Analysis of impact of offshore platform pile under the waves and ice load

Introduction

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Abstract: This article uses finite element software to simulate the internal force and deformation of pile-soil under the wave and ice load. The group pile foundation model is simplified in the plane as a single pile affected by other piles. Calculating wave force based on Morison Equation, the effect of wave force and ice load calculated with the measured wave force and ice load on the pile is compared. According to the time history curve, when the absolute value of acceleration is maximum, the curves of bending moment, axial force, shear and displacement of the pile with the depth of the pile under the action of wave force, ice load and joint force are analyzed. The time history curves of pile top displacement under the combined action of wave force and ice load are analyzed, the displacement time history curves of different positions of piles are compared. Finally, the effect of buried depth, pile diameter and free length on the pile body interaction under the wave force and ice load is analyzed.

1. Introduction

High pile cap structure is broadly applied in engineering, especially in bridge structure, water conservancy project wharf, offshore structure[1]. High pile group foundations are more common in China’s coastal engineering. Besides, the ocean engineering structure differs from the land structure, as the ocean structures bear more load changed in spatial and temporal in the service period, and the wave load takes the longest time and counts as the most underlying dynamic load. The ice load also impacts the ocean structure in the area suffering from severe cold in winter, and exerts a greater impact on the internal force of the high pile cap of pile foundation[2]. Accordingly, the analysis is critical on the state of force of pile foundation with high pile cap under the wave and ice load, and it can lay a foundation for engineering design. High cap pile group foundation is complex in stress situation, and the stress complicatedly calculated. Some common methods can better design and calculate pile, inclusive of supposed fixed point method, the pile group efficiency method, plane-m method and finite element method[3], simplified calculation method of internal force of pile group. Given this, the design
of engineering structure is crucial.

The dynamic effect exerted by the high pile cap foundation on the wave force and the ice load has been studied by numerous researchers. Finite element analysis model and dynamic equilibrium equation, structure of the bridge pier are analyzed numerically by Jia Lingling[16] under 3 kinds of environmental incentives, i.e. load, ice load and seismic wave through establishing deep-water pier structure; and the impact exerted by hydrodynamic pressure, dynamic response of deepwater pier structure are discussed, whereas the interaction between pile and the soil is inadequately considered, the pile bottom fully constrained rigid consolidation. The numerical method of Wang Ruixue[7] for sea ice dynamics has been optimized, and the mixed method of the day - Euler method for numerically simulating sea ice in small and medium scale is perfected.

A simplified calculation model of pile group was proposed in this paper, and the calculation equation of pile was expressed following the down part of any position under horizontal force, the overall design of pile foundation was acquired for engineering designers, and the large displacement of broken pile, pile, pile cap cracks and other phenomena was prevented to a certain extent. Besides, the relevant knowledge of wave mechanics and soil mechanics, structural dynamics, ocean engineering and finite element theory, and a single high cap pile foundation were selected as the research objects, the rational calculation model, distribution and calculation of pile foundation moment, shear force and axial force high pile are established through adopting large finite element calculation software ANSYS under different loads as the displacement varies with time. The factors of the foundation internal force and deformation are anatomized, and the impact exerted by the depth, the pile diameter and the length of the pile on the internal force and deformation of the pile foundation are studied.

2. Wave action

As asserted by Morison and others, three parts are contained in the horizontal wave force on the cylinder of arbitrary height of \( f_h \): first, the wave force of water point horizontal velocity caused by \( \mu \) of the pile horizontal drag force \( f_d \), second, the horizontal acceleration \( \mu \) wave force caused by the water point of the pile horizontal inertia force \( f_i \), third, part the quality level of additional water \( f_w \), wave force of the pile is calculated as:

\[
f_h = f_d + f_i + f_w = \frac{1}{2} C_d \rho D (u - x) |u - x| + C_m \rho A u - C_m \rho A x
\]

