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DEM-FEM Modelling Interaction between Level Ice and Conical Jacket Platform

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ABSTRACT

In this study, a coupled discrete element method (DEM) and finite element method (FEM) approach is proposed to simulate the interaction between sea ice and conical jacket platform. The DEM with bonding-breaking glue between each element is adopted to describe the breakage of level ice. The FEM consisted of the beam and shell elements can simulate the dynamic response and stress distribution of the jacket platform structure induced by ice load. Additionally, an efficient contact algorithm is developed to get the equivalent nodal force of the element based on the shape function of the triangle element. In this study, the ice-induced vibrations of the platform structure are simulated under different ice conditions. The simulated ice forces of platform structure are compared well with the ISO19906 standard. The numerical results show that the proposed DEM-FEM approach can be aided for the anti-ice design of jacket offshore platforms.

KEY WORDS: sea ice, conical jacket platform, DEM-FEM modelling, structure dynamic response

INTRODUCTION

Jacket platforms have been widely used in ocean oil explorations in the high latitude sea area in China, such as the Bohai Gulf and the northern part of the Yellow sea. The vibrations of these platforms occur during the ice-platform interaction, affecting not only the routine production but also the serviceability and safety of platforms (Liu et al, 2009).

Timco et al. (1992) performed model tests on the four legs jacket platform in the Bohai sea, China, in order to analyze the ice load on the offshore structure (Timco et al. 1992). Huang (2010) found that the ice failures around the cone are related to the ratio of the water line diameter to the ice thickness through series of model tests. When this ratio is larger than 25, the ice failure becomes nonsimultaneous, and the rubble piece size and the ride-up height are found to be proportional to the ratio (Huang 2010). Määttänen et al. (2012) studied the effects of varying ice and structural parameters on the ice-structure interaction, especially on the frequency lock-in vibrations through scale-model tests (Määttänen et al. 2012). Recently, numerical methods have been recognized as playing key roles in the studies of ice-structure interaction (Lu et al. 2014).

Due to the complexity of mechanical properties of sea ice and the interaction between sea ice and platform, numerical simulations of ice-induced vibrations of jacket platforms meet up with great challenges. It is not appropriate to apply traditional continuum mechanics to study the mechanical behaviors of sea ice. Discrete element method(DEM) can effectively simulate the failure process of sea ice transforming from the continuum to bulks (Polojärvi and Tuhkuri 2015), thereby, reasonably reflect the characteristics of the ice load on different types of offshore structures (Polojärvi et al.2011). Sea ice models have been constructed using spheres (Shunying Ji et al. 2015), polyhedra (Lau et al. 2011) and expansion disks (Sun and Shen 2011). The DEM with the bonding-breaking function has also been developed to simulate the breakage characteristics of ice cover and the relative ice load on conical structure.

On the other hand, offshore platforms are continuous structures. Structural analyses under external loads have become quite handy after decades of research and practice. The finite element method (FEM), as a powerful numerical tool, is convenient to analyze the responses of offshore platforms. Therefore, a combined DEM-FEM method is necessary in order to accurately analyze the interaction between discrete ice and continuous platform (Chung and Ooi 2012).

This paper aims to develop a coupled DEM-FEM method to analyze responses of jacket platform under sea ice. A contact algorithm is proposed at the contact surface of ice and platform. The failure mode of sea ice and the platform vibrations are simulated with the proposed DEM-FEM model and compared with field data of the JZ20-2-NW conical platform in the Bohai Gulf, China.

THE DEM MODEL OF SEA ICE

Figure 1 shows the DEM model of sea ice. Ice particles are modeled by spheres, incorporating the bonding-breaking parallel bond between spheres to simulate the breakage of ice cover. The bond strength is the function of the temperature and salinity of sea ice. A force and a moment are developed within the bond induced by the relative motion at the contact. The force and moment can be resolved into normal and shear components F_n and F_s, M_n and M_s respectively. The maximum tensile and shear stresses acting on the bonding region can be calculated based on the beam theory as follows,

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

where the variable A, I and J, denote s t he area,radius,polar inertia moment of bonding section,respectively.

