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A Local-Global Analysis Method for Arctic Drilling Riser Suffering from Ice Load

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Abstract. As world energy consumption intensifies, the oil and gas exploitation technology in the polar region are drawing more and more attention. However, due to the harsh environment, the oil and gas exploitation operation in the polar region are faced with enormous challenges, such as low temperature and sea ice collision, etc. This paper mainly focuses on the structural strength and integrity study of the arctic drilling riser suffering from the floe collision loading. First, the discrete element software IceDEM is employed to develop a local drilling riser - sea ice interaction model subjected to the floe collision loading in the splash zone, and the corresponding dynamic collision response between the drilling riser and the floe ice could be calculated and acquired. Then, a global drilling riser model is built within the framework of general finite element analysis software ABAQUS to investigate the dynamic behavior of the arctic drilling riser in the polar environment, and the dynamic collision loading derived from IceDEM simulation is also introduced in this global model. Finally, the dynamic responses of the arctic drilling riser based on the finite element simulation are investigated to research the riser's security and integrity, which can provide reference for the design and application of the drilling riser in the polar region.

Keywords. Arctic drilling riser, oil and gas exploitation technology, global drilling riser model

1. Introduction

On account of the harsh polar environment, the oil and gas production in the polar region is faced with great challenges. The safety and integrity of the arctic drilling riser during the drilling operation is a demanding and meaningful issue in the offshore engineering. And the riser end angle is one of the key concerns in the safety and integrity management, which should be ensured not to exceed the allowable limits, ideally within ±2°. As illustrated in figure 1, the drilling riser connects the surface platform to the seabed to conduct the drilling operation. The drilling riser in the polar region will be subjected to the vessel offset and hydrodynamic loads. And large vessel offset and hydrodynamic loads will result in the excessive riser end angle. Then the tension applied at the top end of drilling riser would be kept within an appropriate

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range to reduce the excessive riser end angle. Therefore, the research on the riser end angle and top tension is of great significant in the drilling operation.

Nowadays there are a large number of studies related to the drilling riser operation. Tucker et al. [1] employed the spectrum method to investigate the influencing factors on the dynamic response of a marine riser subjected to the combination of random wave and steady current. Then, Dai et al. [2] adopted ABAQUS software to conduct the static/dynamic analyses of offshore drilling riser with various environmental conditions. Mao et al. [3] developed a dynamic analysis model for a drilling riser with its two ends hinged in the plane. To avoid the excessive riser end angle, some researchers tend to introduce the dynamic positioning system into the drilling platform to optimize the platform movement. Sørensen et al. [4] developed a riser angle position reference system according to the values of end angles and top tension. Nguyen et al. [5] put forward an optimal set-point chasing algorithm to control the riser end angles within the feasible range. This ice load model [6] was employed to simulate the interaction between the vessel and sea ice. Based on the discrete element method, Dalian university of technology developed the software IceDEM to model the dynamic interaction between the sea ice and offshore structures [7-9]. However, the study on the dynamic response of the arctic drilling riser subjected to ice load is very rare and should be paid enough attention to.

In this study, two models were proposed to investigate the dynamic response of the arctic drilling riser subjected to the platform movement and hydrodynamic loads caused by ocean current, wave and ice: local drilling riser-ice interaction model and global drilling riser model. In the local riser-ice interaction model, IceDEM software was adopted to simulate the collision interaction between the drilling riser segment and floe ice in the splash zone. The corresponding collision load was introduced into the global riser model developed by ABAQUS software. In addition, the global riser model also takes account of the platform movement and hydrodynamic loads due to ocean current and wave. To make sure the safety and integrity of the arctic drilling riser during the drilling operation, the riser's dynamic responses including the riser end angle and top tension are obtained from the finite element simulation and checked according to API 16Q specification.

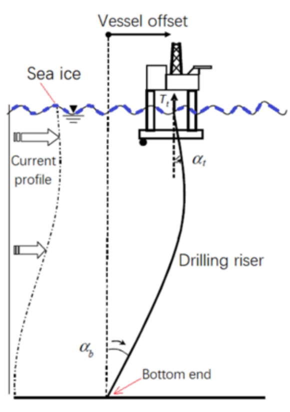


Figure 1. Typical drilling riser system [4].

