Research on a new-type caisson with conic ice resistant structure in wharf application

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Abstract. Wharf structure in frozen areas is easily influenced by the heavy ice load and therefore it is necessary to adopt anti ice strategy in wharf construction. The conventional ice resistant strategies generally include designing the structure by using the extreme ice load and using solid structures in the ice-affected parts, which make the structure investment cost high due to the large ice load. To resolve above problems, this paper proposes a new type of ice resistant structure, namely the round caisson with conic ice resistant structure. The structure can transform failure type of the flow ice from compressive failure to bending failure, which can greatly reduce the ice load and therefore the project investment. To validate the ice resistant effect of the structure, a comparation of the ice load of the proposed structure with non-conic structure is conducted by mathematical calculation, and this paper develops a physical model experiment considering the natural condition of Changxing Island Port Area. The results obtained from above experiments show that (1) the measured ice load obtained by model experiment is reduced, (2) and the ice load on the conic ice resistant structure is much smaller than that on the non-conic structure.

1. Introduction

In recent years, with the development of specialized, large-scale and deep-water ports, the port sites have been gradually transferred from the nearshore sea area to the open sea area, where the environmental conditions are more complex and worse. In the open frozen areas, ice load has become a main control load when designing and constructing the wharf. Due to the severely frozen and open marine circumstances in Changxing Island Port Area, wharf structures can be damaged greatly by the heavy ice load, and structural safety and stability are hard to guarantee. On the one hand, the initial investment of port construction increases sharply due to the conservative design considering the large ice load. On the other hand, the wharf structure can be seriously destructed if severe ice load is not fully considered. Therefore, it is urgent to study the economically and technically feasible ice resistant strategy for constructing wharf structure faced with severely frozen and open environmental conditions in Changxing Island Port Area.

Ice load is the main environmental factor that influences safe operation and maintenance of ports in frozen area. The study of ice load originally concentrated on the effect of sea ice on marine navigation, and began in the early 19th century [1]. Subsequently, the researches turned into the interactive force between the sea ice and offshore oil platforms, wharf structures and artificial islands. The damage effect of sea ice on offshore buildings mainly depends on the damage mode of sea ice, mainly consisting of
static compression damage, bending and flexion. And among these damage modes, static compression damage is the most harmful to the structure [2]. At present, there are many researches on the ice resistant structure of offshore platforms, and the design method of ice resistant structure has been put forward and applied successively [3-4]. Ice resistant structure can be divided into two categories: ice breaking structures and ice protection structures. Most of the ice resistant structures are pile or pile combination structures and gravity structures with inclined plane, which are placed in front of the protected structure [5]. The main functions of ice resistant structures are to break flow ice and prevent the ice from directly contacting with the protected structure to reduce ice load. Jochmann and Evers analyzed the ice resistant performance of pile row structure suitable for shallow water through experiments [6]. Gurtner and Berger conducted a comparative experimental study on vertical row piles and inclined row piles in shallow sea area, and pointed out that inclined row piles have better effects than vertical row piles under the same pile spacing [7]. Besides, Zhang and Yue [8] analyzed the ice loads on vertical and conical structures and pointed out that the ice load on a conical structure is much smaller than the load on a cylindrical structure with the same diameter. Xu proposed to design a cone structure on the surface of the offshore platform structure, transforming the compression failure mode of the sea ice into a bending failure mode to reduce the ice load [9].

However, there are few researches on ice resistant strategies for wharf structures. Based on analyzing the site selection and structure type of the wharf in the frozen area, Meng pointed out that the current ice resistant strategies mainly include the following aspects: 1) While designing and constructing the wharf structures, the ultimate ice load acting on the structures should be fully considered and adopted. 2) Without influencing the normal use of the wharf structures, the ice-facing surface of the structures should be designed to slope or cone. 3) The part of the wharf structures affected by the ice load should be designed to solid structure [10]. The mooring pier structure of the 300,000-ton oil terminal in Caofeidian Port Area are designed with concrete circular truncated cones as an ice resistant structure [11], which has been proved to resist greatly the heavy load of severe flow ice in winter.