Where, \( u \) and \( \ddot{u} \) denote wave particle horizontal velocity and acceleration at the height of a pile, respectively; \( x \) and \( \dot{x} \) denote the cylindrical particle horizontal velocity and acceleration, respectively; \( A \) represents a unit to the Yu Bo high pile vertical projection area; \( \rho \) refers to the density of water; \( C_d \) denotes the pile axis perpendicular to the drag coefficient (damping coefficient); \( C_m \) refers to the inertia coefficient (quality coefficient); \( C_m \) represents the added mass coefficient. The M equation of wave force is expressed as:

\[
[M] \ddot{x} + [c] \dot{x} + [k] x = \rho A \ddot{u} + C_m \rho A \left[ u - x \right] + C_d \rho \frac{D}{2} \left[ u - x \right] \dot{u} - x
\]

Mass damping and stiffness matrix of structure of \([M],[c],[k]\). Because the horizontal velocity and the acceleration of the pile body are much less than those of the wave water quality point, the quality of the additional water can be consequently simplified as:

\[
[M] \ddot{x} + [c] \dot{x} + [k] x = C_m \rho A \ddot{u} + \frac{1}{2} C_d \rho D \sqrt{\frac{\pi}{8} \mu} |u|
\]
This paper selects the measured wave data at 11 July 8, 2012\cite{9}, wave height is 1.85m, the maximum wave height is 3.1m, effective period of 2.28s, the data record for the 100s time. The measured wave velocity, acceleration curve and time history curve of the wave force are presented in Fig. 1–3.

3. Ice load

The ice force function is adopted to calculate the ice load\cite{10}:

\[
F(t) = \begin{cases} 
F_0(1 - \frac{t}{\tau}) & (0 \leq t < \tau) \\
0 & (\tau \leq t < T) 
\end{cases}
\]

Where, \(F_0\) denotes the ice force amplitude, \(T\) represents the ice force period, and \(\tau\) refers to the action time of the ice and the pile body.

Equation of ice force amplitude calculation adopting fixed offshore platform in China\cite{11}:

\[
F_0 = \text{Im} KDH\sigma_c
\]

In the equation, Denotes the local extrusion coefficient, \(M\) refers to the shape factor, the column is 0.9, the square cylinder is 1, and the \(K\) represents the contact coefficient.

The ice force time history was detected on the JZ20-2MUQ platform in 2001\cite{12}, The measured ice time history curve is presented in Fig. 4:

4. simplified calculation model

The calculation of pile foundation is excessively complex. To simplify the calculation, the pile foundation model in the plane is simplified as studied by other pile single pile. A simplified calculation model is developed in this paper, as presented in Fig. 5. Pile under horizontal load, vertical force and bending moment, other research on pile lateral stiffness of the pile is simplified into impact stiffness coefficient for spring sliding bearing \(K\), the bearing stiffness of pile cap, the pile body can be considered merely lateral displacement, no rotation, sliding bearing spring can satisfy the foregoing requirements, and can also be bent. Assuming that the pile in the ground below the depth of \(Z\) is fully
embedded, horizontal load at the ground is above the $H_1$ height, the pile body stiffness is $EI$.

Fig. 5   Simplified calculation model

5. Finite element model introduction
As studied by other pile single pile, the pile foundation model in the plane is simplified, the basic parameter of structure model for the pile body is 1m×1m square pile, the pile length ranges from 31m to 19m, depth reaches 12m, and the level of load position is14m above the ground. The thickness of the base plate reaches 1m, and the foundation soil is sized as 21m×21m×20m.

6. simulation results analysis
The loading on the model at 14m above ground level x positive direction, take the wave force and the ice load before 28s were calculated in this paper, three conditions are considered to analyze the structure, wave force and ice loads taken on by condition 1; 2 cases, single wave force; case 3, ice load alone. To load the pile top displacement, pile body displacement, bending moment, axial force and shear force, calculation load and time history curve were adopted.

6.1 modal analysis
Prior to the dynamic analysis, the basic characteristics taken on by the structure are first acquired. Accordingly, the modal analysis of the model is performed. The structure natural frequency and natural vibration period count as critical dynamic characteristics take on by the structure. The first five order natural frequencies and corresponding natural frequencies of the structure are listed in Tab. 1.

| order | first   | second  | third   | fourth  | fifth  |
|-------|---------|---------|---------|---------|--------|
| natural frequency(1/Hz) | 0.34345 | 1.8533  | 1.8985  | 1.8998  | 2.1837 |
| natural period (T/s)    | 2.912   | 0.540   | 0.527   | 0.526   | 0.458  |

