Numerical Simulation of Interaction between Kulluk Platform and Laminar Ice

Yincheng Liu*

Department of marine engineering, Dalian Maritime University, Dalian, China

*Corresponding author: Yincheng.Liu@student.cup.edu.cn

Abstract. Over the years, the development of the Arctic region has been increasingly emphasized, and the research and development of offshore platforms has become a research hotspot for many countries. Among them, all kinds of platform equipment used in the polar region must consider the special conditions when operating in extreme environments. For the floating ice-resistant marine platforms, the calculation of ice load is of considerable importance and value for the applicability and reliability design. In this article, the Kulluk platform has been chosen for the study. The interactions between the structure and the sea ice, such as collision and extrusion, are numerically simulated through the finite element method. In this paper we will explain how to calculate the ice loads acting on the floating platform and the specific loads. By setting the real scale in the program, the maximum correspondence with the real situation can be achieved. Subsequently, the numerical simulation values were analyzed and compared with the actual situation and empirical formulas to verify the reliability of the numerical simulation. The applicability of the Kulluk platform model to the problem of interaction with the leveling ice has been validated.

Keywords: Floating platform; Ice load; Finite element method; Ice speed.

1. Introduction

Although today's international community is advocating the use of cleaner and more environmentally friendly energy sources, traditional fossil energy sources cannot be completely replaced. As the oil and gas reserves in the Arctic can provide a significant portion of the resources consumed, exploration and exploitation activities in the Arctic have never been at a standstill.

Among the offshore platforms that have been put into operation, the number of floating ice-resistant platforms is very small. The existing floating platforms are still relatively weak in ice-resistant capability, and the design form and structural safety needs to be further optimized. As ice-resistant floating platforms may offer unprecedented advantages in polar waters and have great potential in the present and the future, and ice load calculations for ice-resistant floating platforms are crucial for their development and design[1,2].

In order to study the ice load of Kulluk platform after interaction with sea ice and to verify the reliability and applicability of numerical models and the selected ice parameters in calculating the interaction between large-scale floating platforms and stratified ice, this paper will use numerical simulation to explore the ice load of Kulluk platform under the interaction with stratified ice in different sea states.

2. Characters of Sea Ice and Ice Load

2.1. Properties of Sea Ice

Compressive strength, bending strength, tensile strength and shear strength are the main components of the mechanical properties of sea ice. These mechanical properties are mainly related to the sea ice's physical properties as well as external factors such as temperature and strain rate[3].

2.1.1 Compressive strength

When sea ice interacts with constituent objects in the vertical direction, the external forces exceed the limit and the sea ice is damaged, resulting in the compression damage of sea ice. Specific factors

affecting the degree of critical force are the physicochemical properties of sea ice, loading speed, and so on. The compressive strength of sea ice is negatively correlated with the icing temperature. The compressive performance is negatively correlated with the relative volume VB value of the gas in sea ice. The loading speed also has an important influence on the compressive performance of sea ice. Due to the differences in the loading angle of the horizontal and vertical directions of the force, there is a significant anisotropy in the compressive performance of sea ice.

(1) The lower the ambient temperature, the higher the compressive strength of the sea ice.

(2) The larger the relative volume of the brine bubbles, the lower the compressive strength of the sea ice.

(3) The compressive strength of sea ice is very much affected by the rate of sea ice loading. Under the condition of low loading speed, as the compressive strength of sea ice and loading speed are positively correlated, the sea ice gets elongation damage; under the condition of considerable change in loading speed, the strength of sea ice at this time has exceeded the maximum critical point, the compressive strength of sea ice and the loading speed are negatively correlated, and the sea ice is subjected to brittleness damage. This shows that the sea ice has elongation - brittleness conversion characteristics[4].

2.1.2 Bending strength

The bending strength of sea ice is low, but is generally about one third of its inherent compressive strength. Corrosion failure is most likely to occur when bending loads are applied to the ice sheet. When sea ice interacts with offshore structures, the sea ice will be affected by the inclined plane of the structure and will be forced to increase its sloping edge along the surface of the structure, causing bending load damage.

2.1.3 Tensile strength

The tensile strength of sea ice is the ultimate load per unit area of sea ice when damaged by a single axial tensile stress. Sea ice breaks under bending stresses on the side facing the structure. A single axial force can be obtained by direct tensile testing to obtain uniaxial tensile strength, or indirectly measured by circumferential tensile or bending tests. Tensile damage to sea ice is essentially brittle.