Most researches on ice resistant strategies are focused on offshore platform structures, including the structure form, ice resistant effect and applicable conditions of the strategies. However, there are few researches on ice resistant strategies for wharf structures. This paper proposes a new type of ice resistant structure, namely the round caisson with conic ice resistant structure. To validate the ice resistant effect of the structure, a comparation of the ice load of the proposed structure with non-conic structure is conducted by mathematical calculation, and this paper develops a physical model experiment considering the natural condition of Changxing Island Port Area.

2. Mathematical calculation of ice load
The following analysis on ice load involves a round caisson with conic ice resistant structure and a round caisson without conic structure, and the geometrical dimensions of these caissons are shown in figure 1 and figure 2. Considering the natural environment where the 300,000-ton oil terminal is located in Changxing Island Port Area, this paper takes the thickness, compressive strength, bending strength, velocity and attacking angle of ice as the ice condition characteristics. Besides, this paper study the effect of water level on the ice load on the terminal structure. In this paper, the thickness of ice is set as 476 mm, and the compressive strength and bending strength of ice is set as 2350 kPa and 835 kPa, respectively. The velocity of ice is set as 1800 mm/s, 1500 mm/s, 750 mm/s, 250 mm/s. In addition, the attack angle of ice is set as 0°.
In order to compare the ice resistant effect of the proposed structure with non-conic structure, this paper adopts the mathematical calculation method of ice load on conic structure and non-conic upright structure in Load Code for Harbor Engineering, JTS 144-1-2010.

2.1. Ice load calculation of conic structure

The conic ice resistant structure studied in this paper is a frustum of a cone structure set on the basis of the round caisson to reduce the flow ice load. Conic ice resistant structure generally causes bending failure of flow ice, and the calculation formula of the ice load acting on this kind of structures is as follows:

\[ F_{v1} = B_1 F_{H1} + B_2 \gamma \sigma H \left( D^2 - D_f^2 \right) \]  
\[ F_{H1} = \left[ A_1 \sigma_f H^2 + A_2 \gamma \sigma H D^2 + A_3 \gamma \sigma H \left( D^2 - D_f^2 \right) \right] A_4 \]

where \( F_{H1} \) is the horizontal ice load acting on the positive cone surface and \( F_{v1} \) is the vertical ice load standard value, kN. \( A_1 \), \( A_2 \), \( A_3 \) and \( A_4 \) are the dimensionless coefficients. \( \sigma_f \) is the standard value of ice bending strength, kPa. \( H \) is the calculation thickness of single layer flat ice, m. \( \gamma \) is the seawater gravity, kN/m³. \( D \) is the diameter of the cone at the surface of the sea, m. \( H \) is the
climbing height of the ice, m. $D_T$ is the diameter of the surface on the cone, m.

### 2.2. Ice load calculation of non-conic upright structure

The non-conic upright structure generally causes compressive failure of flow ice, and the calculation formula of the ice load acting on this kind of structures is shown as follows:

$$ F_I = I_m k B H \sigma_c $$  \hspace{1cm} (3) 

where $F_I$ is the standard value of extreme ice load, kN. $I$ is the local extrusion coefficient of the ice. $m$ is the shape coefficient of the pier surface. $k$ is the contact condition coefficient between the ice and the pier. $B$ is the width of the pier ice projection, m. $H$ is the calculation thickness of single layer flat ice, m. $\sigma_c$ is the standard value of uniaxial compressive strength of ice, kPa.

