Experimental Study on Sedimentation Characteristics of Foundation Piles under Super-Large Tonnage Static Load Test

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Abstract. Based on the combination of theoretical analysis and site test, regarding sedimentation problem of super-large tonnage static load test, this paper studies pile sedimentation, lateral friction resistance of pile, pile tip resistance, relative displacement of pile and other physical and mechanical changes characteristics. The results show that the Q-s curve of the pile shows a slow change characteristic, and the rebound rate of the test pile is 29.26%. The sedimentation curve of the pile gradually changes from the elastic phase to the plastic stage with the increase of the load. With the increase of the applied load at the tip of the pile, the variation curve’s slope of the axial force of the pile shaft gradually decreases, and the lateral friction resistance of the shallow soil show trends of gradually decrease compared with deep soil, while the relative displacement of pile top and bottom is gradually increasing. The resistance and displacement of pile tip also show a significant proportional relationship. The lateral friction resistance of silty clay has a greater effect on the pile shaft. With the further increase of the depth, the axial force of the pile shaft is obviously decreasing, the decay speed is faster, the pile tip resistance is gradually increased, showing a distinct feature of the friction pile. In this paper, the calculation and analysis procedure of large diameter bored pile is proposed. The nonlinear sedimentation problem of the pile and the surrounding medium is simulated by nonlinear treatment module of the finite element method in the software. The prediction results are basically the same as those of the on-site monitoring results, and the overall prediction accuracy reaches 88.79%.

Keywords: Pile foundation; Static load test; Sedimentation; Load transfer; Effect of pile and soil.

1. Introduction
The pile foundation can provide a large bearing capacity, has the ability of effectively reducing the sedimentation of the superstructure, so that it has become the most widely used foundation form in civil and industrial buildings, bridges, harbors and marine buildings [1]. The static load test of foundation pile is the most accurate and reliable method to test the ultimate vertical compressive bearing capacity of pile foundation [2-3]. With the rapid development of science and engineering construction, as well as the more and more appearance of high-rise, super high-rise buildings, cross-river bridge, large-scale
deep-water terminals and other construction, the bearing capacity and deformation requirements of the upper structure on foundation pile is higher and higher [4-5]. It forces the pile developing to the large diameter, super large diameter, long pile, super long pile and other trends, also contributes to the static load test of foundation pile developing from large tonnage to super large tonnage. While the studies regarding to pile sedimentation, lateral friction resistance of pile, pile tip resistance, relative displacement of pile other physical and mechanical changes characteristics are seriously lagging behind engineering practices [6].

Through theoretical analysis and numerical simulation, many scholars at home and abroad had studied the vertical bearing characteristics of static load test of large tonnage foundation pile, and achieved considerable results [7]. Meyerhof GG [8] and Clark JI [9] studied the size effect of pile tip resistance and pile side resistance in large tonnage static load test. Meyerhof G G [10] studied the vertical bearing capacity of large diameter pile; Omar M. T. [11] comparing researched on the self-balancing method and static pressure load test results of the large tonnage; Zhao Puri, V. K. [12] analyzed the bearing capacity and load transfer mechanism of large diameter and super-long bored pile; Pincus, H. J. [13] and Xiao Hanna A M. carried out numerical simulation on static load test of single pile by using FLAC3D software. It can be seen that it is of great engineering significance to study the sedimentation and load transfer mechanism of large diameter piles with large tonnage static load test.

Based on the combination of theoretical analysis and site test, regarding to sedimentation problem of super-large tonnage static load test, this paper studies pile sedimentation, lateral friction resistance of pile, pile tip resistance, relative displacement of pile other physical and mechanical changes characteristics. The study conclusions can provide reference for sedimentation of foundation piles and pile soil interaction issue under super-large tonnage static load test.

2. Engineering Background and Site Test Design

2.1. Engineering Background

The project is an underground space of core area of the central business district which is located in Panyu District, South Village in Guangzhou City, the surface is the municipal road, the underground is commercial buildings, the project is built for a three-dimensional commercial form. The proposed pile foundation adopts bored pile, uses medium (micro) weathered rock formation as bearing layer. The natural compressive strength at the pile tip is 29 MPa, the depth of the hole in bearing layer shall not less than 3d (d denoted the pile diameter), and not less than 5 m as well. When the pile-side soil is strong and middle weathered rock formation, the standard value $Q_{sk}$ of the total limit side resistance of the pile is account for 60% of the characteristic value $R_a$ of the vertical bearing capacity of single pile. The distribution and characteristics of the site soil along with the depth of the site are shown in Table 1.

