Cohesive Element Method for Ice Load on Conical Structures

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ABSTRACT

Simulating ice loads accurately will provide a powerful support for the design and manufacture of polar structures. The cohesive element method is highly effective to conduct ice load numerical simulation. In this paper, ice load is simulated based on finite element method and cohesive element theory. The fracture and accumulation of level ice can be well simulated by inserting cohesive elements between finite elements.

Based on finite element method and the cohesive element theory, a cohesive element model of level ice was established. Numerical simulation of the interaction between level ice and vertical cylinder with conical structure was carried out and the failure form of sea ice and the response of structures were analyzed. The numerical simulation results are in good agreement with the experimental, measured results and ISO standard. The results show that cohesive element model can be used to simulate the interaction between ice and structures. The ice load on structures is positively correlated with ice thickness. For the cylinder with an ice-resistant cone, ice load is closely related to the value of cone angle, for it affecting the form of ice formation.

KEY WORDS: Ice; ice load; ice-structure interaction; cohesive element method; conical structure; ice-resistant structure

INTRODUCTION

With the continuous development of global industry, human demand and dependence on energy and resources are increasing. In the circumstances of urgent need to seek new resources and energy, more and more countries have focused their attention on the polar regions. Although the polar regions are covered with snow and ice all the year round, the rich resource contained under the ice sheets are a valuable asset for human beings. In recent years, human exploitation of marine resources has gradually extended and developed to the cold regions.

The study of sea ice loads is an important part of polar science. Ice load is the main environmental load in cold regions. Sea ice exists in the forms of level ice, crushed ice, ice ridges and icebergs, among which level ice is one of the most common forms of polar sea ice and is also one of the most importantly considered forms of ice load when studying the interaction between sea ice and structures.

The research methods of this kind of ice load mainly include measurement, experiment and numerical simulation. Direct measurement of ice force is made by installing pressure test sensors on the legs of ice platforms to measure the force of sea ice on structures (Qu, 2006; Timco, 2003; Brown and Maattanen, 2009). The data obtained by direct measurement is accurate and reliable, which is the best estimate of ice force. However, the measurement operation is difficult and the installation and maintenance cost of the equipment is high. Usually, the actual measured ice force data can be used as the basis and reference for the international ice force specification. Sea ice experimental methods are also commonly used (McGovern and Wei, 2014; Ettema and Nixon, 2005). The tests are usually carried out in ice pools, using artificial ice or alternative materials such as wax.

In terms of numerical simulation, scholars at home and abroad have adopted a variety of methods to simulate the sea ice load, among which the discrete element method and the finite element method are the two most commonly used methods. With the discrete element method, ice was simulated into cohesive particles (Lau and Lawrence, 2010; Ji, Di, Li and Bi, 2013; Cai and Ji, 2016). By changing the interaction form between particles and the parameters of the force, it can accurately simulate the damage and accumulation effect of the level ice, which has obvious advantages in simulating the discrete characteristics of sea ice. By using the discrete element method, the numerical simulation of ice-platform and icebreaker sailing in the ice area can be carried out to obtain the response of structures and the results of sea ice fragmentation and accumulation. Another commonly used numerical method is the finite element method. The emphasis and advantage of this method is that it can better study the deformation of ice structure and can fully analyze the dynamic process of ice collision (He, 2013; Jin, Hu and Liu, 2017).

The cohesive element method is gradually developed on the basis of the finite element method, which inserts cohesive elements between finite elements, so the deformation and failure of sea ice can be considered simultaneously in the study. Wenjun Lu et al. (Lu, Loset and Lubbad, 2012) conducted a numerical simulation study on the interaction...
between level ice and conical structures using the cohesive element method, verified the simulation results based on previous experimental results and discussed the convergence and objectivity of the mesh under different methods. Wang et al. (Wang, Zou and Ren, 2019) introduced the cohesive element model and combined it with the linear softening elastic-plastic constitutive based on the nonlinear finite element method to conduct numerical simulation of the collision between level ice and the vertical fixed cylinder. Cohesive element method can accurately simulate the deformation, fragmentation and accumulation of sea ice and has been widely used in numerical simulation of sea ice.

