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The Attributes of Local Ice Pressure Analyzed by Discrete Element Method

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ABSTRACT

The local ice pressure of the ice-structure interaction plays an important role in structure design. The discrete element method (DEM) with bonded particles is adopted to simulate ice pressures during the crushing failure of level ice interacting on the vertical structure. The major attributes of ice pressure are explored to compare with existing empirical models, including pressure distribution and the relationship between the global and local pressures. The results show that the high-pressure zones (HPZs) always concentrate on the horizontal middle line of contact area. In this case, the maximum local pressure exceeds 100 MPa, while the maximum global one is only 3 MPa. The influence of structure width on the local pressure is analyzed to compare with the ISO. The ice pressure always decreases with the increasing of contact area which can be expressed as a pressure-area plot. Moreover, as the loading rate increases, the failure mode of sea ice changes from ductile failure to brittle failure in the numerical simulations. Therefore, the numerical analysis of local pressure provides a reference for stiffening elements of vertical structures.

KEY WORDS: local pressure; sea ice; DEM; crushing failure.

INTRODUCTION

The analysis of ice pressure during the action between level ice and vertical structure is of great significance to the structural design. Generally, the ice pressure is divided into the global ice pressure and the local ice pressure. The global pressure (P_G) is the ice pressure averaged over the nominal contact area associated with the global action which is important for overall structure design and stability. The local pressure (p) is the pressure acting on some local and small zones relative to the whole contact area. These zones with stress concentrations are produced by the non-simultaneous destruction of ice cover interacted with the vertical structure, which is called the high-pressure zone (HPZ) (Masterson et al., 1993). Many studies have shown that the local pressure is much greater than the global pressure (Frederking, 2004). It indicates that local ice pressure plays an important role in structural failure, which could be adopted to strengthen the local structural elements, for instant the plating between frames.

It is found that the high pressure zone is mainly distributed along the centerline of the ice-structure contact area which is called ‘line-load’ contact geometry during the crushing failure of ice (Dempsey et al., 2001). The contact area between ice and structure is related to the ice pressure directly. It has been widely recognized that the ice pressure decrease with the increasing contact area in the research field of sea ice characteristics. Masterson et al. (2007) proposed a pressure-area plot for local pressures based on the data from the Molikpaq offshore platform, indenter tests and some flat jack tests by $p=7.4A^{-0.7}$ for areas up to 10 m^2, where p is the pressure (in MPa) and A is the contact area (in m^2). This relationship has been employed into the ISO 19906 (2010).

Most of the researches on ice pressure are based on the measured and experimental results, but the related numerical simulation methods are less applied. The finite element method is also used in the ice pressure distribution of the slope structure by Paavilainen and Tuhkuri (2013). Considering that the numerical simulation is required by the accuracy and time of calculation, the discrete element method (DEM) based on GPU high performance algorithm has certain advantages in simulating ice-structural interactions. This method with a high computational efficiency has an advantage on describing the failure process of sea ice realistically (Ji et al., 2015).

In this paper, the discrete element method with the bonding and crushing functions is adopted to simulate the ice-structural interaction. The simulated results of local pressure distribution and ice load are compared with the Frederking (2004)’s filed experiments to verify the rationality of the DEM. The influences of contact areas and load speeds on local ice pressures were analyzed. The comparison with ISO standard indicates that DEM is suitable to study the attributes of ice pressure.

PARALLEL-BONDING MODEL

The DEM with the parallel-bonding model is adopted to simulate sea ice as shown in Figure 1 (Potyondy and Cundall, 2004). An elastic bonding disk between two particles is set to transfer both forces and moments. The parallel bond can be regarded as elastic springs with constant normal and shear stiffness, which is distributed over a circular disk lying on the contact plane and centered at the contact point.

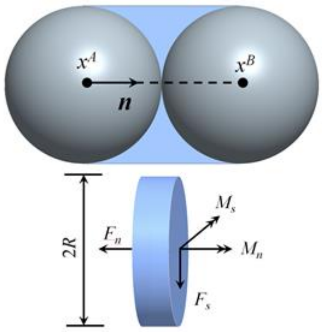


Figure 1. Bonding model between two spherical particles

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 tensile and shear stresses acting on the bonding disk are calculated based on the beam theory as

$$\sigma_{\max} = \frac{F_{\mathrm{n}}}{A} + \frac{|M_{\mathrm{s}}|}{I} R, \quad \tau_{\max} = \frac{|F_{\mathrm{s}}|}{A} + \frac{|M_{\mathrm{n}}|}{J} R \tag{1}$$

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

$$A = \pi R^2, \quad J = \frac{1}{2}\pi R^4, \quad I = \frac{1}{4}\pi R^4 \tag{2}$$

If tensile stress exceeds the normal strength, or shear stress exceeds the shear strength, then the parallel bond breaks.