2.1.4 Shear strength

The maximum stress at which sea ice breaks in shear is called the sea ice's shear strength, which increases with decreasing temperature, decreases with increasing brine volume, and decreases with increasing loading rate. The test results can be obtained directly by applying a load to the shear surface of the sea ice sample.

2.2. Methods for Determining Ice Load

2.2.1 Empirical as well as theoretical formulas

Historical ice loading studies mainly focus on the effects of sea ice on the ship-shape structure. Most of the empirical formulas derived from these studies are only applicable to the calculations of structures of this shape and cannot be used to calculate the ice load on other structural forms. For laminar ice and more common forms of marine structures, such as cylinders, cones and domes, preliminary ice force calculations can generally be carried out using the theoretical formulas recommended in the standards or domestic ice loading codes for offshore platforms[5,6]. For complex marine structures and irregular sea ice, the previous theoretical formulas will no longer be applicable.

2.2.2 Numerical simulations

The finite element method (FEM) is the most basic method for the numerical calculation of ice load and can be used with commercial programs to perform relatively reliable and fast calculations of sea-ice interactions with marine structures. The ALE(Arbitrary Lagrange-Euler) method can solve

the drag and buoyancy of air and seawater on sea ice. Using this method, a large number of numerical analyses of sea ice-structure interactions have been carried out by researchers[7-10].

The discrete element method (DEM) is one of the main methods currently used for the numerical calculation of ice loads. It divides the system into a number of independent units with corresponding physical properties, calculates the mechanical relationship between the units by using the force-displacement theorem through the contact model, and obtains the motion relationship of each unit through the time-step iteration[11,12].

3. Platform-Layer Ice Interaction Modeling

3.1. Platform Modeling

The platform called Kulluk is a floating platform used in the polar waters of the Beaufort region of the Arctic Ocean and has undergone extensive model testing in various countries, which has added some very meaningful real-world measurements of ice load data for offshore platforms.

Kulluk is built by Japan and delivered in 1983 with a design draft of 24-55m and a main deck OD of 81m. Designed to operate at a minimum temperature of -50°C and to withstand low-velocity impacts of 1.2m thick ice. The main body is an inverted cone with a double shell that allows sea ice to break up and leave the body of the main system as it interacts with the main system, thus securing the drilling riser system and the mooring system.

In this paper, the simulations use a 1:1 scale model so that the numerical results are as close as possible to the real situation. In the numerical model, the diameter of the platform model at the waterline is 67.5 m, the angle between the inverted cone and the horizontal plane is 31.4 degrees, and the bottom is not simplified to keep the real situation as much as possible. The 3D model of the Kulluk platform is shown in Figure 1. The numerical simulation assumes the platform model as a rigid body, and the material parameters are chosen as density 7850, modulus of elasticity 2.1e11Pa, and Poisson's ratio 0.3. According to the actual situation, the thickness of the shell of the platform model is 0.1 m.

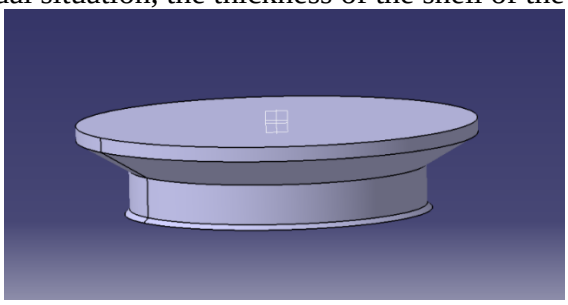


Fig.1 3D model of Kulluk platform

3.2. Sea Ice Parameterizations

The exact location of the Beaufort Sea is 69°-75°N (69°N to 75°N) and 125°-152°W (125°W-152°W). The environmental conditions of the Beaufort Sea area can be found in ISO 19906 (2019), including data on wind, waves, currents, and sea ice. In this paper, the thickness of the leveling ice is chosen to be 2 m. Statistical methods are used to compare the values of nonlinear FEM, DEM, and empirical formulas. The comparison is based on the average values of ice loads at different ice speeds for the same ice thickness. Analyzing only a single ice velocity may result in an insufficient statistical sample to ensure its reliability. Therefore, the data at multiple ice speeds are selected for statistics.