The pile diameter of the test pile is 1.8 m, the pile length is 22m, and the vertical ultimate bearing capacity of the pile is set as 44000kN. The ultimate bearing capacity of the cushion layer on both sides of the test pile was 350 kPa at the site with the area of 14 m×18 m which center on the test pile. Figure 1 is the super-large tonnage static load test site graph.

2.2. Test design

Design of vertical ultimate bearing capacity test pile is 44000kN in the static load test, according to the industry standard "Technical code for inspection of building foundation piles" (JGJ 106-2014), the loading method adopts the slow maintenance load method, step-by-step loading, the rating load is 1/10 of the maximum load value, that is 4400kN, the first two loading value is twice of rating load, while loading up to 44000 kN and pile sedimentation remain relatively stable, stop loading. Equal un-loading step-by-step, each unloading value shall be twice of rating load, that is 8800kN. When loading and unloading, load transfer shall be evenly, continuous, no impact. After unloading to zero, residual sedimentation of pile top is measured.
Table 1. The elevation and basic physical index of main soil layers

| Name                        | Soil layer thickness/m  | Basic physical index |  
|-----------------------------|-------------------------|----------------------|
|                             |                         | Water cut/%          |
|                             |                         | $\rho/(g/cm^3)$      |
|                             |                         | void ratio           |
| Plain Fill                  | 1.99~ -3.82             | 21.31                |
| Silty Clay                  | -3.82~ -7.92            | 25.38                |
| Clay                        | -7.92~ -14.47           | 33.19                |
| Strongly Differentiated     | -14.47~ -30.18          | 24.38                |
| Sandstone                   |                         | 1.93                 |
| Medium Differentiation      | -30.18~ -33.36          | 32.71                |
| Sandstone                   |                         | 1.88                 |
| Silty Clay                  | -33.36~ -59.33          | 27.48                |
| Interlayer Soil             | -59.33~ -70.27          | 26.12                |

Fig. 1 Site graph of vertical compressive static load test of super-large tonnage

In the experiment, 10 hydraulic jacks were installed in parallel, and the displacement meters were installed at pile shaft as shown in Fig.2. The sedimentation of the pile was measured regularly. The calibrated reading was carried out and used as reference data before the sensor was buried. The loading and end of loading were carried out according to the relevant standards.
3. Sedimentation Theory of Bored Pile with Static Load Test

3.1. Calculation principle and method

The bearing capacity of bored pile as foundation is mainly related to soil conditions, length and diameter ratio of pile shaft-to-pile soil stiffness ratio and so on. Due to the effect of the upper load, the pile will have the action of friction and relative slip with the surrounding soil. Set the radius of the cross-section of the single pile as R0, the circumference as U0, the area as A, the elastic modulus as Ep while the depth of the soil is Z, set the shear stress of pile body with the soil contact surface as τp, the cross section axial stress is Np. The vertical compression formula, equilibrium formula and control formula of the pile are as follows respectively:

\[
\frac{\partial w_p}{\partial Z} = -\frac{N_p}{AE_p} \quad (1)
\]

\[
\frac{\partial N_p}{\partial Z} = -U_0 \tau_p \quad (2)
\]

\[
\frac{\partial^2 w_p}{\partial Z^2} - \frac{U_0}{AE_p} \tau_p = 0 \quad (3)
\]

Based on the formula 1-3, combined with the soil shaft balance conditions, the load—displacement model of the pile is obtained.

\[
\begin{align*}
  w_p (r) &= \int r \frac{\partial w_p}{\partial r} dr = \frac{\tau_p R_0}{G_s} \ln \frac{r_m}{r} \\
  \tau_r (r) &= \tau_p \frac{R_0}{r} \\
  \gamma_z &= \frac{\partial w_p}{\partial r} = \frac{1}{G_s} \frac{\tau_p R_0}{r} \\
  r_m &= 2.5L \rho_m (1-v) 
\end{align*} \quad (4)
\]

Gs is shear modulus of soil shaft; γz is shear strain; τsz is the shear stress of the soil at depth of z; ρm is attenuation influence coefficient; rm is the maximum neglected radius for shear deformation; wsz is pile shear displacement.