6.2 Pile top displacement analysis
The water structure should stringently control the displacement of the pile top, and the water on the building has higher requirements than the general construction on the ground. Different force displacements of pile top are presented in Fig. 6~8. As indicated in Fig. 7, the wave force displacement of pile top is remarkably small, the impact of measured wave force, at t=14.2s, the negative maximum value of displacement is reached as is 0.306mm; the maximum value is t=24.2s when the displacement reaches 0.935mm. The ice load and wave force, impact of ice load for the impact of pile top displacement surmount those of the wave force. As indicated from the comparison between Fig. 6 and Fig. 8, the force displacement of the top of pile is approaching to the ice load displacement of pile top. Load and force under the action of t=6.4s in the pile top displacement maximum value is measured in the ice, the maximum value were 23.790mm and 23.757mm, reached the maximum value at t=19.2s negative displacement, displacement are -7.686mm and -7.767mm, respectively, presenting merely a small displacement difference. The wave force is known conducive to the pile top displacement, whereas it is comparatively small.
6.3 Pile body displacement analysis
The displacement curve of the pile is acquired through taking the forward maximum value $t=23s$ and the acceleration negative to the maximum $t=21.6s$ data, as presented in Fig. 9.

The time of the maximum value of the resultant force is acquired from Fig. 10~11.
As presented in Fig. 10, in the pile force calculation under the maximum displacement of 13m, the measured load displacement of the pile at the maximum value occurred at 12m position, increased progressively from the beginning of the pile top displacement of piles increases. In the load position offset position displacement of pile up the maximum value, the maximum value was 21.0mm and 36.6mm, respectively. On that basis, the downward displacement decreases progressively from small to large and once again to small. It is negative in the displacement of -6m piles, negative growth at the beginning, at -9m, until the negative displacement reaches the maximum, then decreases, until the bottom of the pile is negative. The absolute value of the pile displacement is in the position of -5m, the minimum value is 0.0378mm and 0.0207mm. As also indicated in the ice load of the pile under the curve of the pile under the force action, wave force is very small under the pile displacement, approaching to the displacement of 0 straight line.

Fig. 10 shows that effect of measured load displacement of pile surmounts the calculated load displacement of pile, the load calculation and the measured value of the mean difference, whereas the discrete, range of measured load value is larger, the maximum value of the measured load surmounts the maximum value caused by load calculation. The maximum point of the acceleration data is adopted in this paper. Accordingly, the pile displacement under measured load surmounts the pile displacement under the load. For conservative design, through multiplying a certain amplification factor, the maximum value can be calculated.

To better illustrate the pile displacement variation, Fig. 8 presents the displacement time history curve of 18S to 28s pile with several representative positions of pile body. Fig. 10 is the displacement curve of the pile at a certain moment, and Fig. 11 is the displacement curve of the pile at different positions and times. Fig. 11 once again confirms the pile body displacement change trend, and can be seen in the pile body mass displacement of the overall change of time, the pile body mass displacement is also like the load, a periodic change.

6.4 pile bending moment analysis
s the depth increase, soil resistance increases with the load, the bending moment of the pile increases. If the pile is the result of the interaction between the pile and the soil. As the pile displacement is changed to the opposite direction, then the bending moment of pile, the depth of 1m in the opposite direction to the position of the maximum bending moment of pile, with the depth increase, soil resistance increases progressively to offset the bending moment of pile, the depth of 1m in the opposite direction to the position of the maximum value. As the depth of the soil resistance continues to increase, the absolute value of the bending moment of the piles reduces progressively from small to large in line with the decreasing trend. Yet, when the depth of 9m, the interaction between pile and soil is smaller, the soil resistance is smaller, the pile bending moment decreases ultimately to the bottom of the pile as the absolute value approaches to 0. The static surface and the surface of the pile are known to be required in a certain range of lateral stiffness. To prevent broken pile, the phenomenon of crack, pile length design should be adequate in length, so as to save material. As indicated in the bending moment diagram of the pile body and the deformation diagram, the impact exerted by the bearing capacity of the pile body level of soil is primarily on the ground below 3~4 times the pile diameter depth range. If the level of the anti-displacement soil rigidity increases within this range, it will increase the bearing capacity of the pile body level. If the soil is weak in this range, the horizontal bearing capacity of the pile will be greatly reduced, and the soft soil layer will be larger in thickness. As presented in Fig. 12, the bending moment changes in the opposite direction when 23S is in the direction of the ice load and the wave force. The wave is much smaller than the ice, so the wave force change trend of small, basically coincide function pile bending moment curve and ice load under the pile bending moment curve, the absolute value of slightly less than the bending moment of pile under ice load. When the wave force direction and ice load direction are consistent, the wave force will increase the dynamic response of the pile body. Instead, the wave force will reduce the dynamic response of the pile body.