The solid part of the sea ice is composed of a model with hexahedral cells, with a size of 100m*120m*2m, and the grid is generated with a grid size of 1m*2m*0.4m, and the material adopts the elastic failure mode of each homogeneity.

The main parameters of the structure during the FEM calculation of the sea ice are: the density of the material is 900kg/m³, the shear modulus is 2.2Gpa, the yield stress is 2.12Mpa, the plastic modulus is 4.26Gpa, the bulk modulus is 5.26Gpa, the truncation pressure is -4Mpa, and the plastic failure strain is 0.35.

Parameters also need to be added for air and water in the finite element calculation. The parameters of air are as follows: the density is 1.25kg/m³, the viscosity coefficient is 1.74e-5, and the cut-off pressure is -10Mpa; the parameters of water are as follows: the density is 1000kg/m³, the viscosity coefficient is 0.9e-3, and the cut-off pressure is -10Mpa

In addition, the main parameters used in the discrete elemental calculation of sea ice are: modulus of elasticity is 1.0GPa, density of seawater is 1035.0 kg/m³, density of sea ice is 920.0 kg/m³, coefficient of friction between the particles is 0.25, coefficient of friction between the sea ice and the structure is 0.25, and the sea ice particles are modeled with isotropic bond strength. The normal bond strength of the particles is 1.57, the tangential bond strength of the particles is 1.57, and the compressive strength of the particles is 2.53MPa.

3.3. Motion Parameters and Contact Algorithm Settings

In the numerical simulation, six degrees of freedom of the platform are restricted to keep it fixed in place, a constant velocity is set for the x-direction of the ice, and the remaining two degrees of freedom are restricted to 0. The platform and ice model is shown in Figure 2.

The contact between the ice and the platform is set to the eroding nodes to surface algorithm for point-to-surface contact in order to make a more accurate and reliable simulation result for the calculation. (as shown in Figure 3(a)(b))

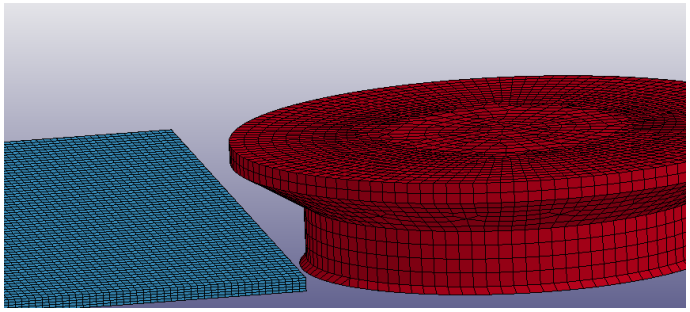
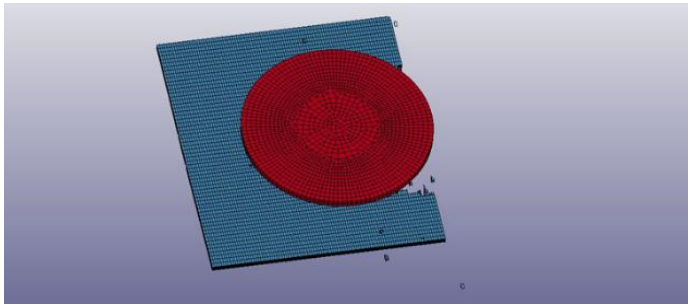
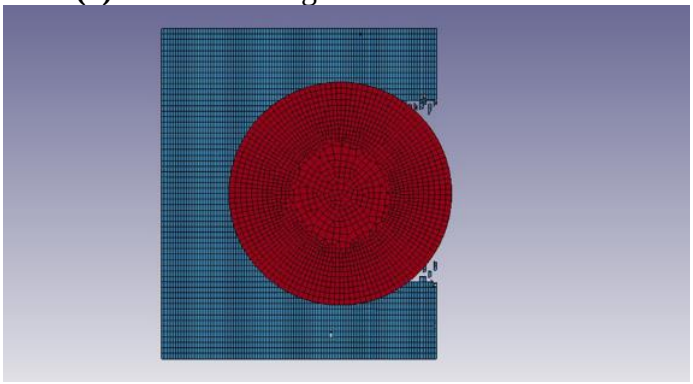


