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Study on the calculation method of ice load of icebreaker in straight line state

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ABSTRACT

Ice action is the primary factor that affecting the navigation of icebreaker in the ice area. The ice-breaking load also directly impacts on the construction and design of the icebreaker. Therefore, reasonable calculation of ice-breaking load has become the most important issue at present. Focusing on ice cover, this paper presented a theoretical model for calculating the ice-breaking resistance of the icebreaker. The presented model is based on the combination of semi-infinite beam and infinite beam along and perpendicular to the moving direction of the icebreaker on elastic foundation, respectively. The influence factors such as buoyancy and ice failure criterion are considered in this model. Then, authors compared the theoretical calculation formula with the existing empirical formula and theoretical formula to verify the feasibility of the presented calculation model in this paper. This model can provide theoretical reference for the design and construction of polar region icebreakers.

KEY WORDS: Ice action; Icebreaker; Semi-infinite beam; Infinite beam; Theoretical analysis.

INTRODUCTION

With the scientific expedition of polar regions, the exploitation of oil and gas resources and the development of Arctic summer navigation, recently, the structural design and shipping performance analysis of ships in the ice area have realized exceedingly severe by an increasing number of people. In the case of interaction between the sea ice and the ship, the method of reasonably determining ice load plays a crucial role for the structural design and safe navigation of ship. (Ji Shunying, et al., 2013) How to calculate the load of icebreaking resistance and judge the mode of action of the icebreaking resistance, which directly affects the safety of the icebreaker and the structure. For the navigation of icebreaker in the ice area, the load of icebreaking resistance has not only complicated relationship with the physical and mechanical characteristics of sea ice and the fracture mode of sea ice, but also has relationship with the size of the icebreaker and the way of breaking ice. Considering the design and construction of icebreakers, the determination methods of sea ice resistance are mostly based on the the Lindqvist formula and the Riske formula. (Yu Chenfang, et al. 2018)

Firstly, in view of the interaction between the icebreaker and the level ice, in this paper, the layer of level ice on the water is considered as the superimposed combination between the semi-infinite long beam along the advancing direction of the icebreaker on the elastic foundation and the infinite long beam perpendicular to the advancing direction of the icebreaker. Then, the model of calculating of icebreaking resistance is established by using the Moor Coulomb failure criterion. Thus the theoretical formula of calculation for the icebreaking resistance of the icebreaker can be obtained. Finally, based on the results of comparing the theoretical formula of calculation derived and existing formula of calculation for icebreaking resistance, we analyzed the similarities and differences between the results.

THE MODEL OF CALCULATION FOR ICEBREAKING RESISTANCE OF ICEBREAKER

The navigation of icebreaker in the ice area includes the following processes. Firstly, the icebreaker gradually contacts with ice layer. As time goes on, the ice layer begins to squash and tilt toward the bottom of the icebreaker. Then, when the stress in the ice layer reaches the bending strength of the ice, the ice layer is broken and forms crushed ice. Finally, the crushed ice slides along the bow of the icebreaker to the bottom of the icebreaker until it slips to the bottom of the icebreaker. Based on the process of destruction between the icebreaker and sea ice, the level ice layer on the water is regarded as the superimposed combination between the semi-infinite long beam along the advancing direction of the icebreaker on the elastic foundation and the infinite long beam perpendicular to the advancing direction of the icebreaker, and the buoyancy of water to ice is displaced by the reaction of the elastic foundation.

In this paper, the icebreaking resistance between the sea ice and the icebreaker consists of three parts. The first part is the ice force caused by the bending failure of sea ice during the process of contact between icebreaker and sea ice. The second part is the action of broken ice on the underwater bow, when the broken ice slide from the bow to bottom of icebreaker. The third part is the action of the broken ice falling into the bottom of the icebreaker.

1. The ice force caused by bending failure

Figure 1 shows the analysis model. The forces of the icebreaker colliding with the sea ice include two parts as shown in model. The first one is vertical force *P*, and the other one is horizontal force *H*. In order to find the relationship between these two forces, the normal force *N* and the tangential force *S* are introduced in this paper.

