Research on the Influence of The Vertical Compressive Static Load Test of The Pile by The Tidal Fluctuation

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Abstract. The settlement of pile top had risen continuously and stabilized difficulty during the vertical compressive static load test of single pile in the tidal fluctuation area. Based on the principle of effective stress, the phenomena can be explained that the reduction of soil effective stress caused by the rising tide level leaded to the decrease of the bearing capacity of the pile, and the reasonable suggestions are given to the designer of the pile foundation affected by the tidal fluctuation.

1. Introduction

The high-piled wharf is a common structure form of the offshore wharf, which pile foundation is formed by driving a series of long piles into the ground, and bears the load from the superstructure [1]. Because the pile foundation of the high-piled wharf is near the coast and in the tidal level fluctuation area, the tidal fluctuation will affect the performance of the pile foundation. During the vertical compressive static load test of the single pile, the settlement of pile top is obviously affected by the tidal level change. The settlement of pile top increases continuously at the loading level during the rising tide level and reaches the stable standard until the tide level reaches its peak and begins to fall. According to previous studies, the foundation soil will be hardened and the post-construction settlement of pile group foundation will increase due to the periodic tide level fluctuation [2-3], but which cannot explain the experimental phenomenon that the settlement of pile top is affected by the tide level. Based on the principle of effective stress and the results of static load test of the single pile, the phenomenon that the settlement of pile top increases continuously with the rising tide level is illustrated in the paper, and the influence of tidal level change on the bearing capacity of the pile foundation of the high-piled wharf is further explained.

2. Project overview

The high-piled beam-slab structure is adopted and the foundation form is the bored cast-in-place pile with the diameter of 1 m in the new wharf construction. In order to verify the bearing capacity of pile foundation, the vertical compressive static load test of single pile is carried out. The length of the test pile is about 52m, and the elevation of the ground is 7.0m at the location of the test pile. The distribution and parameters of the soil layer are shown in Table 1. The tide is a half-diurnal tide, and the tidal level varies from 0.4m to 6.9m during the period of test.
Table 1. The distribution and parameters of the soil layer at the location of the test pile.

| The stratum name                  | Thickness m | ω (%) | γ kN/m³ | e | I₀ (%) | Iₚ kPa | φ ° | ψ ° |
|-----------------------------------|-------------|-------|---------|---|--------|--------|-----|-----|
| Medium and coarse sand            | 5.6         | 18.0  |         |   |        |        |     |     |
| Soft clay                         | 8.5         | 76.5  | 15.4    | 2.066 | 1.37   | 31.4   | 10  | 13  |
| Medium and coarse sand            | 5.3         | 18.0  |         |   |        |        |     |     |
| Clay                              | 21.1        | 64.1  | 16.0    | 1.816 | 0.84   | 32.6   | 29  | 11  |
| Medium and coarse sand            | 6.1         | 18.0  |         |   |        |        |     |     |
| Clayey medium and coarse sand     | 5.4         | 19.0  |         |   |        |        |     |     |

3. Vertical compressive static load test
The method of slow sustaining load is adopted in the vertical compressive static load test of single pile in this project. The settlement of pile top is measured at 0, 5, 10, 15 and 30 min of each stage loading, and then every 30 min. Each stage load is maintained for at least 120 min and the stability criterion is that the settlement of pile top per hour is less than 0.1 mm under a certain level of load. The interval time of each stage unloading is 60 min, and the settlement of pile top should be measured for 180 min when unloading to zero. When the total settlement of the pile top exceeds 40 mm, and under the load of a certain stage, the settlement of the pile is 5 times under the load of the previous stage or when the Q-S curve appears a steep drop section which can determine the ultimate bearing capacity, the test is terminated. The experimental results are shown in Fig. 1 and Fig. 2. From the result curve, it can be seen that in the process of the vertical compressive static load test, the larger settlements will occur every few stages of load, and it will take a long time to reach the stability standard. It can be founded at the test site that when this happened, it was during the rising tide level.

4. Influence of the tidal level on the static load test
Corresponding the change of the tide level with the loading process at all levels in the static load test of the single pile with time, as shown in Fig. 3, it can be clearly seen that the settlement of pile top increases significantly when the loading level rises, and the time to reach stability is longer. The later the loading level, the more obvious the trend is, for example, the 12th loading level and the 14th loading level, at the low tide level, the settlement of pile top changes slightly, but with the rise of tide level, the settlement of pile top increases significantly, and reaches the maximum at the high tide level. With the beginning of the decline of the tide level, the settlement of pile top no longer increases, reaching the stability standard. At the damage loading level of the 16th, the settlement of pile top also
increases continuously during the rising tide level, and finally meets the damage standard of the test. The settlement of pile top is smaller when the tide level decreases or the tide level is low, and it reaches the stability standard within the minimum loading maintenance time required by the code. From the results, it can be seen that the fluctuation of tidal level has a great influence on the settlement of pile top. On the other hand, it also shows that it has a great influence on the bearing capacity of the pile foundation.

![Graphs showing settlement and tide level during loading process](image)

5. Analysis of the influence of tide level on the settlement of pile top

From the general situation of the project, it can be seen that the elevation of the ground at the location of test pile is 7.0m, and the tidal level changes from 0.4m to 6.9m during the test. When the overburden soil layer on the pile foundation is in the tide level range, the fluctuation of the tide level will affect the effective stresses of the soil layers below the lowest tide level. According to the principle of effective stress, there is equation (1).

$$\sigma = \sigma' + u$$ (1)

When the rising value of tide level from the lowest tidal level is $\Delta h$, the vertical total stress $\sigma$ does not change at the lowest tidal level, but the increment of the pore water pressure $u$ is $\gamma_{w} \Delta h$. From equation (1), the vertical effective stress $\sigma'$ of the soil decreases $\gamma_{w} \Delta h$. It can be seen from Fig. 4 that the reduction of the vertical effective stress $\sigma'$ per m of the soil below the lowest tide level is $\gamma_{w} \Delta h$.