Fig.2 Finite element calculation model of Kulluk platform and layer ice



(a) Schematic diagram of FEM simulation

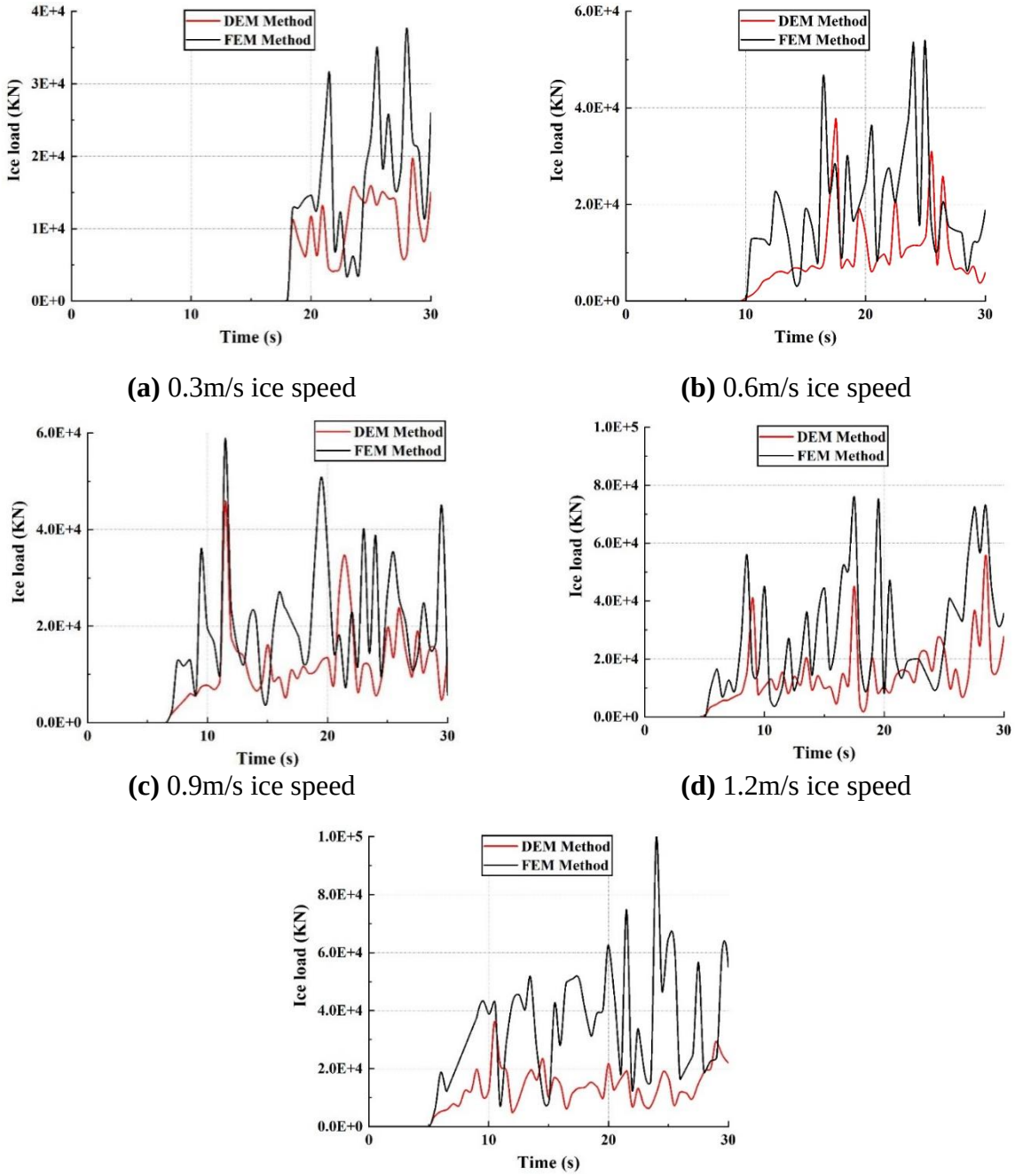


(b) Top view of FEM simulated platform-ice interaction

Fig.3 Finite element method simulation of Kulluk platform and layer ice

4. Numerical Results and Analysis

In this paper, using FEM to analyze the ice load on the Kulluk platform, and the ice load on the platform is calculated with selection of five groups of different ice speeds at intervals of ice speeds ranging from 0 to 1.5 m/s. In addition, in order to better analyze the applicability of numerical simulation, this paper will also take DEM to calculate the five groups of models with the same ice speed, and compare the results with FEM. Among them, the x-direction ice force applied to the platform by FEM and DEM at different ice speeds is shown in Figure 4. It is not difficult to conclude that the overall ice load on the platform increases with increasing ice velocity.