In cold area with high ice coverage, anti-ice structures are usually set near the waterplane of the conventional marine platform columns to increase the anti-ice performance. The common anti-ice structure is the ice-resistant cone. Since the bending strength of sea ice is far less than its compressive strength, the ice-resistant cone with a specific cone angle can change the failure form of sea ice from crushing failure to bending failure during the interaction between sea ice and ocean platform, thus greatly reducing the load on the platform. Ice-resistant cone is a very reliable and effective anti-ice method. (Di, 2015)

In this paper, the finite element model of sea ice was established based on the cohesive element method and the interaction between the level ice and the fixed platform column with ice-resistant cone is simulated. The numerical simulation explored the effects of sea ice thickness, collision velocity and other conditions on structural forces. Besides, for the columns with ice-resistant cones, the angle of the cones has a certain influence on the force on the columns, which will also change the breaking and accumulation of sea ice, which is another focus of this paper. The results of numerical simulation were compared with the experimental and measured data under similar environmental conditions and they had good consistency in a certain range. The results show that the cohesive element method and the sea ice model established in this study have good applicability in the study of the interaction between level ice and fixed platform with ice-resistant cone, which is of great reference significance for the subsequent ice load simulation and ice resistance design of structures in cold regions.

ICE MODEL BASED ON COHESIVE ELEMENT METHOD

Sea ice is a temperature sensitive composite material with very complex properties. Its physical and mechanical characteristics are closely related to its salinity, porosity, loading rate and ambient temperature. It usually shows brittle and plastic characteristics under different conditions. In addition, when sea ice interacts with different forms of structures, its failure forms are also varied, including bending failure, extrusion failure, bending failure and so on. Therefore, it is very important to determine the constitutive model, material parameters and failure form of sea ice in the study and numerical simulation of ice load.

Finite element method is a very effective method to study sea ice load and can get good simulation results. The finite elements arranged according to certain rules can simulate the deformation and failure of sea ice, and this method can also quickly obtain the stress and response of structures, which has been widely applied. But in the use of finite element method, scholars found that the limitations of the method. The units of ice fail and are deleted immediately after collision damage. Therefore, the finite element method cannot well simulate the accumulation phenomenon after sea ice fragmenting and the subsequent effect of crushing ice on the structure. The mass of the whole simulation process is not conserved so that the simulation results are quite different from the measured and experimental results. In order to solve this problem, scholars have proposed many solutions, such as discrete element method with bond effect, FEM and SPH coupling method, cohesive element method and so on. In this paper, the method of cohesive element is used to simulate the level ice and its mechanical behavior in collisions.

Cohesive element method is a numerical simulation method which is optimized and developed based on finite element method. In this method, the sea ice elements established by the finite element method are discretized and cohesive elements are inserted into the model between two ice elements. The inserted cohesive unit shares a node with the ice unit, and it is of no thickness, which is shown in figure 1. The sea ice units and the level ice model are constructed by cohesive element method.

The level ice model is a commonly used 8-node hexagon model. This model is commonly used in finite element simulation of sea ice in the way of meshing and the unit will be divided into serrated cracks at the broken section of sea ice, which is closer to the actual situation of sea ice fragmentation. When using the cohesive element model to simulation the interaction between level ice and structures, the level ice is first discretized into discrete solid units that are not directly connected. Then cohesive units are inserted between the inner interfaces of all adjacent solid units. This process can be realized by using LS-DYNA to divide the eight-node hexagon mesh and insert the cohesive unit.

![Fig1. Detailed illustration of cohesive element method](image)

**Fig1. Detailed illustration of cohesive element method**

In the process of the interaction between level ice and structures, the original finite element of sea ice deforms and transfers forces and displacements through the joint shared with the cohesive element. The inserted cohesive element will deform according to the constitutive model of sea ice material property parameters. When its displacement
reaches the set critical point of failure, the cohesive element will break down, while the connected finite element of sea ice will fall off. In the cohesive element model of the whole level ice, the failure only occurs at the cohesive element.

The damage of the cohesive element is determined by a given traction-displacement curve. The curve stipulates the relationship between traction force and displacement of cohesive elements. There are some significant parameters of the traction-displacement criterion, such as fracture stress, fracture toughness, maximum separation of displacement, curved linear form. According to the different kinds of parameters above, the models are divided into different kinds. The current common adhesion cluster destruction criterion models have three kinds: linear softening model, index softening model and trapezoid softening model (also known as ductile softening model). Figure 2 shows curves of the three models above (Kuutti, Klari and Marjavaara, 2013). The area between the curve and the coordinate axis is the energy required to break the cohesive element.

ISO ICE LOAD STANDARD

The ice load of structures in the interaction between different types of sea ice and ocean structures is given in the ISO-99906 standard (ISO, 2010) and the ice force calculation in the interaction between level ice and conical structures can be used as a reference for the simulation results in this paper. In the calculation, it is considered that the bending failure of sea ice is the main failure form when level ice is crushing on a conical structure. Based on different failure modes of sea ice, the calculation formulas of ice force are also different, mainly including plastic failure and elastic failure of sea ice.

