Research on the overall bearing behavior characteristics of the all-vertical-piled wharf under horizontal load

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Abstract: Based on the ANSYS model, the simulation analysis of the all-vertical-piled wharf is carried out. It is found that the zero point of the pile displacement of the all-vertical-piled wharf is about 6 times the depth of the pile width (pile diameter) below the mud surface. The difference in pile displacement changes under various working conditions below this position is very small, and the pile displacement above this position is positively correlated with the horizontal load. Through research, the pile displacement curve and load-displacement curve of the all-vertical-piled wharf are constructed, and the method for determining the overall ultimate bearing state of the all-vertical-piled wharf is established. The research results can provide a reference for the study and judgment of the overall bearing safety of the all-vertical-piled wharf under horizontal load.

1. Introduction

The all-vertical-piled wharf has the characteristics of simple structure, good wave reduction and wave cutting effect, and adapts to the large-scale offshore deep water. It has become a type of high-piled wharf and it is widely used in open seas and inland rivers. The main loads of high-piled wharf structures are horizontal loads caused by wave load, current load, wind load and ship load [1]. Ship load is often the controlling horizontal load of high-piled wharves in the open sea, which is one of the main reasons for the deformation and damage of high-piled wharves. Therefore, this article mainly studies the characteristics of the overall load-bearing behavior of the all-vertical-piled wharf and the judgment method of the overall ultimate bearing state of the all-vertical-piled wharf under the horizontal load of the ship.

At present, domestic and foreign scholars mainly use the methods of finite element simulation analysis and model test to study the working behavior of high-piled wharfs. Xie et al. [2] simulated and analyzed the high-piled wharf model of fork-pile combinations with different cross-sectional dimensions and slopes under a variety of loads, and proposed the lateral load-horizontal displacement formula of single pile and high-piled wharf. Wang et al. [3] studied the all-vertical-piled wharf, solved the p-y curve by using the finite difference method, obtained a method for calculating the ultimate bending moment of the all-vertical-piled wharf, and verified it with engineering examples and ANSYS calculation results. Liu and Zhang [4] used ANSYS finite element analysis software and Monte Carlo
method to analyze the reliability of the high-piled wharf under the impact of the ship. Liu and Li [5] used a combination of mathematical theory derivation and dynamic time-history simulation calculation to study the dynamic response and dynamic amplification effect of the high-piled wharf structure under the impact of berthing ships. Deb and Pal [6] used 3D finite element modeling to numerically analyze pile rows under combined vertical and lateral loads. Teramoto et al. [7] used 3D elastoplastic finite element method (FEM) to analyze and study the horizontal bearing capacity of large pile groups, and observed the load sharing of large pile foundations. Muthukkumaran and Arun [8] used the finite difference method to analyze the 3D modeling of a fixed offshore platform, and found that the lateral displacement of the pile top increases with the increase of the seabed slope. Fan and Yuan [9] developed a finite element model of ship-structure-soil interaction and determined four interaction stages, namely initial contact, approximate velocity load, unloading and free vibration. Bonakdar and Oumeraci [10] conducted a small-scale model test in a 2 m-wide wave flume to investigate the influence of pile groups on the wave load of slender piles, and tested different pile arrangements. Based on a high-piled wharf project, this paper considers the horizontal load of the ship, uses ANSYS finite element software to simulate the working behavior and bearing capacity of the all-vertical-piled wharf structure under horizontal load, and provides reference basis for engineering design and engineering safety research and judgment.

2. Engineering background and ANSYS model

2.1. Engineering background
It is a 50,000DWT all-vertical-piled wharf with a length of 300m and a width of 30m. The design high water level of the wharf is 3.66m, the design low water level is -3.04m, the design mud surface elevation of the wharf front is -17.20m, and the wharf surface elevation is 5.40m. The upper structure of the wharf is composed of concrete members such as beams, longitudinal beams, and panels. The lower pile foundation adopts 15mm thick steel pipe piles with a diameter of 1200mm, the pile length is 41.2m, and the pile foundation depth is 22.8m, the center distance between the first pile and the last pile is 26.16m, the pile foundation adopts an all-vertical-piled arrangement.

