Ocean Engineering 146 (2017) 282–297

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Discrete element simulation of ice loads on narrow conical structures

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ARTICLE INFO

Keywords:
Ice loads
Narrow conical structure
Discrete element method
Numerical model

ABSTRACT

This paper investigates a numerical approach to predict the ice loads on a conical structure through simulating the failure process of level ice sheet using the discrete element method (DEM). In the simulation, the level ice sheet is modeled with the bonded spherical particles, which can be de-bonded based on the bonding-breaking criteria. The ice sample compression and three-point bending tests are used to set up the relationship between the ice strengths, i.e. compression strength and flexural strength, and the bonding strengths in the DEM model; the sensitivity of particle size, normal and shear bonding strength, normal and shear contact stiffness are analyzed. The ice loads on narrow conical structures with different cone angles are simulated using the DEM model. Meanwhile, a comparison between numerical results and the ISO ice force standard is carried out. In addition, the interaction between level ice and multi-legs conical structure is simulated to study the shadowing effect.

1. Introduction

The failure of sea ice cover against a conical structure is a fragmentation process where a continuous ice sheet is broken into discrete blocks mainly under the bending failure. For designing of offshore structures in ice covered waters, it is important to well understand this process and properly estimate ice loads. The ice load measurements on full-scale structures can obtain the significant accurate ice force data. There have been scarce published full-scale ice load data measured on conical structures around the world. Some well-known tests were the Finnish Kemi-I test in the Gulf of Bothnia (Määttänen et al., 1996; Brown and Määttänen, 2009), the Confederation Bridge ice load measurements in the Southern Gulf of Lawrence (Brown et al., 2010) and the ice forces measurements on a jacket platform equipped with cones in the JZ20-2 field in the *Bohai* Sea of China (Yue et al., 2007). Compared with the full-scale tests of the ice loads on conical structures, the model scale tests conducted in ice tanks have some advantages of studying the influences of various factors (ice thickness, ice speed, water line diameter, etc.) on the ice loads of conical structures (Huang, 2010; Huang et al., 2013; Dalane, 2014). Meanwhile, there were some numerical models developed to simulate the failure process between ice sheet and conical structures and to calculate the ice loads acting on the conical structures.

Matlock simulated the interaction between ice sheet and conical structure in 1971 (Matlock et al., 1971). In this model, he described structures and ice with a spring-mass-damper system and moving bars separately. The “Matlock-model” is able to simulate the ductile and brittle ice crushing, corresponding to low and high velocities of moving ice, respectively (Withalm and Hoffmann, 2010). Although it is available for the structures with a high ratio between structure width and ice thickness, the ice sheet is divided into several zones by cracks instead of fails as one piece across the structure. Based on this, Eranti (1991) presented a zonal model of ice interacting with a cylindrical structure, and introduced two fracture lengths in ice advancing direction and radial direction to estimate the maximum ice force. This method is practical for modeling small-scale configurations and has a highly agreement with model-scale measurements.

However, it is difficult to determine the fracture length in the Eranti's model which is only available for conical structures. Therefore, it is crucial to investigate some more effective and accurate numerical methods to simulate the interaction processes between sea ice and offshore structures with complex geometries. DEM method has been used in the simulation of pancake ice floes on cylindrical piles by Sun and Shen (2012) (Sun and Shen, 2012), and rubble pile formation process against a wide inclined structure by Hopkins (1997) and Paavilainen et al. (2011) (Hopkins, 1997; Paavilainen et al. 2011). The combined finite-discrete element method is also an effective approach to model ice sheet and its failure with FEM and subsequent pile-up process with DEM (Polojärvi and Tuhkuri, 2009).

This paper examines ice sheet failure process against a narrow conical structure with the discrete element method by treating the ice as elastic-brittle material. The failure mode of ice is strongly dependent on the ice conditions, structure geometry and the relative velocity between the ice

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https://doi.org/10.1016/j.oceaneng.2017.09.033
Received 10 February 2017; Received in revised form 26 August 2017; Accepted 24 September 2017

and structure. The simulation results have high agreement with the measurements on a conical structure in the *Bohai* sea (Yue and Bi, 2000; Yue et al., 2007; Xu et al., 2011) as the purpose of deploying a conical structure is to reduce the ice loads on the flexible vertical structure (Qu et al., 2006). The peak ice loads are analyzed as well against conical structures with different slope angles and diameters.

Firstly, this paper introduces the discrete element model for sea ice. Secondly, the parameter sensitivity analysis of this numerical method, mainly including the choice of micro-parameters, is presented. Numerical tests of uniaxial compressive and three-point bending of sea ice are performed to determine the stiffness and strength parameters in the failure criterion of the bonding model. Finally, the influence of the particle diameter on ice mechanical properties is investigated. With this model, simulations are conducted to study the failure process of level ice advancing against a conical structure. The results are verified with full-scale measurements from the JZ20-2 MUQ platform in *Bohai* Bay. Furthermore, the maximum ice loads on offshore structures with different slope angles and diameters are studied and compared with the ISO ice force standard.