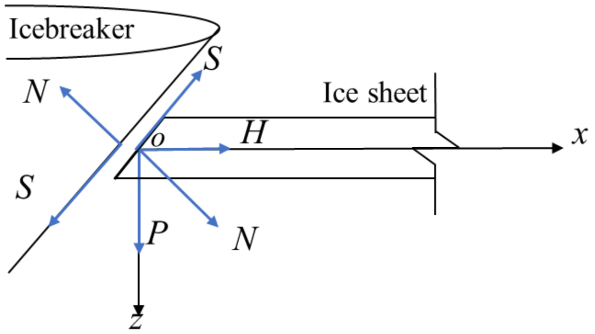

Figure 1. The force model between the icebreaker and the sea ice.

According to the balance principle of force, the relationship between the above forces is:

$$H = N\sin\alpha + S\cos\alpha \tag{1}$$

$$P = N\cos\alpha - S\sin\alpha \tag{2}$$

According to the principle of friction, the relationship between the horizontal force *H* that is caused by the interaction between the sea ice layer and the icebreaker and the vertical force *P* is:

$$H = N\sin\alpha + \mu N\cos\alpha \tag{3}$$

$$P = N\cos\alpha - \mu N\sin\alpha \tag{4}$$

Where μ is dynamic friction coefficient, and α is the dip of bow of icebreaker.

Further, the relationship of horizontal force *H* and the vertical force *P* can be obtained:

$$H = \frac{\sin\alpha + \mu\cos\alpha}{\cos\alpha - \mu\sin\alpha} P = \zeta P \tag{5}$$

$$\zeta = \frac{\sin\alpha + \mu\cos\alpha}{\cos\alpha - \mu\sin\alpha} \tag{6}$$

In order to determine the load of the icebreaker on the layer of sea ice, the layer of sea ice is considered as the superimposed combination between the semi-infinite long beam along the advancing direction of the icebreaker on the elastic foundation and the infinite long beam perpendicular to the advancing direction of the icebreaker. Then, we divide the vertical force *P* into the force P_1 acting on a semi-infinite long beam along the advancing direction of the icebreaker and the force P_2 acting on an infinite long beam perpendicular to the direction of the icebreaker. Thus, the *P*, P_1 and P_2 have the following relationship:

$$P = P_1 + P_2 \tag{7}$$

(1) The semi-infinite long beam along the advancing direction of the icebreaker

The forced state of the semi-infinite long beam is shown in Figure 2. The semi-infinite long beam has a width L and a thickness h, the semi-infinite long beam extends along the positive direction of the x-axis. The vertical force P_1 acts at the endpoint of the semi-infinite long beam. In this paper, we consider the buoyancy of sea water as the elastic foundation. Thus, the semi-infinite long beam is supported by the elastic foundation.

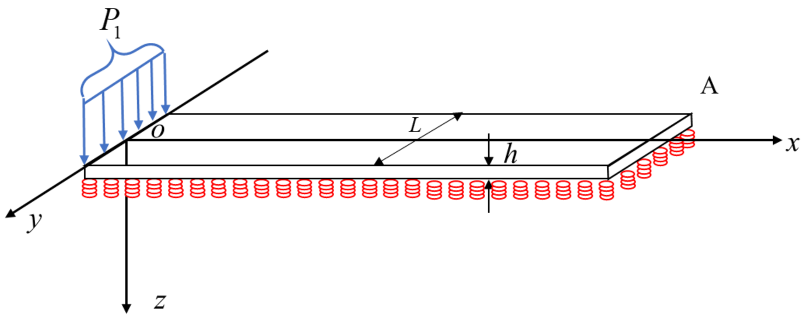

Figure 2. The force state of the semi-infinite long beam.

When studying the deflection curve of a semi-infinite long beam acting on the elastic foundation, the general representation of the deflection curve is:

$$z_A = e^{\beta_A x}\left(A\cos\beta_A x + B\sin\beta_A x\right) + e^{-\beta_A x}\left(C\cos\beta_A x + D\sin\beta_A x\right) \tag{8}$$

The formula of coefficient β_A is:

$$\beta_A = \frac{1}{l_c} \tag{9}$$

Where l_c is the characteristic length of the sea ice, and the formula of it is:

$$l_c = \left(\frac{Eh^3}{12\rho_w g\left(1-v^2\right)}\right)^{\frac{1}{4}} \tag{10}$$

Where E is the elastic modulus of sea ice, h is the thickness of sea ice, g is the acceleration of gravity, ρ_w is the density of sea water and v is the Poisson ratio of sea ice.