6.5 pile body shear force analysis

As indicated in Fig. 13, under the horizontal load above the ground, the shear value of the pile decreases slightly as the pile body absorbs some energy, but the amplitude is small. Sudden change of pile body shear force at the position of the load, the absolute value of the pile body shear force remains unchanged from the load position to the ground position. With the inversion of the upper horizontal load, the shearing force of the pile drops sharply to 0 and goes in the opposite direction. With the increase of buried depth, displacement of the pile decreases, soil resistance decreases, reaches the maximum in the depth of 4m. As the pile displacement is changed to the opposite direction, then the shear force of the pile decreases linearly, until the end of the pile approaches to 0. The shear force of the pile top is slightly smaller than that without the wave action under the wave action. It is found that...
the wave force is consistent with the direction of ice load, which will increase the shear value of the pile. In contrast, the shear strength of the pile will be reduced.

6.6 axial force analysis of pile

The axial force distribution of pile is presented in Fig. 14, when the pile is in the joint action of wave force and ice load. The axial force of the pile increased linearly from the top to the ground under the impacts exerted by the pile body weight. From the ground to the -6m, as buried depth increases, pile shaft force began to increase sharply until the location depth of the 6m pile axial force is peaked. This arises from the impact exerted by the side friction of the pile under the ground makes the axial force of the pile increase rapidly, and the axial force of pile shaft increases. With the depth increases, the pile side friction into the opposite direction, and because the soil energy spread in the process of absorption, pile shaft force decreases rapidly, and reached the minimum in the bottom of the pile. Can be seen from Fig. 14 that the horizontal load has no effect on the axial force of the pile.

![Fig 14 Axial force of pile under different loads](image)

6.7 comparison of theoretical calculation and numerical simulation

The calculation parameters are presented below:

\[ z = 4m, h_1 = 14m, h_2 = 5m, F_p = 1.2 \times 10^4 N \]

Calculated by the simplified model of the foregoing equation can be calculated:

\[ M_A = 3.67 \times 10^4 N\cdot m \quad M_c = 9.18 \times 10^4 N\cdot m \]

Numerical value:

\[ M'_A = 3.32 \times 10^5 N\cdot m \quad M'_c = 31 \times 10^4 N\cdot m \]

The moment value of A is compared with that of 1.105 times of numerical simulation results, which acquires very close result. The calculation model of the bottom is assumed as a fixed end, numerical calculation results and the calculation results differ slightly from each other, whereas with the results of numerical simulation of pile bottom moment value is very close, so the simplified calculation model and numerical simulation results differ evidently.

The comparison is drawn between A and 1.105 times in moment value of numerical simulation results, and the result is very close. The calculation model of the bottom is assumed as a fixed end, numerical calculation results and the calculation results differ slightly from each other, whereas with the results of numerical simulation of pile bottom moment value is very close, so the simplified calculation model and numerical simulation results differ evidently.

7. Conclusions

The dynamic response of the structure is analyzed under the action of wave and ice load, and the variation of the internal force and the deformation of the pile under the action of wave force are compared and studied. As indicated in analytical results, when the wave force and ice load are in the
same direction, the impact will increase the ice load, pile displacement, bending moment and shear force. Conversely, it will weaken the impact exerted by ice load, pile displacement, bending moment and shear force. The maximum value of the absolute value of the pile displacement and of the absolute value of the bending moment overall occur at the horizontal load position under the combined action of wave force and ice load. In the tall platform pile foundation for offshore structures, should consider the wave force and impact exerted by ice load on the sea, and can according to local information based on the pile body stress and deformation characteristics of reinforced design in some parts of the focus, to enhance the safety and durability of the structure.

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