2. Local Riser-Ice Interaction Model by IceDEM

The local impact of sea ice acting on the arctic drilling riser is a critical issue in the global dynamic drilling riser analysis, which may result in the riser's local damage and failure. Therefore, the self-developed discrete element software IceDEM is adopted to simulate the dynamic interaction between the sea ice and offshore structure based on the discrete element method. The process of the interaction between the sea ice and offshore structure can be reflected by the behavior of the discrete spherical particles. The calculation procedure of the proposed discrete element method is a time stepping and explicit scheme. In the IceDEM software, the local riser-ice interaction model mainly consists of three models: offshore structure model, sea ice model and water model.

The interaction between the offshore structure and sea ice is a complex dynamic contact and collision problem. It not only depends on the sea ice factors, like ice type, strength and drift velocity, but also depends on the outline, shape and structural stiffness of the offshore structure. During the calculation and simulation process of IceDEM software, the offshore structure is regarded as a rigid body with certain mass, stiffness and damping characteristics. Meanwhile, the sea ice is discrete as plenty of sphere particles tied together. When conducting the global dynamic drilling riser analysis in the arctic region, the floe ice is one of the main categories for the sea ice acting on the arctic drilling riser. Therefore, in this local riser-ice interaction model, the floe model is employed to simulate the sea ice. In addition, due to the regular shape of the drilling riser, the offshore structure model is chosen as cylinder structure to simulate the drilling riser, which is described by the radius and height of the cylinder. The whole riser-ice interaction model by IceDEM is illustrated in figure 2. Detailed theoretical description, such as viscoelastic plastic constitutive model for sea ice dynamics and bonding strength of ice particle, can be referred to the introduction of software "IceDEM".

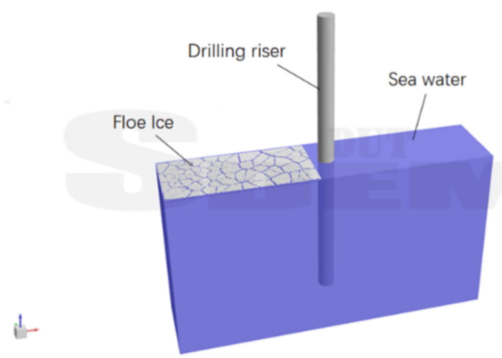


Figure 2. Local riser-ice interaction model illustration by IceDEM.

2.1. Sea Ice Model

As depicted in figure 3, the floe ice in the broken ice field shows the strong discrete distribution and irregular polygon geometry under natural conditions. To realistically simulate the irregular distribution and random geometry characteristics for the floe ice in the broken ice field, Voronoi tessellation algorithm (figure 4) is employed to randomly produce numerous polygons with disparate sizes and shapes. Then IceDEM software adopts Minkowski sum theory to generate the extended polyhedron units, which can accurately describe the geometrical morphology of the random-shape particles and calculate the collision loading between the particles.

Figure 3. Distribution of pancake ice in broken ice field of the Bohai Sea (January 27, 2002).

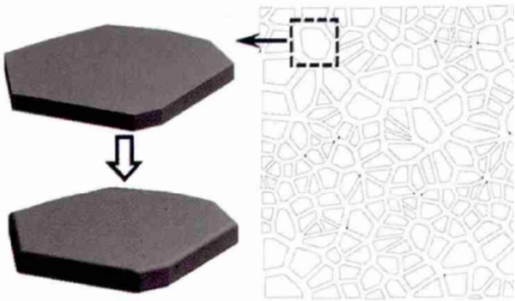


Figure 4. Generation of polygonal ice floes with Voronoi tessellation algorithm in broken ice.

During the collision process with the offshore structure, the floe ice may exist the failure mode of extrusion and crushing, and then produce the random ice load. Besides, the floe ices may superimpose together, which is closely related to the temperature, thickness and density of the sea ice, etc. In the IceDEM software, the contact force model is used to simulate the particle interaction.

