice thicknesses.

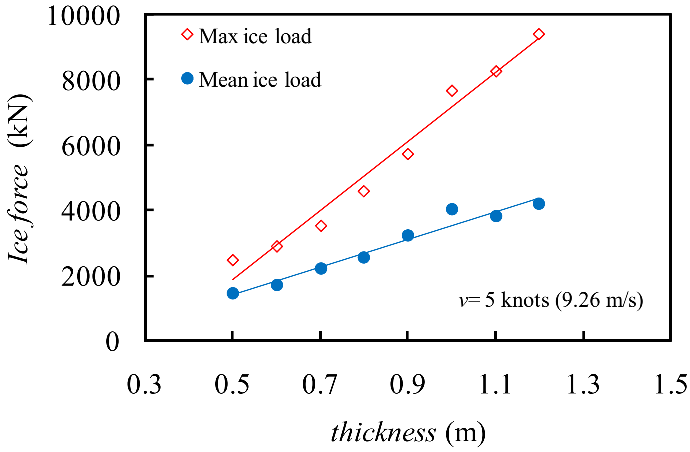


Figure.8 Simulated maximum and mean ice load on ship hull under different ice thicknesses.

5. Conclusions

Interactions between level ice and the ship hull are simulated using discrete element method (DEM). The ice cover is modeled with 3D bonded spherical elements considering the buoyancy and gravity, and the ship hull is constructed with triangle plane elements. The break-up of ice cover are obtained, and the dynamic ice loads on ship hull are simulated. The influences of ship maneuvering speeds and ice thicknesses on global ice resistance are discussed based on the DEM results.

In the next studies, the distribution of ice load on hull will be considered. And a heave and pitch motions will be also investigated in the DEM simulations. Moreover, the numerical results will be validated with trial experimental data.

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