The upper beam of the wharf is an inverted T-shape, the upper beam size is 1.4m×2.0m×30.0m, the lower beam size is 1.8m×2.2m×30.0m, and the longitudinal beam section size is 0.6m×2.0m (middle longitudinal Beam) and 0.8m×2.0m (track beam), the thickness of the panel is 0.4m.

Based on the high-piled wharf design theory, one of the representative lateral bent frames can be used to simulate and analyze the working behavior of the all-vertical-piled wharf.

The engineering design ship type is 50000DWT bulk carrier. Its ship length L is 225m, type width B is 32.3m, type depth H is 18.0m, and full-load draft T is 13.0m. In this paper, the ship's controllable horizontal load is used as the representative horizontal load for the calculation. The load action method is uniformly loaded on the cross-beam section. The loading method is shown in Figure 1.
2.2. ANSYS model

The finite element simulation model is established with ANSYS software.

2.2.1. Basic assumptions of the model

1. In the model, the soil is isotropic, continuous and homogeneous, and the boundary conditions are given.
2. The pile and soil are elastoplastic, and the soil follows the Drucker-Prager Yield Criteria.
3. The elastic modulus and Poisson's ratio of the soil remain constant with the pile embedded in it.
4. The pile is a friction pile, and the material properties of the soil at the bottom of the pile are the same as those around the pile.

2.2.2. Pile foundation section treatment

The actual steel pipe pile section in the project is a circular (thin-walled annular) section with a wall thickness of 15mm. Considering the needs of modeling, using the method of equivalent mass and equivalent stiffness, the wall thickness of the steel pipe pile 15mm is magnified by 10 times to obtain a model pile wall thickness of 0.15m, the circular pile section is equivalently converted into a square section. After equivalence, the side length of the section of the pile in the model is 1.6m, the density of the pile is 503.6kg/m³, the elastic modulus of the pile is $6.68 \times 10^9$Pa.

The steel pipe pile in the model adopts the elastic-plastic model, the foundation pile steel is Q345 steel, and its yield strength is 345MPa. The constitutive relationship can adopt the elastic-plastic strengthening model. The elastoplastic strengthening model is a two-broken line model, which simplifies the stress-strain relationship of the steel after yielding into a gentle inclined straight line. The elastic modulus of the steel strengthening section can be taken as $E_0=0.01E$. According to the principle of equal strain, the equivalent constitutive relationship of Q345 steel is used in the model, its equivalent yield strength is 10.68MPa.

2.2.3. Model calculation parameters

In this paper, the all-vertical-piled single-bent structure is selected as the research object. The single-bent model is 5m on both left and right sides. The soil along the beam direction is 15 times the pile width, and the soil height is 2.5 times the insertion depth of the pile. The soil is homogeneous and
identical. The soil size of the single-bent model is 10m×76.8m×75.4m.

2.2.4. Contact surface setting
The pile-soil interaction in the high-piled wharf structure belongs to rigid-flexible contact. The pile should be set as the target surface, and the soil should be set as the contact surface. Select the part of the pile body into the soil and the bottom of the pile, use the target unit as the target unit, and use the contact unit as the contact unit.

3. Deformation analysis of single-bent frame model under ship load

3.1. Ship load calculation
The ship load mainly considers the ship impact force. The kinetic energy formula for berthing of a ship is calculated by the following formula:

\[ E_0 = \frac{1}{2} \rho m V_n^2 \]  

In the formula, \( E_0 \) is the effective impact energy generated by the collision of the ship. \( \rho \) is the effective kinetic energy coefficient, which is taken as 0.7-0.8. m is the mass of the ship (t), calculated according to the full-load displacement of the designed ship type. \( V_n \) (m/s) is the normal direction of the ship berthing speed.

