Research on overall bearing characteristics of high-piled wharf under horizontal load

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Abstract: Based on ANSYS model, this paper conducts simulation analysis of high-piled wharf. This paper studies the maximum stress of each pile in the bent frame, and obtains its change law. Through research, the load-displacement curve of the high-piled wharf is constructed, and the method for judging the overall ultimate bearing state of the high-piled wharf is established. The research results can provide a reference for the study and judgment of the overall bearing safety of high-piled wharf under horizontal load.

1. Introduction
High-piled wharves are widely used in large-scale deep-water seaport projects on soft soil foundations. The main horizontal loads of high-piled wharf are wave load, current load, wind load and ship load [1], and the ship load is often the controlling horizontal load of the high-piled wharf in the open sea. This paper mainly studies the overall bearing characteristics of high-piled wharf under horizontal ship load, which is expected to provide a reference basis for the research and judgment of high-piled wharf projects design and safety.

Domestic and foreign scholars mainly use the methods of finite element simulation analysis and model test to study the working behavior of the high-piled wharf. Xie et al. [2] simulated and analyzed the high-piled wharf model of fork-pile combinations with different cross-section sizes and slopes under a variety of loads, and proposed a formula for lateral load-horizontal displacement of single pile and high-piled wharf. Liu and Li [3] did a research by combining mathematical theory derivation and dynamic time history simulation calculation. Li et al. [4] used ANSYS to establish a finite element model of the transverse bent frame under different fork pile torsion angles for analysis. Wang and He [5] established a 3D elastic-plastic finite element model to analyze the load bearing capacity of vertical pile-supported wharf under horizontal loads based on pseudo-static method. Teramoto et al. [6] used 3D elastic-plastic 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 [7] used the finite difference method to conduct a 3D modeling analysis on a fixed offshore platform. Bonakdar and Oumeraci [8] conducted a small-scale model test in a 2 m-wide wave flume to study the influence of pile groups on the wave load of slender piles.

Based on a high-piled wharf project, this paper considers the ship berthing load effect, and uses
ANSYS finite element software to simulate the working behavior and bearing capacity of the high-piled wharf under horizontal load.

2. Engineering background and ANSYS model

2.1 Engineering background
It is a 50000DWT high-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 lower pile foundation adopts 15mm thick steel pipe piles with a diameter of 1200mm, the pile length is 41.2m, and the depth of the pile foundation is 22.8m. The distance between the wharf structure bent frames is 9m, and the center distance between the first pile and the tail pile is 26.16m. The pile foundation layout forms are one-set-inclined-piled form and two-set-inclined-piled form, and the slope of the fork piles is 1:5. The upper beam of the wharf is an inverted T shape, the upper beam is 1.4m×2.0m×30.0m, and the lower beam is 1.8m×2.2m×30.0m.

In this paper, the ship load is used as the representative horizontal load for calculation. The load action method is uniformly loaded on the 1400mm-wide and 3800mm-high part of the middle beam section. Based on the high-piled wharf design theory, one of the representative bent frames can be used to simulate and analyze the working behavior of the high-piled wharf.

2.2 Simulation modeling

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 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 6.68×10⁹Pa.

The steel pipe pile in the model adopts the elastic-plastic strengthening model, the foundation pile steel is Q345 steel, and its yield strength is 345MPa. According to the principle of equal strain, the equivalent yield strength in this model is 10.68MPa.

2.2.3 Model calculation parameters
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 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. This paper select the part of the pile body into the soil and the bottom of the pile, use the target170 unit as the target unit and the contact174 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. Calculate with the kinetic energy formula of ship berthing:

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

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. 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 initial stress of the soil is in a balanced state with the gravity force of the soil.

3.2.2 One-set-inclined-piled bent frame model

There are 6 piles in the one-set-inclined-piled bent frame model, and the whole model adopts free grid. Among them, the 1# and 2# piles near the front of the wharf are set as inclined piles. The grid division of the bent model is shown in Figure 1.