COMPARISON WITH A FIELD TES

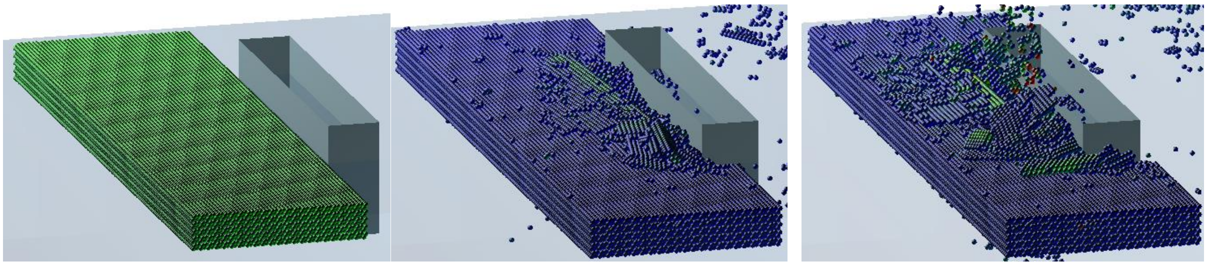
Ice-structure Interaction

A mass of field measures and tests show the existence of high pressure zones. The field test of Frederking (2004) is simulated to validate the DEM mode. In the field test, an indenter with 1.5m width and 0.5m height is driven to act with a sea sheet with 168 mm thickness. As the test data, the strength of ice is about 2.46 MPa. The sensor elements over the contact face are adopted to measure the ice load and local pressures. A DEM simulation is designed according to the test data and the major DEM parameters are listed in table 1. In this simulation, the ice cover with 0.8 m length and 2 m width is composed of regularly arranged spherical particles. The indenter is regarded as a rigid body with a load speed of 3 mm/s.

The failure process of ice acted on the indenter is presented in Figure 2 which indicates that the sea ice will be evidently accumulated in front of the structure. These accumulated ices have little direct influence on the ice load on indenter because of the lower compressive strengths. However they have a vertical squeezing effect on the ice cover that can make the particles in middle cover bonded stronger during the crush.

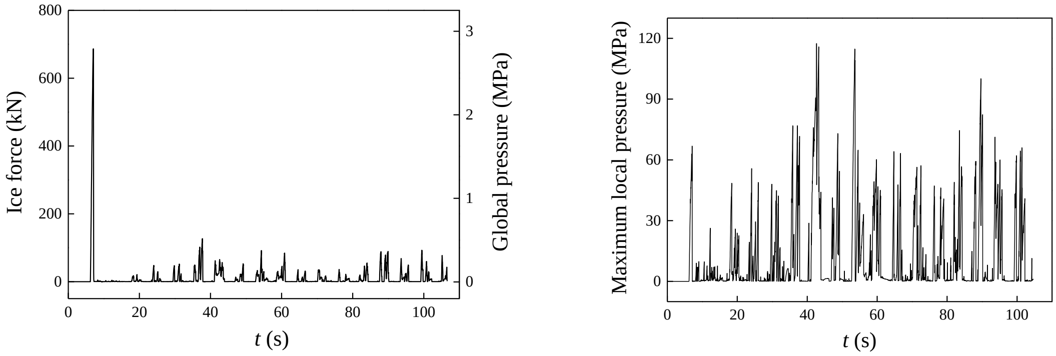
Table 1. Major parameters in DEM

Definition	Symbol	unit	value
Ice elastic modulus	E	MPa	10^9
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	0.6
Particle friction	μ_p		0.2
Particle restitution	e_p		0.3
Structure friction	μ_w		0.15
Structure restitution	e_w		0.3



(a) t = 0s (b) t = 50s (c) t = 100s

Figure 2. The failure process of ice-structure interaction at different time



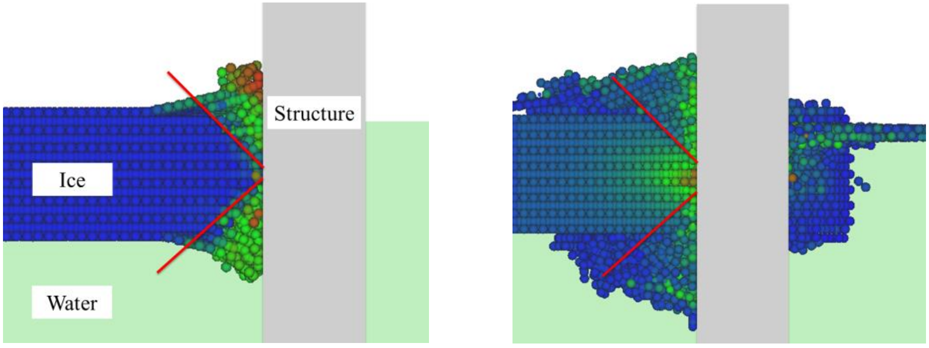
(a) (b)