If \( V_n \) is 0.15m/s, it is obtained that \( E_0 \) is 549.9kJ. The supporting project adopts TD-A1000H rubber fender, and the corresponding impact force is 500kN according to its performance curve. In the same way, if \( V_n \) is 0.25m/s, the impact force can be calculated to be 950kN.

3.2. Deformation analysis of bent frame model

3.2.1. Soil stress balance
In order to eliminate the influence of the initial soil stress on the numerical calculation of the model, the soil stress balance should be performed firstly. Gravity field is the main factor that produces initial soil stress. In order to make the foundation soil in a state without initial stress, a gravitational field is applied in the model beforehand, and then the initial soil stress is applied to the model for calculation, so as to balance the soil stress. After the soil stress is balanced, the initial vertical displacement of the soil is very small, with an order of \( 10^{-3} \), which can be ignored. The effect of zero displacement is achieved, and the initial stress of the soil is in a balanced state with the gravity force of the soil.

3.2.2. All-vertical-piled bent frame model
There are 6 piles in total in the all-vertical-piled horizontal bent model. The upper main structure beam adopts free grids, and the lower soil and piles adopt mapped grids. The piles start from the front of the dock platform and are numbered sequentially to the rear of the dock platform (1#pile to 6#pile). The bent frame model meshing is shown in Figure 2.
The deformation of the high-piled wharf structure mainly depends on the deformation of the pile foundation. A horizontal load of 500kN-4000kN is applied to the straight pile bent frame, and the load is gradually increased by 500kN each time.

Under the action of 1000kN horizontal load, the Y-direction displacement and stress distribution diagrams of the all-vertical-piled bent frame model are shown in Figure 3 and Figure 4.
Figure 3 and Figure 4, it is found that the displacement distribution of each pile in the bent structure is relatively close. The overall displacement shows a decreasing trend from the top of the pile to the bottom of the pile, the displacement of the upper structure is almost unchanged, and the maximum displacement of the bent frame is 0.084m. The stress distribution of each pile is also relatively similar, among which the stress near the top of the pile and near the mud surface are higher. The maximum stress of the pile body is 5.92 MPa, and the actual maximum stress after conversion is 191.24 MPa, which is less than the yield stress of Q345 steel, therefore the pile body is in an elastic state.

The load-bearing characteristics of the wharf bent under various horizontal loads are similar. The results are shown in Table 1.

| Horizontal load (kN) | Maximum displacement of the bent frame (m) | Calculated maximum stress of pile (MPa) | Actual maximum stress of pile (MPa) |
|----------------------|-------------------------------------------|----------------------------------------|-----------------------------------|
| 500                  | 0.040                                     | 3.48                                   | 112.42                            |
| 1000                 | 0.084                                     | 5.92                                   | 191.24                            |
| 2000                 | 0.195                                     | 10.1                                   | 326.26                            |
| 3000                 | 0.346                                     | 11.1                                   | 358.57                            |
| 4000                 | 0.677                                     | 12.1                                   | 390.87                            |

3.3. Analysis of the properties of all-straight pile bent frame

3.3.1. Pile displacement curve
Select the 3# pile in the model and get the pile displacement under four loads of 1000kN, 2000kN, 3000kN, and 4000kN. The pile displacement curve is shown in Figure 5.
Figure 5. The pile displacement curve of the all-vertical-piled bent frame under different loads

It is found from Figure 5 that the pile displacement is positively correlated with the horizontal load, and the displacement increment is also positively correlated with the load. Under the action of a horizontal load of 4000kN, the displacement of the pile body has increased significantly. It can be inferred that the pile body is in a yielding state under the action of a horizontal load of 4000kN and is close to failure. The main displacement change of the pile is from the vicinity of the displacement zero point to the pile top, and the difference of the pile displacement below the displacement zero point is very small. The positions of the pile displacement zero point under different loads are also different, which are shown in Table 2.

| Horizontal load (kN) | Pile displacement zero point (m) |
|----------------------|----------------------------------|
| 1000                 | 25.01                            |
| 2000                 | 26.13                            |
| 3000                 | 27.47                            |
| 4000                 | 28.60                            |

In summary, the distance between the pile displacement zero point and the pile top is about 26.80m on average. In other words, it is about 9.6m below the mud surface, which is about 6 times the pile width.