(a) 0.3m/s ice speed

(b) 0.6m/s ice speed

(c) 0.9m/s ice speed

(d) 1.2m/s ice speed

(e) 1.5m/s ice speed

Fig.4 X-direction ice force values of two methods

From the calculation results shown in Table 1, it can be seen that the time-distance curves of ice loads calculated by both methods show irregular fluctuations in the trend, and the moments when the peaks appear roughly coincide with each other. The difference is that the peak value of the ice load

using the FEM is larger than that of the DEM calculation. Among them, the DEM results are more stable, and the FEM is closer to the value of the empirical formula. In the finite element calculations, there is no cushioning effect of the fluid, which causes the sea ice to generate greater forces when it comes into contact with the structure. The erosion contact setup in turn makes the contact frequency between sea ice and structures smaller. Therefore, compared to DEM results, the calculation of FEM leads to a large fluctuation of the ice load.

Table 1 Calculated ice load on Kulluk platform

method / speed of ice(m/s)	DEM (kN)	FEM (kN)
0.3	5139.514	13137.33
0.6	7303.29	16066.92
0.9	10109.97	23273.74
1.2	11125.82	28472.08
1.5	12193.12	38966.97
average value	9174.3428	23983.4086+
empirical formula	36313.797	

5. Conclusion

Calculating and analyzing ice loads on the Kulluk as it interacts with a flat ice surface is detailed in this paper. The numerical results obtained from FEM and DEM are compared. The results of FEM are closer to empirical formulations, while results of DEM are more stable. The following conclusions can be drawn from the numerical results:

(1) The ice force on the Kulluk platform is closely related to the ice drift speed, and the larger the ice drift speed is, the larger the ice force on the Kulluk platform is. Therefore, in order to determine the design strength of the platform, the actual situation of the local sea area and the ice drift speed must be considered.

(2) The ice force on the x-up platform usually shows a large fluctuation pattern, and its fluctuation usually shows a high frequency in the time domain, and there is no regular simple harmonic load. Therefore, the negative influence of the fluid-solid coupling phenomenon on the platform must be considered when designing this platform, and the influence of vibration on the strength of the platform must be fully eliminated through structural design.

References

[1] HaKun, JangMooHyun Kim. Kulluk-shaped arctic floating platform interacting with drifting level ice by discrete element method. Ocean Engineering, 2021.

[2] Wang J, Derradjiaouat A. Numerical Assessment for Stationary Structure (Kulluk) in Moving Broken Ice. 2012.

[3] Li Chunhua, Liu Yu, Bai Shan, et al. Introduction to the Integrated Sea Ice Forecasting System. National Marine Environment Prediction Center, Beijing, 2003.

[4] Wettlaufer, J. S. Icy Patterns. Collision, Eruption and Destruction. American Geophysical Union, Fall Meeting 2010, 2010.

[5] Ren Guiyong. Marine movable platform. Tianjin: Tianjin University Press, 1989.

[6] Li Renpei, Wang Zhinong. Strength analysis of offshore platforms. Shanghai: Shanghai Jiaotong University Press, 1992.

[7] Bereznitski A, Roodenburg D. JBF Arctic-A Mobile Offshore Drilling Unit with High Performance in Ice Covered Waters and in Open Seas. Offshore Technology Conference. Offshore Technology Conference, 2011.

[8] Ereznitski A. A Novel Design of Mobile Offshore Drilling Unit for Arctic Conditions. ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering. American Society of Mechanical Engineers, 2011: 865-871.

[9] Li Youlong. Research on the collision mechanism between semi-submersible ocean platform and ice. Harbin Institute of Technology, 2017.

[10] Dong Ke, Li Youlong. Damage analysis of semi-submersible offshore platforms subjected to ice floe impact action. Ship Science and Technology, 2018.

[11] Xu Shu. Discrete meta-analysis of the interaction between mooring structures and sea ice. Professional Master's Thesis, Harbin Engineering University, 2020.

[12] Di Shaocheng. Discrete Elemental Analysis of Ice Loads on Offshore Platforms and Ship Structures Based on GPU Parallel Algorithm. Dalian University of Technology, 2015.