Because the deflection and bending moment tend to zero as the distance x increases, based on the initial condition of coordinate origin, we can take the constant A=B=0, then the constants C and D are:

$$\begin{cases} C = \dfrac{P_1}{2\beta_A^3 EI_A} \\ D = 0 \end{cases} \tag{11}$$

Where I_A is the sectional moment of inertia of the semi-infinite long beam, and it can be calculated by:

$$I_A = \left(\frac{Lh^3}{12}\right) \tag{12}$$

Therefore, the expression of the deflection curve of a semi-infinite long beam acting on an elastic foundation is:

$$z_A = \frac{P_1 e^{-\beta_A x} \cos \beta_A x}{2\beta_A^3 EI_A} \tag{13}$$

Further, the expression of the bending moment is:

$$M_A = -\frac{P_1}{\beta_A} e^{-\beta_A x} \sin \beta_A x \tag{14}$$

(2) The infinite long beam perpendicular to the advancing direction of the icebreaker

Figure 3 shows the force state of the infinite long beam. The infinite long beam has a width l_c and a thickness *h*. The width of the uniform load is defined as *L* extending along the positive and negative direction of the *y*-axis.

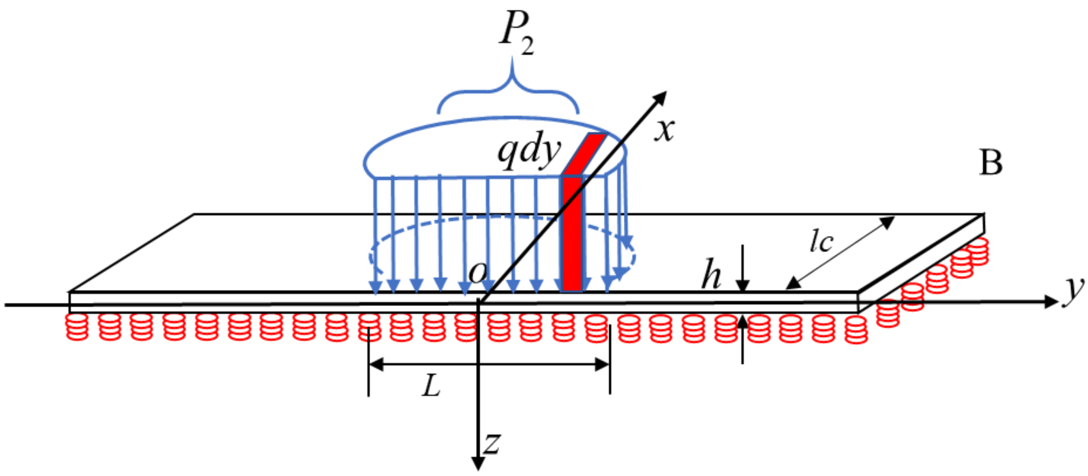

Figure 3. The force state of the infinite long beam.

In order to solve the deflection equation of the infinite beam, this paper considers the uniform load of length *L*. We study the arbitrary point *B*, and denote the specific position of point *B* by *b* and *c*, as shown in Figure 3. Using *qdy* displaces the load P_2, the deflection produced by the element of load *qdy* at point *B* is:

$$dz = \frac{qdy}{8\beta_B^3 EI_B} e^{-\beta_B y} \left(\cos \beta_B y + \sin \beta_B y\right) \tag{15}$$

Where *L* is the width of the icebreaker at the contact of the icebreaker with the sea ice and I_B is sectional moment of inertia of the infinite long beam. The formula of I_B, *q* and β_B is:

$$\begin{cases} I_B = (\frac{l_c h^3}{12}) \\ q = \frac{P_2}{L} \\ \beta_B = \frac{1}{l_c} \end{cases} \tag{16}$$

Therefore, we can integrate the formula (12) over the entire uniform load length *L*, and obtain the deflection of the load uniformly distributed over the length at the point *B*:

$$z_B = \int_0^b \frac{qdy}{8\beta_B^3 EI_B} e^{-\beta_B y}\left(\cos\beta_B y + \sin\beta_B y\right) + \int_0^c \frac{qdy}{8\beta_B^3 EI_B} e^{-\beta_B y}\left(\cos\beta_B y + \sin\beta_B y\right)$$
$$= \frac{P_2}{8EI_B\beta_B^4 L}\left(2 - e^{-\beta_B b}\cos\beta_B b - e^{-\beta_B c}\cos\beta_B c\right) \tag{17}$$