As depicted in figure 5, based on Mohr-Coulomb shear friction law, the interaction force between the sea ice particles or between the ice particle and offshore structure element can be calculated by the elastic-viscous contact model, where M_A and M_B are the masses of ice particles A and B respectively; K_n and K_s denote the normal and shear stiffness respectively; C_n and C_s are the normal and shear damping coefficients respectively; μ represents the friction coefficient. In the elastic-viscous contact model, the spring and damper are employed to simulate the normal contact between the two particles; the spring, damper and sliding friction apparatus are used to simulate the tangential contact. The normal force F_n can be calculated as following:

$$F_n = F_e + F_v = K_n x_n - C_n v_n \tag{1}$$

where x_n and v_n are the relative normal displacement and velocity between the two contacted ice particles. In addition, the normal damping coefficient can be expressed as:

$$C_n = \frac{-\ln e}{\sqrt{\pi^2 + \ln^2 e}} \sqrt{2MK_n} \tag{2}$$

where, e and M represent the restitution coefficient and mean mass of two particles respectively.

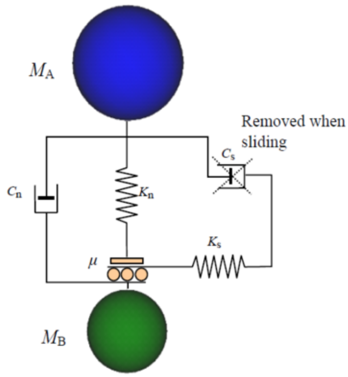


Figure 5. Elastic-viscous contact force model.

According to figure 5, a slide option is defined in the tangential direction. Then the friction limit is set as:

$$F_t = \min(K_s x_s - C_s v_s, \mu F_n) \tag{3}$$

where, x_s and v_s are the relative shear displacement and velocity. The relationship between the normal and shear stiffness and damping coefficients can be expressed: $K_s=\alpha K_n$, $C_s=\beta C_n$. Normally, the values α and β are set as 1.0 and 0.0, respectively [8].

2.2. Interaction between Offshore Structure and Sea Ice

When calculating the dynamic interaction response between sea ice particles and offshore structure, the neighborhood of particles with offshore structure should be found firstly and the contact condition should be determined. For the drilling riser cylinder model, as shown in figure 6, there are three different contact modes: particle i with cylinder j side face; particle i with cylinder j edge; particle i with cylinder j top surface and bottom surface. To decide whether the particle contacts with the offshore structure, as illustrated in figure 7, define the top surface center A and bottom surface center B, the cylinder radius $R_{cylinder}$, particle center P and particle radius R_{ball}. When $(\mathrm{AP}\cdot\mathrm{BA})(\mathrm{BP}\cdot\mathrm{BA}) \le 0$ and $|\mathrm{QP}|<R_{cylinder}+R_{ball}$, particle contacts with the top surface of the cylinder. When $(\mathrm{AP}\cdot\mathrm{BA})(\mathrm{BP}\cdot\mathrm{BA}) > 0$ and $|\mathrm{BQ}|<R_{ball}$, particle contacts with the bottom surface of the cylinder. When $(\mathrm{AP}\cdot\mathrm{BA})(\mathrm{BP}\cdot\mathrm{BA}) > 0$ and $|\mathrm{QP}|>R_{cylinder}$, BP-$R_{cylinder}\cdot\mathrm{QP}/|\mathrm{QP}|<R_{ball}$, particle contacts with the edge of the cylinder.

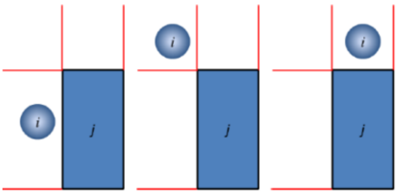


Figure 6. Three ways for particle in contact with the cylinder.

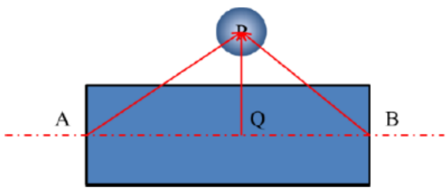


Figure 7. Contact condition judgment.