The sea ice model constructed by cohesive element method can be regarded as plastic material in this paper. The calculation of ice load in plastic failure mode is discussed below.

In ISO standard, plastic theory is adopted to study the interaction between level ice and conical structures. The model mainly includes two parts of ice load: level ice bending failure and the force exerted by crushed ice when climbing on the conical structure.

The horizontal ice force $H_R$ and vertical ice force $V_R$ on the structure when crushed ice is climbing can be expressed as:

$$H_R = \frac{W \tan \alpha + \mu \sigma_f \cos \alpha}{1 - \mu g_f} \quad \ldots \quad (7)$$

$$V_R = W \frac{\cos \alpha \left( \cos \alpha - \mu \alpha - \mu g_x \right) + H_R h_f}{2} \quad \ldots \quad (8)$$

The horizontal ice force $H_B$ and the vertical ice force when level ice is crushing can be expressed as:

$$H_B = \frac{\sigma_f h^2}{3} \frac{\tan \alpha}{1 - \mu g_f} \left[ 1 + \frac{1}{x-1} + G(x-1)(x+2) \right] \quad \ldots \quad (9)$$

$$V_B = H_B h_f \quad \ldots \quad (10)$$

where several coefficients above are defined by conical structures, friction coefficient between ice and structures, the diameter of cone tip and cone at waterplane and the height of crushed ice climbing.

The total horizontal ice force and total vertical ice force on the conical structure can be expressed as:

$$F_H = H_R + H_B \quad \ldots \quad (11)$$

$$F_V = V_R + V_B \quad \ldots \quad (12)$$

According to the above formula, the ice load on conical structures based on the plastic theory can be calculated.

NUMERICAL SIMULATION PARAMETERS SETTING

Model of the conical structure

A numerical simulation of the interaction between level ice and a vertical column with an ice-resistant cone was carried out in this paper. A similar model was established based on the results of the actual ice load measurement of the platform JZ20-2 MUQ in Bohai area (QU, 2006; DI, 2017), as is shown in Figure 3. Figure 4 shows the column model, where the diameter of the top cylinder is 1.8m and the height of the cone part is 2.5m. The effect of the cone angle of the ice-resistant cone on ice load reducing was simulated. Angle $\theta$ between the inclined plane of the cone and the waterplane is defined as the size of the cone angle. $\theta$ is taken as 40°, 45°, 50°, 55°, 60° and 65° respectively. The diameter of the cone at the waterplane is ensured to be the same in each calculation case (2.8m).

![Fig. 3. The Model of the Platform JZ20-2 MUQ and JZ20-2 MUN](image)

![Fig. 4. The Model of Column with Ice-Resistant Cone](image)
The deformation of the platform was not considered during the collision, so the material of the column was chosen as rigid material. The specific material properties are shown in Table 1.

Table 1. Parameters of column rigid material

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $\rho$</td>
<td>7850 kg•m$^{-3}$</td>
</tr>
<tr>
<td>Young Modulus $E$</td>
<td>200 GPa</td>
</tr>
<tr>
<td>Poisson Ratio $\nu$</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Model of sea ice

The finite element solid model of sea ice is modeled by 8-node hexahedral elements and the size of the level ice is 40m * 18m. A sufficiently long leveling ice length and simulation time can ensure a stable result of the interaction and a maximum ice load. To study the effect of level ice thickness on ice force, the ice thickness $h$ was taken 0.2m, 0.25m, 0.3m, 0.35m and 0.4m respectively. The mesh size of the ice cell is 0.05m * 0.05m * 0.01m. An isotropic linear elastoplastic material was used to simulate the deformation of sea ice solid elements, and the linear softening curve model was selected for the traction-displacement curve of the cohesive elements.

The basic parameters of sea ice materials are influenced by many factors and it is difficult to have a definite value. A large number of mechanical tests have been carried out on sea ice by scholars and the recommended range of sea ice parameters for engineering applications has been given considering the effects of sea ice temperature, salinity and porosity on sea ice properties (Timco and Weeks, 2011; Kuehn, Lee and Nixon, 1990; Frederking and Timco, 1986). According to the recommended range, the material parameters of the sea ice cohesive model are selected to meet the engineering requirements of the case. The specific parameters are shown in Table 2.