Taking $c = L/2$ 和 $b = L/2$, we can obtain the formula of bending moment:

$$M_B = \frac{P_2}{2\beta_B^2 L} e^{-\beta_B L/2}\sin\beta_B \frac{L}{2} \tag{18}$$

(3) Superimposed combination

The relationship between P_1 and P_2 can be obtained based on the same deflection the contact icebreaker and sea ice respectively. Then, the relationship between P_1 , P_2 and P is determined by equation (15):

$$\frac{P_1}{P_2} = \frac{\beta_A^3 EI_A (1 - e^{-\beta_B \frac{L}{2}}\cos\beta_B \frac{L}{2})}{2EI_B\beta_B^4 L} = f \tag{19}$$

$$\begin{cases} P_1 = \dfrac{f}{f+1}P \\ P_2 = \dfrac{1}{f+1}P \end{cases} \tag{20}$$

When the sea ice layer interacts with the icebreaker, the sea ice layer failure is mainly divided into two types: the annular failure and radial failure. In order to determine the ice breaking resistance, the stress state at the beginning of the annular and radial crack fracture is considered and analyzed. The Figure 4 shows the stress state of micro-body. In this method, σ_A represents the bending stress under the action of the moment M_A, σ_B represents the bending stress under the action of the moment M_B, and σ_H represents the compressive stress under the action of the horizontal force H.

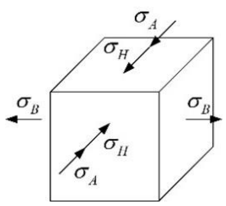

Figure 4. The stress micro-body.

The principal stress of the stress micro-body is:

$$\sigma_1 = \frac{-\sigma_A - \sigma_H + \sigma_B}{2} + \frac{1}{2}\sqrt{\left(-\sigma_A - \sigma_H - \sigma_B\right)^2} = \sigma_B \tag{21}$$

$$\sigma_3 = \frac{-\sigma_A - \sigma_H + \sigma_B}{2} - \frac{1}{2}\sqrt{\left(-\sigma_A - \sigma_H - \sigma_B\right)^2} = -\sigma_A - \sigma_H \tag{22}$$

The mohr-coulomb criterion can be used in the sea ice failure model. (Sveinung Loset, et al., 2006), Ji Shunying (Ji Shunying, et al., 2004) also adopted the mohr-coulomb failure criterion to describe the sea ice destruction process and obtained good results. In this paper, the mohr-coulomb failure criterion was used to simulate the sea ice failure process.

For the stress micro-body:

$$\begin{cases} -\sigma_A - \sigma_H = -f_c^{'} + m\sigma_B \\ m = f_c^{'} / f_t^{'} \end{cases} \tag{23}$$

Where $f_c^{'}$ is the simple compression strength of sea ice, and $f_t^{'}$ is the simple tensile strength of sea ice.

That is:

$$f_c^{'} = \frac{|M_A|}{W_A} + \frac{H}{Lh} + m\frac{|M_B|}{W_B} \tag{24}$$

Then:

$$P = \frac{f_c^{'}}{A_1 e^{-\beta_A x} \sin \beta_A x + A_2 + A_3} \tag{25}$$

Where

$$\begin{cases} A_1 = \dfrac{\dfrac{f}{f+1}}{\dfrac{1}{6}Lh^2\beta_A} \\ A_2 = \dfrac{\zeta}{Lh} \\ A_3 = m\dfrac{\dfrac{1}{f+1}e^{-\beta_B L/2}\sin\beta_B L/2}{\dfrac{1}{3}l_c h^2 \beta_B^2 L} \end{cases} \tag{26}$$

In this paper, the value of x is obtained when the bending moment of the semi-infinite long beam is largest. Thus, we can get the formula: $dM_A/dx = 0$. At this time, there is the following value $x = \pi/(4\beta_A)$. Then the vertical force P is obtained as follow:

$$P = \frac{f_c^{'}}{A_1 e^{-\frac{\pi}{4}} \sin\left(\frac{\pi}{4}\right) + A_2 + A_3} \tag{27}$$

Horizontal force H is:

$$H = \zeta P = \zeta \frac{f_c^{'}}{A_1 e^{-\frac{\pi}{4}} \sin\left(\frac{\pi}{4}\right) + A_2 + A_3} \tag{28}$$

2. The force of sea ice debris on the bow under the water

The force on the icebreaker comes from sea ice debris that are totally submerged, the force achieves maximum when sea ice debris all cling to the tilted sloping bow. We can perform a force analysis on the bow to calculate the force of the icebreaker on sea ice. (horizontal force H_1 and vertical force P_1)