2.3. Hydrodynamic Model

In the polar ocean environment, the floe ice is mainly subjected to the gravity, buoyancy, drag force and inertia force. Hydrodynamic lift force herein is not taken into account. Considering the different submergence variation of the floe ice in the movement, the infinitesimal method is used to calculate the floe buoyancy. According to Morison's equation, the drag force F_d acting on a floe ice caused by the current and wave can be given by:

$$\boldsymbol{F_d} = \frac{1}{2} C_d \rho_w A \left(\boldsymbol{V_w} - \boldsymbol{V_i} \right) \left| \boldsymbol{V_i} - \boldsymbol{V_w} \right| \tag{4}$$

where C_d is the drag coefficient; $\boldsymbol{V_w}$ and $\boldsymbol{V_i}$ are the ice velocity and water velocity; ρ_w is the water density; A is the floe area. The inertia force of the floe ice is the sum of the added mass and floe mass. The added mass M_a on a floe then can be expressed as following:

$$M_a = C_m \rho_w V_{sub} \frac{d\left| \boldsymbol{V_i} - \boldsymbol{V_w} \right|}{dt} \tag{5}$$

where C_m is the added mass coefficient; V_{sub} is the submerged volume of the floe ice. Besides, the rotational drag M_d on a floe can be calculated:

$$M_d = -\frac{1}{2} C_d \left(r^i \right)^2 \rho_w A \omega \left| \omega \right| \tag{6}$$

where, ω is the rotational angular velocity and r^i is the radius of the particle.

3. Global Dynamic Drilling Riser Analysis

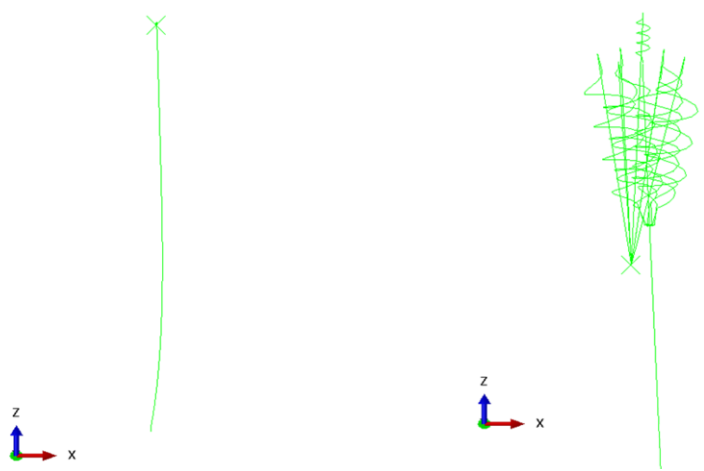
Drilling riser is an essential component for the operation process of offshore deepwater drilling. Generally, risers are from the drilling platform to the seabed BOP group. In this section, a finite element model for drilling riser is created by ABAQUS software to simulate the riser dynamic response under operational condition. The dynamic ice load calculated by IceDEM software is introduced to the model and the related effect will be well discussed. The top end of the drilling riser is connected to the platform by several tensioners under the drilling conditions. Meanwhile, its bottom end interacts with soil and can be considered as pinned. The bending and axial stiffness of the drilling pipe are not considered in this model.

The drilling riser is located in the waters of the Gulf of Mexico and its water depth is 3048m. The geometry dimension and material grade of the selected riser are shown in table 1. The beam element B31H is selected to simulate the drilling riser structure because the three-dimensional loads are well considered in the analysis. The whole drilling riser is divided into 509 elements and 510 nodes. The drilling platform is modelled as several rigid beams coupling at a reference point. Additional six nonlinear springs are employed to simulate the tensioners which connect the drilling platform to the drilling riser. Meanwhile, 59 nonlinear springs are also used to model the interaction between the riser casing and seabed soil.

Table 1. Drilling riser parameters.

Length	Diameter	Thickness	Material grade
3075.62m	546.1mm	25.4mm	X80

The finite element model of drilling riser is depicted in figure 8. For the convergence and accuracy, there are five steps for the strength analysis of the riser including static analysis and dynamic analysis. The static analysis can be divided into three steps. Firstly, the model should be initialized and then the pre-tension is applied to the top end of the riser. The riser gravity is also loaded in this step. Secondly the pre-tension is replaced by the tensioners and the current load using the AQUA module is applied. The displacement of the platform is still set as zero. Thirdly a small displacement of platform is introduced as the boundary conditions, which is used for the better convergence. The following dynamic analysis is conducted based on the static analysis. These steps begin with a restart analysis. The fourth step, which is similar to the third one, is moving the platform to a suitable position. The motions of the platform only including the translational degrees of freedom are applied at the fifth step. Moreover, this step includes the ice load applied at the horizontal plane of the riser.