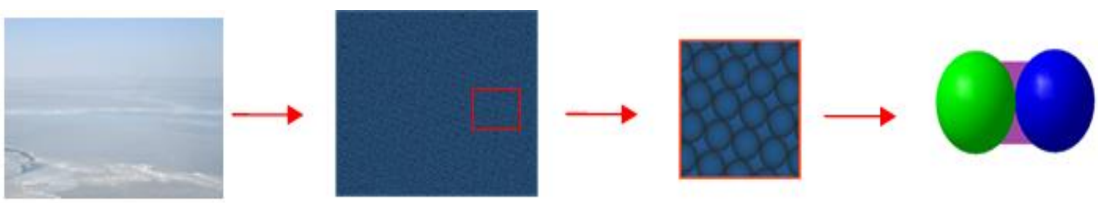


Figure 1. The DEM model of sea ice

THE FEM MODEL OF THE CONICAL JACKET PLATFORM

The JZ20-2 NW conical platform in the Bohai sea, China, as a case study, is used to verify the proposed DEM-FEM method. The platform mainly consists of three parts: the superstructure, the jacket and the pile foundation, as shown in Figure 2. For the platform FEM model, some simplifications are necessarily required for computational efficiency, as shown in Figure 3. In this paper, the ice-anti cone, with some stiffeners, is consist of the flat triangle shell elements and beam elements in the FEM model, which is main part of the platform. The final FEM model of the platform has 1034 elements and 566 nodes.

Figure 2. The JZ20-2 NW conical jacket platform

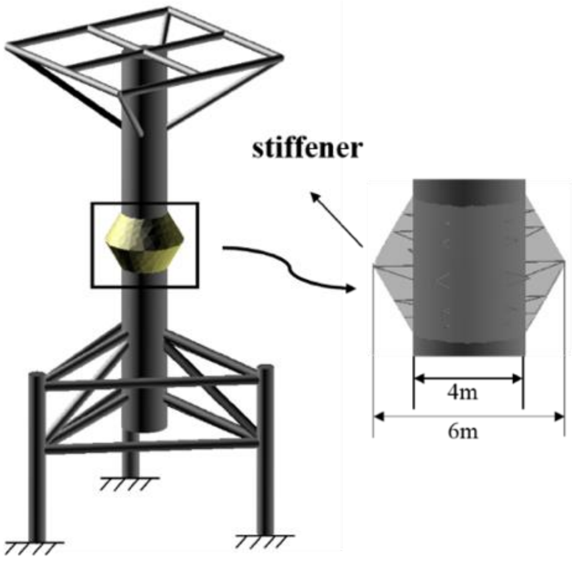


Figure 3. The FEM model of JZ20-2 NW conical jacket platform

THE COMBINED DEM-FEM METHOD

The transmissions of mechanical variables at the interface between DEM and FEM play a criticle role in the coupled DEM-FEM analysis of ice-induced vibrations of jacket platform. Here, the contact forces calculated from the ice DEM are transferred to the structural FEM as external loads, and the deformations of the platform are transferred back to the ice DEM as boundary conditions.

The contact force obtained from the DEM is randomly located on shell elements during the ice-platform interaction process. However, external loads should be appropriately treated so that their action points are located on element nodes in the finite element analyses of the platform. The area coordinate is proposed here to obtain the equivalent nodal ice loads of the FEM in the local coordinate, as shown in Figure 4. The equivalent nodal ice load is expressed as

$$P_{\mathrm{f}}^{\mathrm{e}} = N^T f_{\mathrm{dem}} \tag{2}$$

where, $P_{\mathrm{f}}^{\mathrm{e}}$ is the equivalent nodal force; f_{dem} is the force of DEM; N is the shape function expressed by triangle area coordinate:

$$N_{\mathrm{i}} = L_{\mathrm{i}} = A_{\mathrm{i}}/A \tag{3}$$

where A is the triangle element area; A_{i} is sub-triangle area.