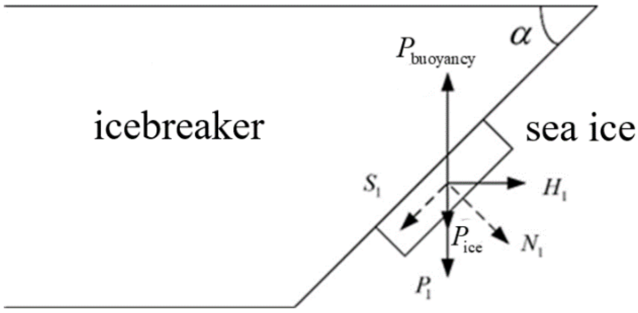

Figure 5. The action of ice at the bow

Calculated the vertical force P_1 is:

$$P_1 = L\frac{\pi}{4}l_c hg\rho_w - L\frac{\pi}{4}l_c hg\rho_i \tag{29}$$

In the formula of P_1 : ρ_i——the density of sea ice.

It is obtained from Figure 5 that since the ice dynamics is not considered herein, the horizontal force H_1 is zero according to the equilibrium condition of the force in the static force.

3. The force of sea ice debris on the bottom of the icebreaker

When sea ice debris achieve the bottom of the icebreaker, the force of the icebreaker is divided into horizontal force H_2 and vertical force P_2, as shown in Figure 6.

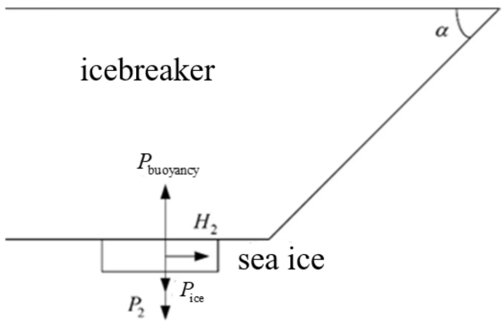

Figure 6. The action of ice at the bottom of the ship

Calculated the vertical force P_2 is:

$$P_2 = L\frac{\pi}{4}l_c hg\rho_w - L\frac{\pi}{4}l_c hg\rho_i \tag{30}$$

Calculated the horizontal force H_2 is:

$$H_2 = \mu\left(L\frac{\pi}{4}l_c hg\rho_w - L\frac{\pi}{4}l_c hg\rho_i \right) \tag{31}$$

Since the interaction force between sea ice and icebreaker is the relationship between force and reaction force, the total resistance to ice breaking and the force received by sea ice are equal and opposite.

4. Ice-breaking resultant force of icebreaker

Through the above analysis, the total ice-breaking resistance force of the icebreaker can be obtained. The maximum value of the total ice-breaking resistance can be obtained by superimposing the forces in each stage, there are sea ice debris in each stage, then the vertical force P_r of the total ice-breaking resistance is:

$$P_r = \frac{f_c^{'}}{A_1 e^{-\frac{\pi}{4}} \sin\left(\frac{\pi}{4}\right) + A_2 + A_3} + L\frac{\pi}{2}l_c hg\left(\rho_w - \rho_i\right) \tag{32}$$

The horizontal force H_r of the total ice-breaking resistance is:

$$H_r = \zeta \frac{f_c^{'}}{A_1 e^{-\frac{\pi}{4}} \sin\left(\frac{\pi}{4}\right) + A_2 + A_3} + \mu L\frac{\pi}{4}l_c hg\left(\rho_w - \rho_i\right) \tag{33}$$

RESULTS AND COMPARISONS

In order to test the feasibility of the calculation model in this paper, the ice load calculation method and theoretical calculation model of the icebreaker such as the commonly used, Lindqvist formula and Riske formula are used for comparison. Figure 7 shows the comparison of ice resistance calculated by existing formulas and calculation model in this paper under different ice thickness. As it can be seen from figure 7, with the increase of ice thickness, the icebreaker's ice-breaking resistance gradually increases. Figure 8 shows the comparison of ice resistance calculated by the existing formulas and calculation model in this paper under different stem inclination angles. Figure 8 shows that the inclination Angle of the stem changes from 20 degrees to 30 degrees, and the icebreaking resistance of the icebreaker slowly increases. Figure 7 and Figure 8 show that the change trend of the ice-breaking resistance calculated by the theoretical calculation model in this paper is consistent with the calculation results of the existing formulas. The calculation result of the theoretical calculation model in this paper is more conservative because it is slightly larger than those of the existing formulas.