(a) whole view (b) connection between riser and platform

Figure 8. Riser's finite element model of operability before dynamic analysis.

4. Results and Discussion

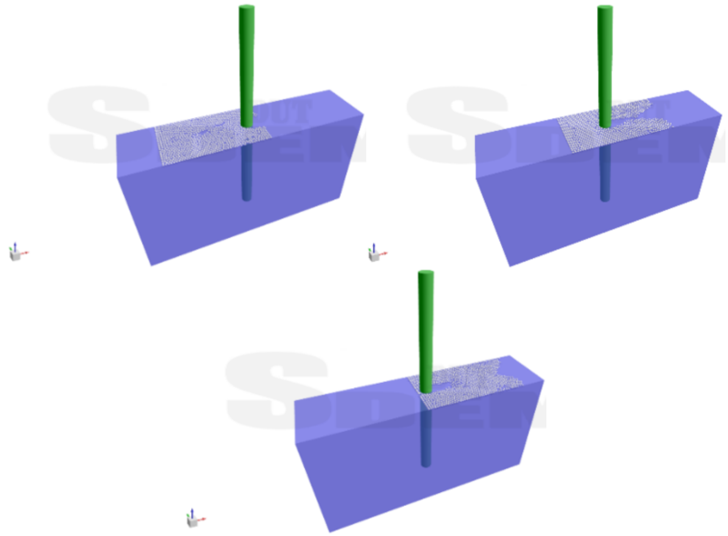
4.1. IceDEM Simulation Results

Table 2 lists the IceDEM computational parameters in the local riser-ice model. In this table, the length and width of floe ice area are measured from the *x*-direction and *y*-

direction, respectively. To avoid the boundary effect on the local model, the length of the drilling riser and width of the floe area are both above ten times the diameter of the drilling riser. In the drilling operation, the drilling riser will irregularly move with the platform motions. However, as IceDEM software can only set the floe ice with a constant kinematic velocity, the drilling riser is reduced to fix in the splash zone in the local model. Besides, figure 9 illustrates the interaction snapshots between drilling riser and sea ice floes at three different stages within the 100 seconds. And the time histories of the collision loads caused by the floe ice in the x-direction and y-direction are shown in figures 10 and 11. Form these two figures, it can be seen that the maximum collision loads in the x-direction and y-direction are about 2250N and 1500N, respectively. Due to the discrete and random characteristics of floe ice, the "up-down" property of the load-time curve is obvious both in the x-direction and y-direction. As the floe ice moves in the x-direction, it can be seen that the ice load in x-direction is significantly greater than that in y-direction. In addition, the ice load in y-direction behaves positive and negative values in the simulation, which is different from that in x-direction.

Table 2. Computational parameters in the local riser-ice model.

Item	Value	Item	Value
Water density	1030 kg/m^3	Ice density	920 kg/m^3
Average size	0.5	Ice thickness	0.2 m
Length of floe ice area	10 m	Width of floe ice area	5.5 m
Initial ice concentration	80%	Ice elasticity modulus	1 GPa
Compressive strength	1.5 MPa	Flexural strength	0.75 MPa
Restitution coefficient	0.5	Normal stiffness	0.5
Floe surface friction	0.5	Flow velocity	0.1 m/s
Normal drag coefficient	0.6	Added mass coefficient	0.0



(a) t=33.3s (b) t=66.7s (c) t=100s

Figure 9. Snapshots of the interaction between drilling riser and floe ice at three different stages.

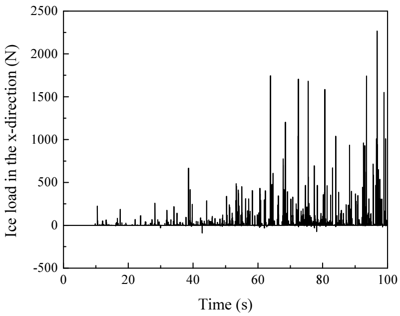


Figure 10. Ice load history in *x*-direction.