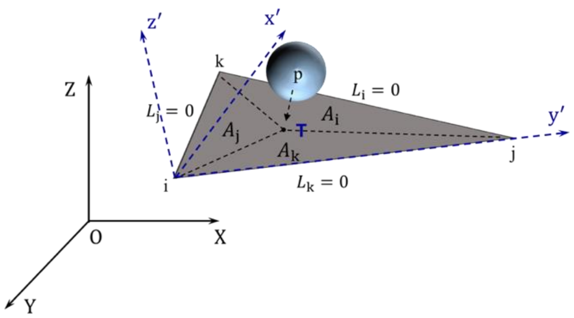


Figure 4.Sketch of contact algorithm between DEM and FEM

DEM-FEM SIMULATION OF INTERACTION BETWEEN SEA ICE AND CONICAL PLATFORM

The parameters of sea ice and platform which are used in the numerical simulation are listed in Table 1. In this paper, four cases with different ice thicknesses are simulated. From Figure 5, it can be found that the phenomenon of bending failure is quite obvious at the area around ice-breaking cones which is also in accordance with field observations (Yue et al.,2007; Tian and Huang, 2013). Figure 6(a) and Figure 6(b) show the close-ups of the sea ice radial failure mode simulated by the DEM-FEM and field monitoring data, which are consistent with each other. The phenomenon of radial failure is quite obvious at the area around ice-breaking cones.

Figure 7 plots the ice loads acting on the ice-breaking cone with $v_{\mathrm{i}} = 0.4\mathrm{m}\cdot\mathrm{s}^{-1}, H_{\mathrm{i}} = 0.2\mathrm{m}$. The force on each pile shows an obvious peak, which is consistent with field monitoring, laboratory model tests and other numerical results (Yue et al., 2007). Meanwhile, the power spectral density (PSD) of the ice load is obtained for analyzing the ice loads in frequency, as shown in Figure 8. It can be seen that the energies of the ice loads are concentrate in a frequency of 0.38Hz.

Table 1. DEM parameters

Parameters	Unit	Value
Sea ice density	kg/m^3	920
Elastic modulus	Gpa	1.0
Ice velocity	m/s	0.4
Ice thickness	m	0.2/0.4/0.6/0.8
Normal stiffness	N/m	8.0e^7
Shear stiffness	N/m	4.0e^7
Normal damping	-	0.36
Particle-particle friction	-	0.1
Particle-wall friction	-	0.3

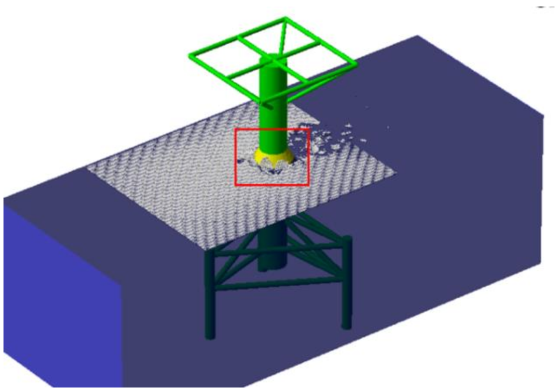
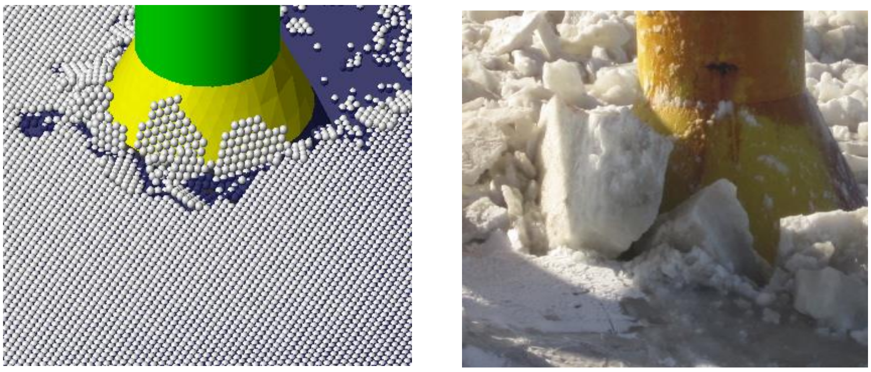