Table 2. Principle parameters of ice model

<table>
<thead>
<tr>
<th>Ice Bulk Element</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elasticity Modulus</td>
<td>2GPa</td>
<td></td>
</tr>
<tr>
<td>Density $\rho$</td>
<td>900 kg•m$^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Poisson Ratio $\nu$</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Yield Stress $F_{y}$</td>
<td>2 MPa</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cohesive Element</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elasticity Modulus</td>
<td>2GPa</td>
<td></td>
</tr>
<tr>
<td>Density $\rho$</td>
<td>900 kg•m$^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Transverse fracture strength</td>
<td>0.5 MPa</td>
<td></td>
</tr>
<tr>
<td>Longitudinal fracture strength</td>
<td>0.7 MPa</td>
<td></td>
</tr>
<tr>
<td>Fracture Energy $E$</td>
<td>30 J•m$^{-2}$</td>
<td></td>
</tr>
</tbody>
</table>

Contact model

LS-DYNA was used to carry out the simulation. The contact mode of the collision needs to be set before calculation. The contact model between the column and level ice adopts the erosion algorithm of surface to surface contact. The algorithm “CONTACT_ERODING_ NODES_TO_SURFACE” is selected, which can define the failure criteria of the sea ice element and delete the failure unit. The coefficient of friction between the level ice and the column is set at 0.2. The contact between the crushed ice is made by the algorithm of single contact. The contact algorithm “CONTACT_ERODING_SINGLE_SURFACE” is selected, which can simplify the action between the crushed ice and reduce the calculation time. The friction coefficient between crushed ice was set at 0.1.

Boundary conditions

In the coordinate system shown in the figure 5, the size of the level ice is 40m*18m. X is the positive side of the sea ice movement. The Z axis is parallel to the thickness of the sea ice, perpendicular to the surface of the water line. The boundary of level ice which contact with the column is set to the free boundary, and the boundary condition of other three sides constrain the degree of freedom of three directions. At the meanwhile, the three sides of the boundary are set up as unreflecting boundary conditions to simulate semi-infinite level ice.

In this paper, the influence of seawater on the collision process is no considered and the buoyancy effect to seawater on sea ice is defined in the vertical direction.

![Coordinate System and Boundary Conditions](image)

Fig 5. Coordinate System and Boundary Conditions

RESULTS AND ANALYSIS

In this study, the simulation results obtained by using cohesive element method are compared with those obtained by different methods such as field measurement, experiment and numerical simulation, so as to verify the feasibility of this method. Figure 6 shows the field observation results of the platform JZ20-2 MUQ and HSVA model test results of level-ice-conical-structure interaction, respectively. The breaking of level ice and the climbing of broken ice can be clearly observed.

![Field Measurement Results of Boahai Bay Platform JZ20-2 MUQ; (b) HSVA Model Test Results.](image)

Fig 6. (a) Field Measurement Results of Boahai Bay Platform JZ20-2 MUQ; (b) HSVA Model Test Results.
Simulation of interaction between level ice and conical column

The above phenomenon was also observed in the results obtained by the cohesive element method in this paper. Figure 7 shows the simulation results of the interaction between level ice and the fixed conical column at the speed of 0.4 m/s. The cone angle of the ice-resistant structure is 60°. The side view at t=60s is shown in the figure.

There was a small climb of broken ice on the inclined plane when the collision happened. When the bending stress of sea ice was bigger than its bending strength, the sea ice broke down. The crushed ice accumulated and interacted with each other near the waterplane and they continued to interact with the column with the level ice advances. Thus, it can be seen that the ice load on the column is mainly composed of two parts, one is the effect of the flat ice on the column, the other is the effect of the crushed ice accumulated after crushing on the column. In the simulation, it was also observed that the crushed ice climbed on the slope of the cone and then slipped off. These phenomena are consistent with the field observation results.

Fig 7. The results of leve ice breaking and crushed ice accumulating

As shown in the figure 8, the time history curve of the ice load in the x direction of the fixed column is given when the ice speed is 0.4 m/s. We can find that during the collision process, the ice force on the column fluctuates and the amplitude is large, which is because the “contact–deformation–destruction–contact” cycle has been going on during the collision process. The average ice force and maximum ice force in the collision process are generally taken as the main objects of study.

Fig 8. Ice Load Time History Curve of x Direction

The relationship of cone angle $\theta$ and ice load

In order to study the effect of cone angle $\theta$ of the ice-resistant cone on ice load, a series of numerical simulations were conducted with the cone angle degree of, 40°, 45°, 50°, 55°, 60° and 65°. The ice velocity is 0.4 m/s and the cone diameter at the water plane is kept unchanged, which is 2.8 m. Other parameters remain unchanged.