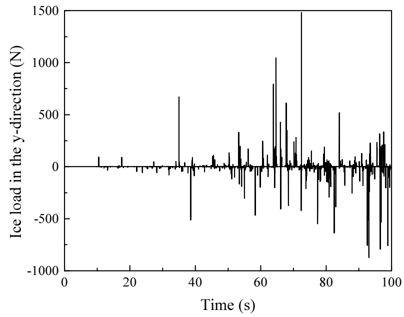


Figure 11. Ice load history in *y*-direction.

4.2. FEM Simulation Results

Based on the global dynamic simulation of the drilling riser system, it can be found the riser end angles are controlled within the acceptable range according to the code API 16Q. In addition, the calculation results of the riser top tensions in the two cases (combined ice load and platform motion case; only platform motion case). As illustrated in figure 12, the relationship between time and top tension considering the combined ice load and platform motion is presented; while in figure 13, the curve shows the time-tension relationship in the only platform motion case. From these two figures, the values of the top tension in the two cases approaches very close. Thus it can be seen that the variation trend of the top tension for the drilling riser is mainly controlled by the platform motion. The main difference between the top tensions in the two cases is that the time-tension curve in the combined ice load and platform motion case behaves small "up-down" and high-frequency oscillation, which may be induced by the ice load and result in additional fatigue. Since the ice load and platform motion are applied at the same time, the effect of platform motion then can be excluded from the results in the two cases to investigate the ice load contribution exclusively. Based on the simulation results of the two working cases, the top tension of the drilling riser under pure ice load can be obtained and shown in figure 14. It can be observed that the increased top tension due to the ice load ranges from -2.5kN to 2.5kN, which can effectively verify the conclusion of ice-induced small high-frequency oscillation load. Although the ice-induced top tension is very small when compared to the total top tension, it can result in the additional fatigue damage under the combined small high-frequency oscillation load and low temperature environment.

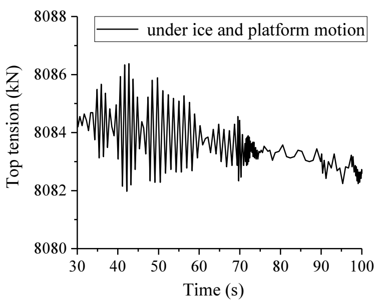


Figure 12. Time-tension relationship under ice load and platform motion.

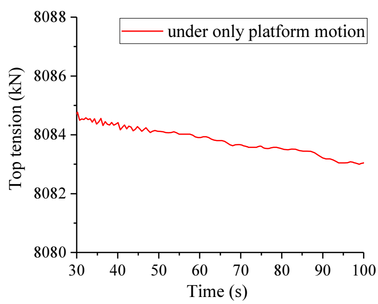


Figure 13. Time-tension relationship under platform motion.

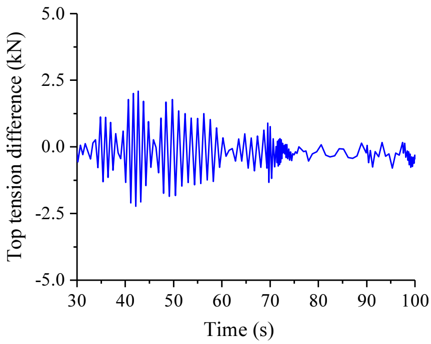


Figure 14. Time-tension relationship under ice load.

5. Conclusions

This paper takes a drilling riser with floating platform located in the ice area as research object to simulate the complex interaction between the ice and the riser. The dynamic collision loading obtained from IceDEM simulation is introduced in the global drilling system. Then a global drilling riser model is developed by the finite element software ABAQUS to research the dynamic behavior of the arctic drilling riser in the polar environment. The dynamic responses of the drilling riser (mainly top tension of the drilling riser) based on the finite element simulation are well investigated to study riser's security and integrity. Although the ice plays a small role in the top tension dynamic response, it can result in the additional fatigue damage under the combined ice-induced small high-frequency oscillation load and low temperature environment.

Acknowledgements

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