Figure 5. The numerical process of the interaction between sea ice and platform



(a)DEM simulation (b)Field monitoring

Figure 6. Close-ups of the sea ice radial failure

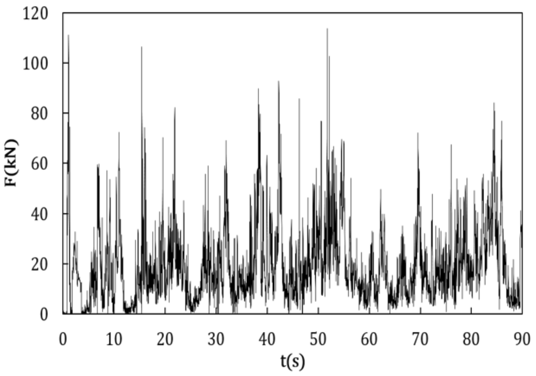


Figure 7. Ice loads obtained by DEM

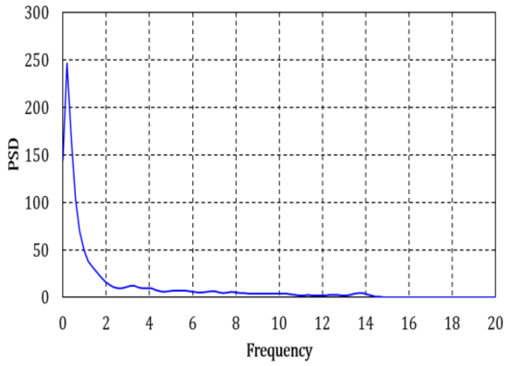


Figure 8. The PSD of the ice force

Figure 9 shows the relationship between the ice thickness and ice force obtained by DEM and ISO19906 standard(ISO19906) with blue triangle and red circle points, respectively. The results indicate the simulated trend is in accordance with the ISO19906. Moreover, the ice force is nonlinearly related to the ice thickness for both the DEM-FEM simulations and ISO19906 standard. The time series of ice-induced vibration acceleration is displayed in Figure 10(a). In Figure 10(b), we plotted the relationship between the ice thickness and the amplitude of vibration acceleration and it indicates that the vibration acceleration of platform is nonlinearly related to the ice thickness.

For analyzing the strength of the conical induced by sea ice, a von Mises stress nephogram of the ice-breaking cone is shown in Figure 11(a) and a time series of the von Mises stress is also plotted in Figure 11(b). As we can see from Figure 11(b), it can be found that the stress curve shows a strong periodicity, which means the fatigue failure of the cone may occur induced by the sea ice.