Figure 3. The ice-force curve of ice-structure interaction

At the early stage of the ice-structure interaction, the level ice constituted by bonding particles has a great compressive strength to prevent the crushing failure. Hence the first force peak is about 710 kN in Figure 3(a) which is evidently larger than others. This strong impact makes the ice break into small pieces, so that the ice force keeps quiet low in later 15s. Then, the ice force gradually increases and changed by a stable period of 5s. During this period the maximum ice force is 125 kN. These attributes of ice force curve in the simulation are in good agreement with the experimental data. Meanwhile the global ice pressure as the ratio of ice force to contact area has the same trend with the ice-force curve.

Local Pressure Distribution

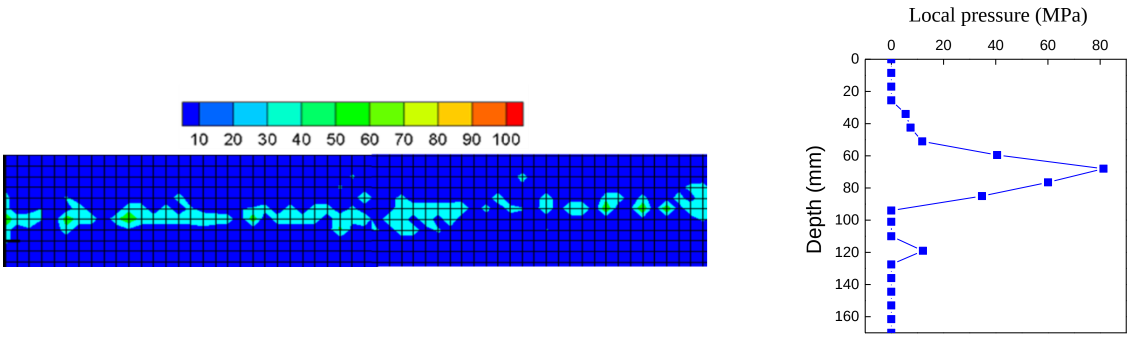
It is clearly observed the crushing process of sea ice in the interface between sea ice and structure by the numerical simulations. Figure 4 shows the failure process in detail by a vertical cross section of sea ice and structure. During this interaction, the particles will be crushed out of the contact area from up and down edge of ice sheet. In Figure 4(a), the different particle velocities which are represented by the colors indicate the trend of particles' movement. The cracks of ice sheet are always along the slops (two red lines) after the first action on the structure. Then the broken ice pieces accumulate before the vertical structure gradually at t = 100s as shown in Figure 4(b) where the colors mean particle forces. It is found that the inter forces of particles at the middle of ice sheet are higher than other places and acted on the structure more strongly. Hence these simulated results indicate that the high pressure zones on structure are caused by the non-simultaneous destruction of ice sheet during the interaction.



(a) t = 10s (b) t = 100s

Figure 4. The vertical profiles of ice-structure interaction at different time

All the particle forces acting on the structure could be recorded based the pre-draw grids on contact area. The grid size is same with the sensor elements of indenter in the test as 0.01m × 0.01m. The pressures on each element are defined as the local pressures as Figure 5(a) (in MPa). The elements in red are regarded as high pressure zones with a 'line-like' distribution. The distribution along thickness direction in Figure 5(b) also indicates that the ice pressure is mainly provided by the middle of the ice layer, instead of the upper and lower edges.



(a) (b)

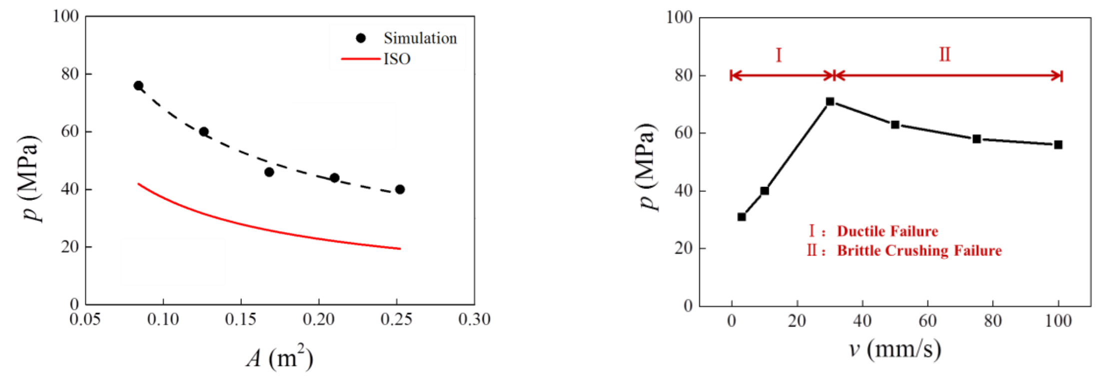
Figure 5. The HPZs distribution on contact area at 100s

There is a big difference between the local pressure and average pressure as shown in Figure 3. The local pressure in Figure 3(b) is the maximum value of the whole contact area at every time step which is much higher than the globe average pressure in Figure 3(a). The max global pressure is corresponded to the first load peak at 6.7s, while the max local pressure is at 42.6s. There is no local failure for ice until the first crushing action, so the local pressure at this moment is lower relatively.