3.3.2 Analysis of the ultimate load-bearing state of the bent frame

The key bearing component of the high-piled wharf is the pile foundation, and its structural displacement is mainly determined by the pile foundation displacement, and the pile foundation displacement has a positive correlation with the load. The maximum displacements of the all-vertical-piled model under different horizontal loads are shown in Table 3 (load ratio and displacement ratio are based on the 500kN working condition).
Table 3. Maximum displacements of pile under different horizontal loads

| Horizontal load (kN) | Maximum displacement of pile (m) | Load ratio | Displacement ratio |
|----------------------|----------------------------------|------------|--------------------|
| 500                  | 0.039                            | 1          | 1                  |
| 1000                 | 0.082                            | 2          | 2.1                |
| 1500                 | 0.133                            | 3          | 3.4                |
| 2000                 | 0.190                            | 4          | 4.9                |
| 2500                 | 0.257                            | 5          | 6.6                |
| 3000                 | 0.337                            | 6          | 8.6                |
| 3500                 | 0.448                            | 7          | 11.5               |
| 4000                 | 0.664                            | 8          | 17.0               |

From Table 3, through fitting calculation, the approximate relationship between displacement ratio $X_r$ and load ratio $F_r$ can be expressed as:

$$X_r \approx 1.426 F_r^2$$  \hspace{1cm} (2)

According to the exponential relationship between the displacement ratio and the load ratio, the load-displacement relationship of the pile body can be obtained: when the load is small, the displacement increases slowly with the load, and when the load is large, especially when the load is close to the maximum load, the displacement increases rapidly, which almost reaching the ultimate bearing capacity of the pile.

The criterion for the structure to reach the ultimate bearing state is that the slope of the load-displacement curve of the structure tends to zero. Let the functional relationship between load $F$ and displacement $x$ be $F = f(x)$, then the criterion for the structure to reach the ultimate bearing state can be expressed as $F' = f'(x) = 0$.

The quadratic function is used for curve fitting, and the result is:

$$F = 104.9 + 11541.3x - 8445.6x^2$$ \hspace{1cm} (3)

Let $F' = f'(x) = 0$, it can be calculated that $x$ is 0.683 and $F$ is 3986.35. That is to say, the maximum displacement is 0.683m and the maximum load is 3986.35kN.

The simulation result of the all-vertical-piled model under 4000kN is normal, there is no non-convergence of the result. Comparing the calculation result with the simulation result, it is found that the displacement does not exceed the calculated maximum displacement, but the load exceeds the calculated maximum load. Therefore, it can be judged that under the action of 4000kN horizontal load, the pile body of the all-vertical-piled model is reaching the critical failure stage, and 4000kN can be considered as the ultimate horizontal load of this structure.

In summary, the approximate relationship between the displacement ratio $X_r$ and the load ratio $F_r$ of the pile body is shown as formula (2). The calculated ultimate load of the equation (3) is 3986.35kN. It is taken as 4000kN after comparing with the simulation result of the model, which is about 8 times the ship load (500kN).

4. Conclusion

In this paper, the working behavior of the all-vertical-piled bent structure is analyzed by establishing a single-bent numerical simulation model of the all-vertical-piled wharf.

The pile displacement zero point of the all-vertical-piled bent is about 9.6m below the mud surface on average, which is about 6 times the pile width. The distance increases with the increase of horizontal load. The displacement gap of the pile body under each working condition below this position is very small, and the variation range of the pile body displacement above this position is positively correlated with the horizontal load. The approximate relationship between the displacement ratio $X_r$ and the load ratio $F_r$ of the pile body is shown as formula (2). The calculated ultimate load of the equation (3) is 3986.35kN. It is taken as 4000kN after comparing with the simulation result of the model, which is about 8 times the ship load.
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