Calculate the average and maximum ice forces on the fixed column in the horizontal (x) and vertical (z) directions during the 90s impact. The relationship between cone angle $\theta$ and ice forces in 90s is shown in the figure 9 and figure 10.

Compared with the calculated results with ISO ice load standard and results based on DEM method (DI, 2017), the ice load results of using the cohesive element method shares the same change trend with other results basically, but the overall results of ice load are smaller. The cause of this result may be as cohesive unit parameters selection of sea ice and the actual sea ice material is not the same; in addition, the ice fragments simulated by the cohesive method are all single units that fall off from the level ice model and their size are basically the same. However, the ice fragments simulated by DEM and the actual situation are usually random, which is also the main reason for the inconformity.

It can also be found that the maximum ice force in x direction are positively correlated with the cone angle $\theta$. The maximum ice force in z direction vary within a certain range and the gap is small, while the average ice force decreases with the increase of the cone angle.

Fig 9. The Relation between $\theta$ and Ice Force of x Direction

Fig 10. The Relation between $\theta$ and Ice Force of z Direction

Considering the interaction process, the main cause of this results may be that the failure form of sea ice changes when cone angle $\theta$ changes. The main failure forms of ice are bending failure and extrusion failure during the collision with the column. Both forms of destruction exist at the same time. When the cone angle $\theta$ is small, the failure of sea ice is
mainly bending. As $\theta$ increased, both bending and extrusion occur simultaneously, while the compressive strength of sea ice is significantly greater than the bending strength. Therefore, as the cone angle $\theta$ increase, the ice force in x direction gradually increases while the ice force in direction decreases.

**The relationship of ice thickness and ice load**

In order to study the influence of ice thickness on ice load, this paper took ice thickness of 0.2m, 0.25m, 0.3m, 0.35m and 0.4m respectively for simulation. The ice velocity was 0.4m/s and other parameters remained unchanged. In the simulation process of t=90s, the relation curves between maximum ice force, average ice force of x direction and ice thickness are shown in the figure 11. It can be clearly seen that the simulation results are in good agreement with those obtained by ISO ice load standard. The ice force is positively correlated with the ice thickness. The calculated results in this paper have the same variation trend with the experimental data and the simulation results of other scholars and some of the values are basically consistent.

![Fig 11. The Relation between Ice Thickness and Ice Force](image)

**CONCLUSIONS**

In this paper, based on the finite element method and the cohesive element method, a cohesive element model of level ice and a vertical column model with ice-resistant cone was established. A series of numerical simulations of the interaction between level ice and a fixed vertical column were carried out using LS-DYNA dynamics analysis software and the following conclusions were obtained:

1. The cohesive element method can better simulate the collision process between level ice and fixed column. Compared with the traditional finite element method, this method has a better performance in the simulation of sea ice fragmentation, accumulation the interaction between crushed ice and structures. The simulation results were basically consistent with field observed results.

2. When level ice interacts with conical structures, the cone can change the failure form of level ice from extrusion failure to bending failure. Therefore, the ice load on the structure consists of two parts, that is, the process of level ice bending and extrusion and the effect of crushed ice on the structure after level ice breaking.

3. The ice load on the column is closely related to the cone angle. The simulation results show that with the increase of cone angle, the horizontal ice load on the column increases while the vertical ice force decreases. The main reason for this phenomenon is that with the increase of cone angle, the components of bending failure gradually become less when sea ice is damaged and the bending strength of sea ice is much less than the compressive strength. At the same time, the increase of cone angle leads to the difficulty of crushed ice climbing, thus causing this phenomenon.

4. The ice force of the level ice is positively correlated with the thickness of level ice and the growth is non-linear. The results are in good agreement with the experimental results.

This paper still has the insufficiency and the follow-up questions which urgently need to solve. Further research needs to carry on. The cohesive element model of sea ice is approximated, the complete properties of sea ice cannot be fully demonstrated, so the simulation results are still far from the actual engineering situation. In this paper, the calculation of the working conditions is insufficient, unable to get a more systematic and complete conclusion. Due to the limitation of the number of grids and the amount of computation, the calculation accuracy is limited, so the subsequent research should continue to optimize the grids to increase the accuracy and reliability of the calculation results.

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**REFERENCES**


Qu, Y (2006), “Random Ice Load Analysis on Offshore Structures Based on Field Tests,” *Dalian University of Technology*.