INFLUENCING FACTORS ON THE LOCAL PRESSURE

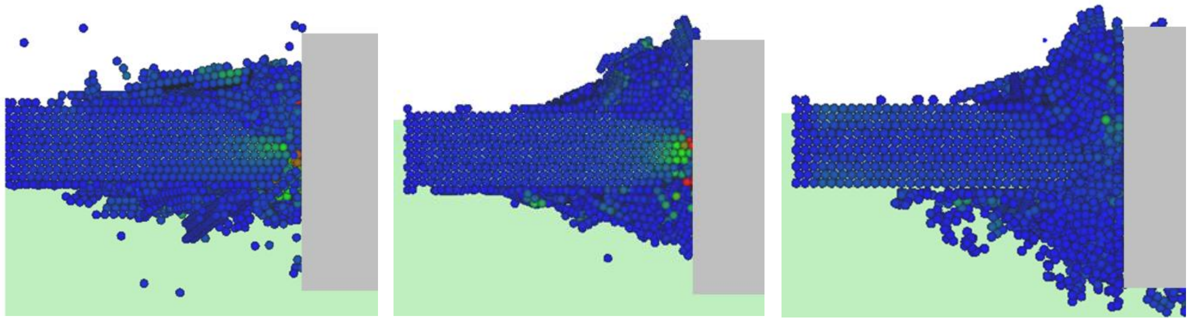
Two major factors are considered in this paper, including structure width and ice velocity. It is widely agreed that the ice local pressure (p) always decreases as the area of contact (A) increases which has been adopt in ISO by a curve of $p=7.4A^{-0.7}$. To research this relationship, a comparison is proposed in this paper by DEM simulations where the same ice cover is acted on the structures with different width from 0.5m ~ 1.5m. The local pressures are analyzed by both maximum and mean peak pressure as shown in Figure 6(a). The simulated curve has a similar trend with the ISO as Equation 3, but the local pressures in simulations are about two times of the standard value which is not considered the effect of other factors, such as load speed. The equation in the ISO is not applicable to all ice conditions, especially for thin ice.

$$p = 16.5A^{-0.6} \tag{3}$$



(a) contact area (b) load speed

Figure 6 The contact area and load speed effect on local ice pressure



(a) v = 10 mm/s (b) v = 30 mm/s (c) v = 75 mm/s

Figure 7 The failure process of ice with different load speeds

On the other hand the load speeds of ice-structure interactions which are not considered in ISO also affect the ice pressures by changing the failure modes of sea ice (Sodhi, 2001; Jordaan et al., 2010; Timco and Sudom, 2013). Hence some simulated cases in this paper with different velocities of ice (3mm/s ~ 100mm/s) are provided to the effect on local pressures. The result in Figure 6(b) indicates that ice velocity is related to the local pressure. The failure processes in Figure 7 at different load speeds and the same moment, illustrate the effect of the load speed on failure modes of ice. When the load speed is low, the upper and lower surfaces of the ice sheet begin to be broken and the middle particles of ice are still bond and solid. Contrarily, when the load speed is high, all the particles on the interacted face are almost broken at same time. Therefore, the results show that brittle crushing of ice occurs at higher speed and ductile failure occurs at lower speed. The local pressure increases with the velocity during ductile failure linearly. Moreover, ice velocity has little effect on local pressure during brittle failure.

CONCLUSIONS

In this paper, the interaction between sea ice and vertical structures is simulated by constructing the spherical DEM model with the functions of bonding and breaking. A comparison with field test from Frederking (2004) is provided to validate the rationality of this numerical model. From the DEM results, both the ice force and the distribution characteristics of local pressures reach an agreement the experimental data. Moreover a 'line-like' distribution of the high-pressure zones also could be obtained in this simulation.

Two factors influencing on the local pressures are researched, including contact area and load speed. The local pressure decreases with the increasing area which is consistent with the relationship of ISO. On the other hand, the load speed has a positive influence on local ice pressures which could lead to the change of the failure modes. The DEM simulations could be applied in the study of ice pressure to reinforce the structures reasonably. Meanwhile some other factors such as the ratio of structure width and ice thickness, and ice strength, are necessary for detailed analysis of ice pressure.

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