![Figure 1. Grid division diagram of one-set-inclined-piled bent frame model](image)

The horizontal loads of 500kN-5000kN are applied to one-set-inclined-piled bent, and the displacement and stress distribution of the bents under different horizontal loads are calculated. The simulation results are shown in Table 1.

| Horizontal load (kN) | Maximum displacement of bent frame (m) | Calculated maximum stress of pile (MPa) | Actual maximum stress of pile (MPa) |
|----------------------|----------------------------------------|----------------------------------------|-----------------------------------|
| 500                  | 0.032                                   | 6.03                                   | 194.79                            |

Table 1. Calculation results of bearing behavior characteristics of bent frame
| Load (kN) | Displacement (mm) | Stress (Pa) |
|----------|------------------|-------------|
| 1000     | 0.058            | 7.86        | 253.90     |
| 2000     | 0.130            | 11.4        | 368.26     |
| 3000     | 0.210            | 11.6        | 374.72     |
| 4000     | 0.310            | 11.7        | 377.95     |
| 4500     | 0.376            | 11.8        | 381.18     |
| 5000     | 0.448            | 11.9        | 384.41     |
| 5500     | 0.554            | 12.1        | 390.87     |

3.2.3 Two-set-inclined-piled bent frame model

The two-set-inclined-piled bent frame model is similar to one-set-inclined-piled bent frame model. Among them, 1# and 2# piles close to the front of the wharf and 5# and 6# piles far from the front of the wharf are set as inclined piles. The grid division of the bent frame model is shown in Figure 2.

![Figure 2. Grid division diagram of two-set-inclined-piled bent frame model](image)

The horizontal loads of 500kN-7000kN are applied to the two-set-inclined-piled bent, and the displacement and stress distribution of the bents under different horizontal loads are calculated. Under the action of 1000kN horizontal load, the Y-direction displacement distribution and stress distribution diagrams of the two-set-inclined-piled bent frame model are shown in Figure 3 and Figure 4.

![Figure 3. Bent frame displacement distribution diagram (unit: m)](image)
It can be seen from Figure 3 and Figure 4 that the displacement distribution of each pile in the bent structure is relatively similar. 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 is 0.044m. The stress distribution of each pile is also relatively similar, among which the stress near the pile top is larger, and the stress near the pile top of 2# pile and 6# pile is larger. The maximum stress of the pile body is 9.72 MPa, and the actual maximum stress after conversion is 313.99 MPa, which has not reached the yield stress of Q345 steel, so the pile is in an elastic state.

The load-bearing characteristics of the wharf bent under other horizontal loads are similar. The results are shown in Table 2.

| Horizontal load (kN) | Maximum displacement of bent frame (m) | Calculated maximum stress of pile (MPa) | Actual maximum stress of pile (MPa) |
|----------------------|----------------------------------------|----------------------------------------|-----------------------------------|
| 500                  | 0.021                                  | 8.63                                   | 278.78                            |
| 1000                 | 0.044                                  | 9.72                                   | 313.99                            |
| 2000                 | 0.095                                  | 11.6                                   | 374.72                            |
| 3000                 | 0.162                                  | 11.7                                   | 377.95                            |
| 4000                 | 0.237                                  | 11.8                                   | 381.18                            |
| 5000                 | 0.330                                  | 12.0                                   | 387.64                            |
| 6000                 | 0.465                                  | 12.2                                   | 394.10                            |
| 7000                 | 0.708                                  | 12.7                                   | 410.25                            |

3.3 Analysis of the ultimate load-bearing state of the bent frame
The high-piled wharf structural displacement is mainly determined by the pile foundation displacement, and the pile foundation displacement has a positive correlation with the load. The pile load-displacement curves of the two models are shown in Figure 5.
The load-displacement curves show a three-stage change trend: (1) early elastic deformation stage: the curve is almost linear and grows rapidly. (2) Mid-term plastic deformation stage: the curve is nonlinear, and the growth rate gradually decreases. (3) Late failure stage: the curve is in the form of an asymptote, the slope is further reduced, and the displacement increment is large with the small load increment. In this paper, the slope of the load-displacement curve of the structure tends to zero is the criterion for the structure to reach the ultimate bearing state. 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 \( F' = f'(x) = 0 \). This paper considers the use of quadratic function for curve fitting, and the results of the fitting are shown in equations (2) and (3):

\[
\text{One-set-inclined-piled model: } F = 29.9 + 17306.8x - 13378.3x^2 \\
\text{Two-set-inclined-piled model: } F = 153.0 + 19726.6x - 14346.0x^2
\]