2. DEM model of sea ice

The ice sheet is represented by a dense packing of uniform-sized spherical particles that are bonded together at their contact points with parallel bonds. Its mechanical behavior is simulated using the three-dimensional discrete element method. In this method, the ice sheet and its fracture are modeled by the beam theory. A comprehensive presentation of the method can be found in the work of Potyondy and Cundall (2004) (Potyondy and Cundall, 2004).

The mechanical behavior of an elastic-brittle bond joining the two bonded particles is approximated by a parallel bond. Fig. 1 shows the sketch of a parallel bond, where $\boldsymbol{x}^A$ and $\boldsymbol{x}^B$ are the position vectors of element A and B, respectively. The parallel bond can be envisioned as a set of elastic springs uniformly distributed over a circular cross-section lying on the contact plane and centered at the contact point. Parallel bond can transmit both force and moment between particles.

The total force and moment carried by the parallel bond are denoted by $\boldsymbol{F}_b$ and $\boldsymbol{M}_b$, respectively, which represent the action of the bond on particle B. The force and moment vectors can be resolved into normal and tangential components as

$$\boldsymbol{F}_b = \boldsymbol{F}_b^n + \boldsymbol{F}_b^s \tag{1}$$

$$\boldsymbol{M}_b = \boldsymbol{M}_b^n + \boldsymbol{M}_b^s \tag{2}$$

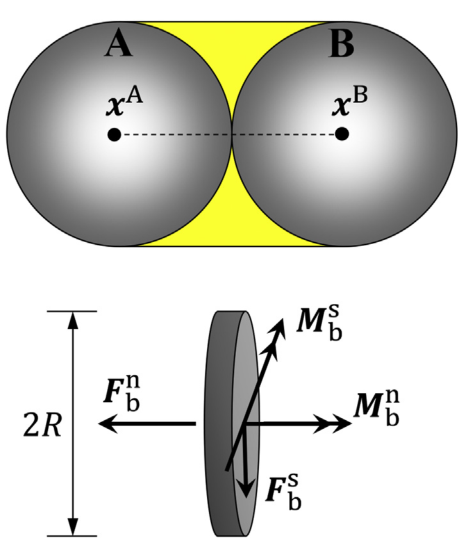

Fig. 1. Parallel bonding model between two spherical particles.

where $\boldsymbol{F}_b^n$, $\boldsymbol{F}_b^s$ and $\boldsymbol{M}_b^n$, $\boldsymbol{M}_b^s$ denote the normal- and tangential-direction forces and moments, respectively. Each subsequent relative displacement and rotation increment produces an increment of elastic force and moment. The increments of elastic force and moment acting on the bond can be written as follows:

$$\Delta F_b^n = k^n \Delta U^n \tag{3}$$

$$\Delta F_b^s = k^s \Delta U^s \tag{4}$$

$$\Delta M_b^n = k^s J \Delta\theta^n \tag{5}$$

$$\Delta M_b^s = k^n I \Delta\theta^s \tag{6}$$

where A $(=\pi R^2)$, I $(=\frac{1}{4}\pi R^4)$ and J $(=\frac{1}{2}\pi R^4)$ are the area, moment of inertia and polar moment of inertia of the parallel bond cross-section, respectively. k^n (Nm^{-3}) and k^s (Nm^{-3}) are the bond stiffness in the normal and tangential direction. ΔU^n and ΔU^s are the relative normal and tangential displacement increments. $\Delta\theta^n$ and $\Delta\theta^s$ are the relative normal and tangential rotation increments.

The maximum tensile and shear stress acting on the parallel-bond periphery are derived from beam theory (Eqs. (7) and (8))

$$\sigma_{\max} = \frac{|\boldsymbol{F}_b^n|}{A} + \frac{|\boldsymbol{M}_b^s|}{I} R \tag{7}$$

$$\tau_{\max} = \frac{|\boldsymbol{F}_b^s|}{A} + \frac{|\boldsymbol{M}_b^n|}{J} R \tag{8}$$

The bonds break when either the maximum tensile stress exceeds the tensile strength ($\sigma_{\max} > \sigma_b^n$) or the maximum shear stress exceeds the shear strength ($\tau_{\max} > \sigma_b^s$). σ_b^n is the inter-particle normal bonding strength, and σ_b^s the inter-particle shear bonding strength. The failure criterion of bond between two particles is indicated as follows (Eq. (9)) (Ji et al., 2016)

$$\tau_b = \sigma_b^s + \mu_b \sigma_n \tag{9}$$

In this failure criterion, the shear strength τ_b is determined by the bonding strength σ_b^s in the shear direction and the friction induced by the normal stress σ_n following the Mohr-Coulomb law, and a sliding friction coefficient μ_b between the two bonded particles also be introduced. The detail of the failure criterion and the determination of the values of σ_b^n, σ_b^s and μ_b can be found in the previous work (Ji et al., 2016).

3. Contact detection between ice particle and cone

A narrow conical structure operating in *Bohai* Bay is selected for the calculation examples in this paper. The jacket leg is shown in Fig. 2. Fig. 3 shows the DEM model of one of the jacket's legs with ice-breaking cone.

Fig. 2. Ice-breaking cone on jacket leg in *Bohai* Bay.