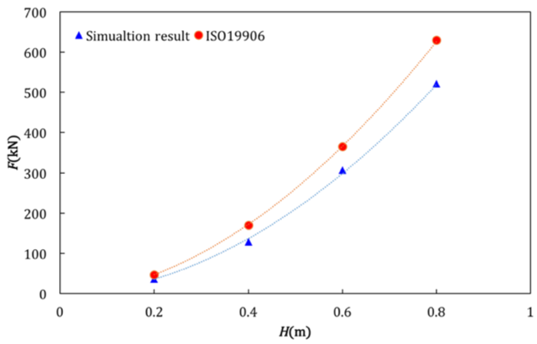
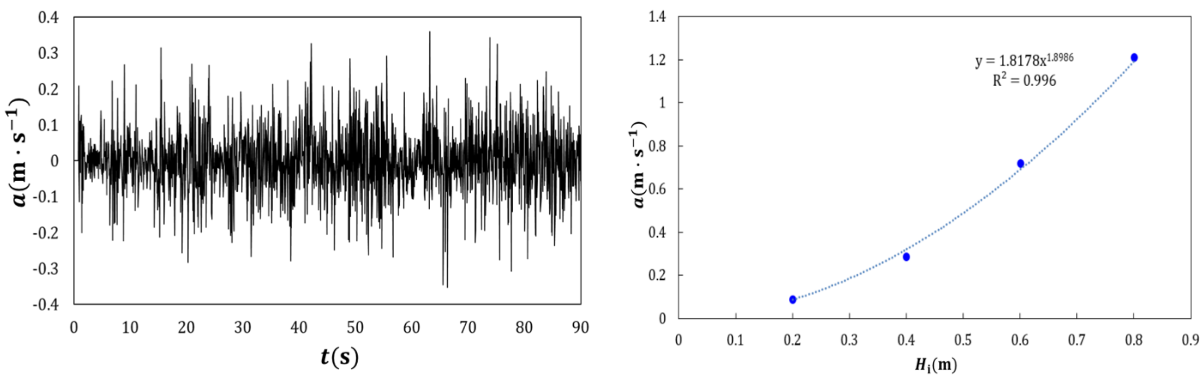
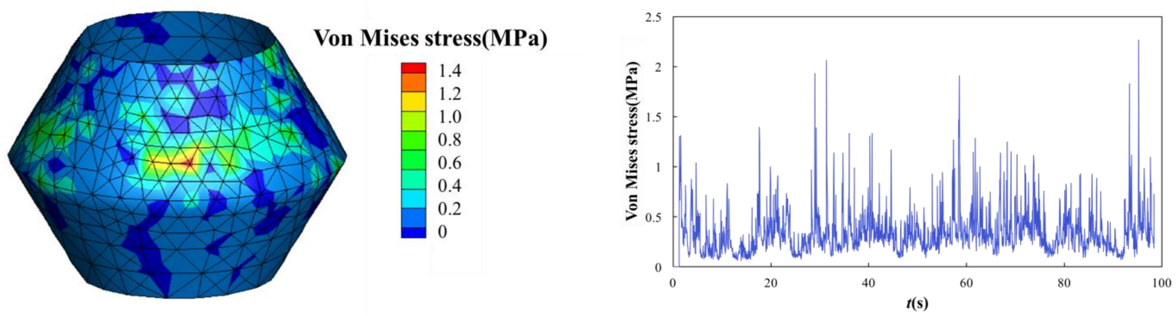


Figure 9. Comparison between numerical results and ISO19906 in ice loads



(a) Vibration accelertion under $H_{\mathrm{i}} = 0.2\mathrm{m}$ (b) Response with different ice thickness

Figure 10. The vibration acceleration of the platform



(a) Von Mises stress distribution of the cone (b)Time series curve of the cone stress

Figure 11. Von Mises stress of the cone induced by the sea ice

CONCLUSIONS

A coupled DEM-FEM method is developed to evaluate the dynamic responses and strength of the offshore platform structure. Spherical particles are bonded together to describe the ice cover, and shell-beam elements are used to analyze the dynamic behaviors and stress of the structure. The ice force acting on the platform are calculated by the DEM and transferred to the FEM as equivalent nodal forces, while the responses of the platform are calculated by the FEM and transferred back to the DEM as boundary conditions. Based on the coupled method, the JZ20-2 NW platform is simulated to obtain the ice force, vibration acceleration and stress induced by sea ice. It demonstrates that the approach can provide an effective way to investigate ice-induced vibration and strength of offshore jacket platform structures.

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