### 2.3. Calculation results

By using the calculation methods shown in section 2.1 and 2.2, the ice loads on the round caisson with conic ice resistant structure and the non-conic upright structure are obtained and the calculation results are compared, as shown in table 1 and table 2.

| Water level                | $F_{IH}$ (kN) | $F_V$ (kN) | $M_{FHI}$ (kN m) | $M_{FV}$ (kN m) |
|----------------------------|---------------|------------|------------------|-----------------|
| Design high water level    | 2560.4        | 1296.6     | 72587.8          | 20083.6         |
| Design low water level     | 5175.9        | 2667.7     | 135763.2         | 45538.1         |
| Extreme low water level    | 6958.6        | 0          | 171181.2         | 0               |

| Water level                | $F_I$ (kN)   | $M_{FI}$ (kN m) |
|----------------------------|--------------|-----------------|
| Design high water level    | 7393.5       | 211365          |
| Design low water level     | 7393.5       | 195691          |
| Extreme low water level    | 7393.5       | 183640          |

From table 1, it can be seen that the horizontal ice load in extreme low water level is maximum, and the value is 6958.6 kN, followed by the value in design low water level and design high water level. And the value of $M_{FHI}$ shows the same change pattern with the value of $F_{IH}$. As shown in table 2, the value of $F_I$ is 7393.5 kN in all the design water level. Besides, the value of $M_{FI}$ reduces with the increase of the value of $F_I$, and the maximum and minimum value of $M_{FI}$ is 211365 kN m and 183640 kN m, respectively.

Comparing the results in table 1 and table 2, it can be obtained that the ice load on the conic ice resistant structure is much smaller than that on the non-conic upright structure. This is because the conic ice resistant structure can transform the failure type of flow ice from compressive failure to bending failure, which can greatly reduce the ice load on the wharf structures. Therefore, for the design of the 300,000-ton wharf structures in Changxing Island Port Area where is severely frozen, the conic ice resistant structure works better in terms of ice resistant effect.

### 3. Physical model experiments

To validate the ice load on the round caisson with conic ice resistant structure by mathematical calculation, this paper develops a physical model experiment. Through the physical model experiment, the ice load on the round caisson structure is measured, and the ice resistant effect is analyzed.

#### 3.1. Model scale

Froude and Cauchy similarity criteria are used to scale the round caisson structure, and the geometric
scale $\lambda$ is set as 1:25. The geometric scales of the main physical characteristics in the experiment are shown in table 3, and the experiment model of the round caisson structure according to the appropriate geometric scale, are shown in figure 3.

| Physical characteristics | Geometric scale | Physical characteristics | Geometric scale |
|--------------------------|----------------|--------------------------|----------------|
| Length                   | $\lambda$     | Strength of ice          | $\lambda$     |
| Time                     | $\lambda^{1/2}$| Thickness of ice         | $\lambda$     |
| Velocity                 | $\lambda^{1/2}$| Modulus of Elasticity    | $\lambda$     |
| Mass                     | $\lambda^3$   | Ice load                 | $\lambda^3$   |

Figure 3. The experiment model of the round caisson with conic ice resistant structure.

3.2. Experiment settings of ice conditions in Changxing Island Port Area
According to the value of ice conditions in Changxing Island Port Area shown in section 2, this paper determine the experiment settings of ice conditions by using the geometric scale, as shown in table 4.

| Parameters                              | Prototype | Experiment model                      |
|-----------------------------------------|-----------|---------------------------------------|
| Thickness of ice (mm)                   | 476       | 19.04                                 |
| Compressive strength of ice (kPa)       | 2350      | 94                                    |
| Bending strength of ice (kPa)            | 835       | 33.4                                  |
| Velocity of ice (mm/s)                  | 1800, 1500, 750, 250 | 360, 300, 150, 50                    |
| Water level                             | Design high water level, design low water level and extreme low water level |
| Attack angle of ice                     | $0^\circ$ |                                       |

3.3. Experiment results
After conducting the experiments, the ice load on the round caisson structure is measured and the time interval curve of ice load is obtained, as shown in figure 4-figure 6. And the measured ice load on the round caisson structure based on the geometric scale conversion is shown in table 5.
Figure 4. The time interval curve of ice load in the design high water level.

Figure 5. The time interval curve of ice load in the design low water level.