Let \( f'(x) = 0 \), the calculation results are as follows:

One-set-inclined-piled model: The displacement value is 0.647m, and the load value is 5627.1kN.

Two-set-inclined-piled model: The displacement value is 0.688m, and the load value is 6934.3kN.

In summary, the ultimate load values of the two models can be taken as 5630kN and 6940kN, which are 11.3 times and 13.9 times the calculated ship load respectively.

The change law of the maximum stress of the pile is different from the displacement of the pile. It can be seen from Table 1 and Table 2 that the maximum stress of the pile body keeps increasing under the horizontal load condition of 2000kN—2000kN, and when load is above 2000kN, the value of the pile body maximum stress shows a linear and slow increase trend as the load increases.

The maximum stress results of each pile are shown in Table 3.

| Load (kN) | 1# pile | 2# pile | 3# pile | 4# pile | 5# pile | 6# pile |
|----------|---------|---------|---------|---------|---------|---------|
| M1       | 500     | 2.08    | 2.98    | 6.03    | 5.81    | 2.08    | 2.03    | 2.74    | 2.03    | 2.74    | 3.29    | 2.08    | 8.63 |
| M2       | 1000    | 2.69    | 3.30    | 7.86    | 7.58    | 3.55    | 3.30    | 4.41    | 3.30    | 3.55    | 3.30    | 3.55    | 9.72 |
| M1       | 2000    | 3.91    | 2.67    | 11.4    | 10.4    | 6.42    | 6.51    | 7.68    | 6.51    | 7.68    | 3.95    | 7.68    | 11.6 |
| M2       | 3000    | 6.55    | 4.04    | 11.6    | 11.7    | 10.4    | 9.14    | 11.6    | 10.4    | 11.6    | 7.86    | 11.6    | 11.7 |
| M1       | 4000    | 10.4    | 7.94    | 11.7    | 11.8    | 11.7    | 11.8    | 11.7    | 11.8    | 11.7    | 11.8    | 11.7    | 11.8 |

Note: M1 is one-set-inclined-piled model and M2 is two-set-inclined-piled model.

Observing the data in Table 3, the following rules can be drawn:

(1) The order of pile body stress in one-set-inclined-piled model: 2# > 4# ≡ 5# ≡ 6# > 3# > 1#.
(2) The order of pile body stress in two-set-inclined-piled model: $6# > 2# > 4# \approx 3# > 5# > 1#$.

(3) Comparing the two models, the maximum value of the pile body stress in two-set-inclined-piled model is larger, the minimum value is smaller, and the vertical pile stress value is relatively smaller.

(4) Under the similar circumstances, the stress values of the pile behind the bent frame (the piles far from the bearing surface) are relatively larger.

4. Conclusion
This paper analyzes the overall bearing characteristics of the high-piled wharf bent structure by establishing a finite element simulation model.

From the load-displacement curve fitting, equations (2) and (3) are obtained. The calculated ultimate loads are respectively: the one-set-inclined-piled model is $5630kN$, and the two-set-inclined-piled model is about $6940kN$, which are respectively 11.3 times and 13.9 times of the ship load. The pile body maximum stress of the bent frame almost reaches the maximum at $2000kN$, and the subsequent increment is small. In the bent frame, the stress value of the $2# (6#)$ inclined pile is relatively largest, followed by the vertical piles, and the $1# (5#)$ inclined pile is relatively the smallest. The pile body stress values behind the bent frame are relatively larger under the similar conditions.

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