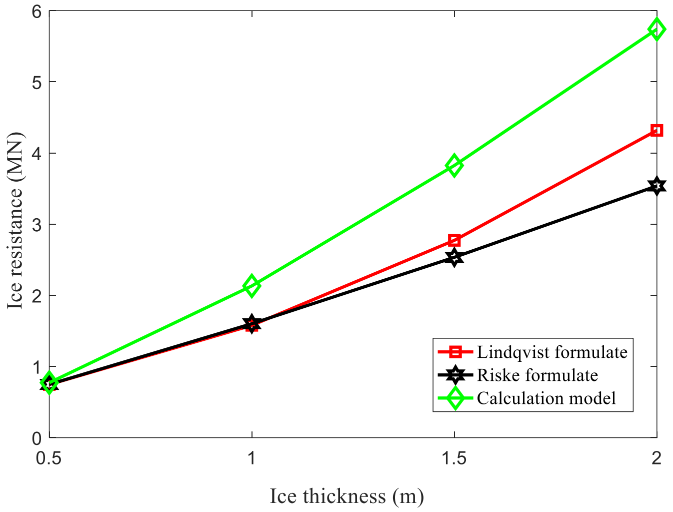

Figure 7. The comparison of ice resistance calculated by existing formulas and calculation model in this paper under different ice thickness.

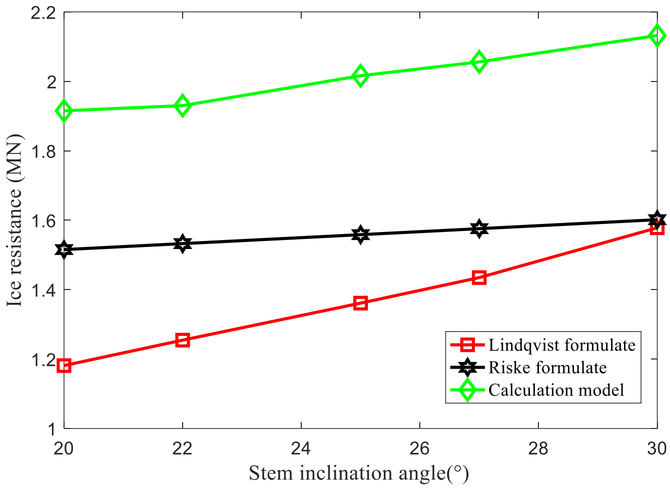

Figure 8. The comparison of ice resistance calculated by the existing formula and calculation model under different stem inclination angles.

CONCLUSION

Based on the elastic foundation beam theory, for the interaction process between icebreaker and flat ice, this paper considers the flat ice above the surface of the water is considered as the superposition combination of the semi-infinite beam along the direction of the icebreaker on the elastic foundation and the infinite beam perpendicular to the direction of the icebreaker. In addition, this paper built the ice-breaking resistance force calculation model and achieved the theoretical calculation formulas of the ice-breaking resistance force by using Mohr coulomb failure criteria and the comparison with the existing ice-breaking resistance force of the icebreaker calculation formula is compared. The comparison results verify the feasibility of this calculation model, and provide a theoretical reference for the calculation of ice load for the structural design of the icebreaker in the polar region.

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REFERENCES

Ji Shunying, Li Zilin, Li Chunhua, Zhang Lin, 2013. Analysis of interaction between ice floe and ship hull with discrete element method in broken-ice field. *Chinese Journal of Applied Mechanics*, 30(4), pp. 521-526.

Yu Chenfang, Lu Liebiao, Liu Weidong, 2018. Research on ice resistance Estimation Method for icebreakers. Ship *Standardization Engineer*, 4, pp.74-81.

Sveinung Loset, Karl N. Shkhinek, Ove T. Gudmestad, Knut V. Hoyland, 2006. *Actions from ice on Arctic offshore* and *coastal structures*. LAN: St. Petersburg.

Ji Shunying, Shen Hungtao, Wang Zhilian, Shen Hayley,Yue Qianjin, 2005. A viscoelastic plastic constitutive model with Mohr-Coulomb yielding criterion for ice dynamics. *Acta* Oceanologica Sinica, 27(4), pp. 19-30.