There are several thicker medium-coarse sand layers in the soil distribution at the site of test pile. For the sandy soil, because of its good permeability, the effective stress decreases with the rising tide level. According to literature 4, the lateral friction resistance of the sandy soil to the pile is mainly related to the horizontal effective stress $\sigma_{H}'$ of the soil perpendicular to the side of pile, and the external friction angle $\delta$ between the pile and the soil. The lateral friction resistance per unit area can be expressed as follows.

$$q_{fi} = \sigma_{H}' \tan \delta$$ (2)
among them:

\[ \sigma_{Hi} = k_{oi} \sigma_{vi} \]  
\[ k_{oi} = 1 - \sin \phi_i \]

then

\[ q_f = \sigma_{vi}(1 - \sin \phi_i) \tan \delta_i \]  

Figure 4. The diagram of the effective stress change as the tidal level rising

In the formula, \( k_{oi} \) is the static earth pressure coefficient of the soil layer and \( \sigma_{vi} \) is the vertical effective stress of the soil layer.

When the diameter of pile is \( d \), the thickness of sand layer is \( l_i \), and the size effect coefficient of pile diameter is \( \psi_{si} \), the lateral friction provided by sand layer is as follows.

\[ Q_{fi} = \psi_{si} \sigma_{vi} \pi d l_i (1 - \sin \phi_i) \tan \delta_i \]  

Due to the increase \( \Delta h \) in tide level, the self-weight of the pile foundation reduced by buoyancy is as follows.

\[ \Delta G = \frac{1}{4} \pi d^2 \gamma_w \Delta h \]  

When the tide level rises, the decrease of bearing capacity of the pile foundation is as follows.

\[ \Delta Q = \sum \Delta Q_{fi} - \Delta G \]

For this project, the medium coarse sand layer below the lowest tide level will be calculated. The thickness and the internal friction angle \( \phi_i \) of soil layer are shown in Table 1.

\[ d = 1m, \ \psi_{si} = (0.8/d)^{1/3} [5], \ \delta_i = 0.5 \phi_i [6], \]  

When the tide level rises from 0.4m to 6.9m, \( \Delta h = 6.5m \). The bearing capacity loss of the single pile can be obtained by substituting (7), (8), and (9), \( Q = 370kN \).

Similarly, when the tide level falls from 6.9m to 0.4m, the bearing capacity of pile foundation will be restored, \( \Delta Q = 370kN \).

It is true that the above formula is an idealized model. However, due to the rise of tide level, the effective stress of soil decreases, resulting in the reduction of the lateral friction resistance, which leads to the overall trend of reducing the bearing capacity of the pile foundation. It can be seen from the calculation results that the bearing capacity of the pile decreases as the tide level rises before the failure load is reached. At the test load level applied during the tidal level rising, the settlement at the top of the pile cannot be stabilized due to the decreasing of the pile bearing capacity until the tide level
reaches its maximum and begins to fall. However, at the test load level applied during the tidal level decreasing, the settlement of the pile top can easily reach the stability standard because the bearing capacity of the pile is gradually restored.

6. Suggestions on the design of the pile foundation for the high-piled wharf
In the code for pile foundation of the port engineering, the value of lateral friction resistance per unit area of sand to pile foundation is related to the number of blows which generally obtained by the SPT in site. For the pile foundation of the high-piled wharfs with overlying soil layers in the tidal level range, the change of tide level will cause the change of effective stress in soil layer and the change of the number of blows obtained by the SPT in site. In general, the number of blows obtained by the designer does not take into account the influence of tidal fluctuations. Therefore, for the pile foundation design with the overburden layer located in the tidal level change interval, the data provided by the SPT test should be corrected or the number of blows at the highest tidal level should be provided as the design basis to ensure that the pile foundation meets the actual situation, and meet the requirements of settlement and bearing capacity.

7. Conclusions
For pile foundation of the high-piled wharf with overlying soil layers in the fluctuation zone of tide level, the rise of tide level will cause the effective stress of soil below the lowest tide level to decrease, resulting in the reduction of the lateral friction resistance of the soil layer to pile and the decrease of the pile bearing capacity when the tide level rises.

For the pile foundation design of the high-piled wharf with overlying soil layers in the fluctuation zone of tidal level, when determining the unit lateral friction value of sand layer according to the number of blows obtained by the SPT in site, the data provided by the test should be revised or the number of blows at the highest tidal level should be taken as the design basis.

References
[1] Xu Juping. (2011) Port Hydraulic Structure [M]. People's Communications Publishing House, Beijing.
[2] Zhou Hao, Zhang Ningning, et al. (2012) Study on The Influence of Tide Level on Settlement of Pile Foundation [J]. Journal of Yancheng Institute of Technology (Natural Science Edition), 25(4):5-7.
[3] Liu Jun, Zhang Ningning, et al. (2012) Model Test on The Influence of Tide Level on Bearing Capacity of Pile Foundation [J]. Journal of Yancheng Institute of Technology (Natural Science Edition), 25(3):16-20.
[4] Yan Shuwang, Dong Wei et al. (2009) Study of Influence of Soil Plug on Driving Piles of Offshore Oil Drilling Platform [J]. Chinese Journal of Rock Mechanics and Engineering, 28(4):703-709.
[5] JTS167-4-2012, Code for Pile Foundation of Harbour Engineering[S].
[6] GB50007-2011, Code for Design of Building Foundation[S].