Figure 6. The time interval curve of ice load in the extreme low water level.

| Water level            | Measured ice load (kN) |
|------------------------|------------------------|
| Design high water level | 660.9                  |
| Design low water level  | 740.6                  |
| Extreme low water level | 2948.4                 |

As shown in figure 4 and figure 5, the failure type of flow ice is bending failure. Besides, the failure type of flow ice is compressive failure, as illustrated in figure 6. From the results in table 5, it can be drawn that (1) the maximum ice load on the round caisson structure appears in extreme low water level, and the maximum ice load is 2948.4 kN, (2) and the measured ice loads on the round caisson structure in the design high water level and design low water level are similar, which are 660.9 kN and 740.6 kN, respectively. The measured ice loads on the round caisson structure in the design high water level and design low water level are much smaller than the ice load in the extreme low water level.

The results obtained above state that the round caisson with conic ice resistant structure can transform the failure type of flow ice from compressive failure to bending failure, which can greatly reduce the ice load. Besides, compared with the ice load obtained by mathematical calculation, the ice load measured by experimental model is correspondingly smaller.

4. Conclusions
The contribution of this paper is to study the ice resistant effect of the conic ice resistant structure by
physical model experiment and mathematical calculation considering the severely frozen environmental conditions in Changxing Island Port Area. Firstly, the structural characteristics of the conic ice resistant structure and ice conditions are analyzed. Then, a mathematical calculation method of ice load is presented to compare the ice resistant effect of the proposed structure with non-conic structure. Finally, physical model experiments are designed to obtain the measured ice load on the conic ice resistant structure to validate the ice resistant effect of the structure.

(1) Compared with calculation results of ice load on the non-conic upright structure, the calculation results of ice load on the conic ice resistant structure are much smaller.

(2) The measured ice loads on the round caisson with conic ice resistant structure obtained by physical model experiments reduce with the increase of the design water level.

(3) The calculation results of ice load on the round caisson structure are much larger than the measured results by physical model experiments. It is a need to design the round caisson structure by combining with the calculation results and experimental results.

(4) According to the calculation and experimental results, the use of conical ice resistant structure caisson in Changxing Island Port Area in severely frozen areas is superior to that of non-conical structures.

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References
[1] Leppäranta M. The Drift of Sea Ice [M]. Second Edition. Heidelberg, Germany: Springer Verlag, 2011.
[2] Zhang FJ, Fei LS. SEA ICE DISASTERS AND DEFENCE MEASURES TAKEN IN CHINA [J]. Marine Science Bulletin, 1994 (05): 75-83.
[3] Gurtner A, Gudmestad OT, Torum A, et al. Innovative ice protection for shallow water drilling - Part I: Presentation of the concept [C]. Proceedings of the 25th International Conference on Offshore Mechanics and Arctic Engineering, 2006 (2): 709-715.
[4] Barker A, Timco G. Overview of ice rubble generators and ice protection structures in temperate regions [C]. Proceedings of the International Conference on Port and Ocean Engineering under Arctic Conditions, POAC, 2005: 793-804.
[5] JW Dong. Physical simulation of sea ice action against cylindrical-piles and inclined structures and their ice protection structures [D]. Dalian University of Technology, 2012.
[6] Jochmann P, Evers KU, Kuehnlein WL. Model testing of ice barriers used for reduction of design ice loads [C]. Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE, 2003 (3): 815-821.
[7] Gurtner A, Berger J. Results from model testing of ice protection piles in shallow water [C]. Proceedings of the 25th International Conference on Offshore Mechanics and Arctic Engineering, 2006 (2): 693-698.
[8] Zhang DY, Yue QJ. Major challenges of offshore platforms design for shallow water oil and gas field in moderate ice conditions [J]. OCEAN ENGINEERING, 2011, 38(10): 1220-1224
[9] Xu N. Research on ice force of conical offshore structures [D]. Dalian University of Technology, 2011.
[10] Meng FZ. Structures and ice resistant measures of wharf in frozen area (Chinese Version) [J]. China Water Transport, 2015 (03): 44-45.
[11] MU S, ZHU H, CHEN JF. Application of conic ice resistant structure in wharf main structure [J]. Port & Waterway Engineering, 2010 (09): 69-72.