According to the formula 1-4, then the differential control formula of pile can be further obtained

\[
\begin{align*}
  \frac{\partial^2 w_p}{\partial Z^2} - \frac{k}{AE_p} w_p &= 0 \\
  k &= 2\pi G \ln \left( \frac{r_m}{R_0} \right) 
\end{align*} \quad (5)
\]

Based on the calculation of formula 5, the shear stress and vertical displacement of the soil around pile shaft are zero. When the medium around the pile is non-linear, Gs is inversely proportional to γz, and the hyperbolic model is used to improve the tangential shear modulus Gt in the soil. It can be expressed as:

\[
G_t = G_0 \left( 1 - \tau_p R_p / \tau_f \right) \quad (6)
\]
G0 is the shear modulus at the initial moment of the soil around the pile; \( \tau_f \) is the shear stress at the distance \( R \) from the pile; \( R_f \) is the failure ratio, then the shear displacement \( w_0 \) under the nonlinear condition can be expressed as:

\[
\begin{align*}
    w_0 &= \tau_R \frac{R}{G} \left[ \ln \left( \frac{R_0 - \sigma}{R_0 - \sigma} \right) + \frac{\sigma(R_0 - \sigma)}{(R_0 - \sigma)} \right] \\
    \sigma &= \frac{\tau}{\gamma R_0 R_f}
\end{align*}
\]

(7)

3.2. Analysis of the calculation results

Based on the above analysis theory, the calculation and analysis program of bored pile is compiled, at the same time, the nonlinear sedimentation of pile and surrounding medium is simulated by the nonlinear processing module of finite element method in software. According to the actual engineering background set the input parameters, calculate the progressive loading of single pile sedimentation prediction curve [19], as shown in Figure 3. The two curves in Figure 3 represent the predictive and actual value, respectively. As shown in the figure, the overall trend of the predictive value is basically the same as the actual value, and the overall prediction accuracy is 88.79%, which shows that the algorithm proposed in this paper is able to realizing effective preliminary prediction of sedimentation of single pile under different loads.

![Fig. 3 Comparison of computer and measured sedimentation values](image)

4. Site results of static load test analysis

4.1. Q-s curve analysis

During the static load test, after the gradual loading and uploading step by step, the sedimentation changes curve of the pile is as shown in Figure 4. The maximum load of the two piles is 44000kN. When the pile tip load reaches the maximum value, the final sedimentation of the test pile is 35.68mm, while gradual uploading to zero, the rebound amount of the two piles is 10.44mm, the rebound rate was 29.26%.

Before loading to 22000kN, the sedimentation of two pile and pile top load is basically show a linear change, when the pile top load exceeds 22000kN, the vertical stiffness (Q/s) of the pile decreases obviously with the sedimentation of the pile, and the sedimentation increases suddenly. It can be seen that when the load is more than 22000kN, the sedimentation curve has entered the plastic deformation stage, and the soil at the end of the pile is gradually compacted. This is because in hole process that the soil around the pile will produce a relaxation effect, then the lateral resistance of the pile will play a insufficient role, at the same time, because the pile length is large, the sediment in bottom is not clean, result in thick sediment.
4.2. Characteristics of axial force and lateral friction of pile

The stress of the reinforcement is read by the frequency recorder connected to the pile shaft, while the axial force of the pile is calculated. The variation law of the axial force of the test pile under the action of different end loads is shown in Figure 5, the axial force curve of the pile at the load of 8800kN, 17600kN, 26400kN and 35200kN is selected. It can be seen from the figure that the slope of the curve of the pile axial force decreases with the increment of the applied load. When the end load is less than 20000kN, the change of the axial force of the pile is less within the depth of 10m, at this point the lateral friction and end resistance of pile shaft at shallow soil are almost ineffective. From the figure it can also be seen, when the depth of the soil is between 10-15m, the changes of pile axial force is larger, as can be seen from Table 1, within the scope, the soil is the silty clay and powder clay and interlayer of clay, we can see the lateral friction of silty clay has a greater effect on the strength of the pile. With the further increase of the depth, the axial force of the pile is obviously decreasing, the decreasing speed is faster and the resistance of the pile tip is gradually increased. When the depth is 30m, the load is 26400kN and 35200kN, the axial force of pile is 8.68% and 20.57% of surface stress respectively, and the pile shows obvious characteristics of the friction type pile.

![Fig. 4 Q-s curve of test pile](image1)

![Fig. 5 The axial force distribution of the test pile with increasing depth](image2)
The lateral friction resistance distribution of the test pile is shown in figure 6 when the surface load is 8800kN, 17600kN, 26400kN and 35200kN, respectively. With the increment of the applied load, the lateral friction resistance of the shallow soil shows decrease trend when compared with the deep soil. The lateral friction of the soil within the depth of 3m is significantly higher than that of the deep soil, which may be caused by compaction and hardening of the surface pavement. In the range of 0-14m depth, when the surface load reaches 26400kN, the lateral friction of the pile within the upper 15m reaches the limit value, and the lateral friction resistance will not increase when the load is further increased. When the surface depth is more than 20m, when the surface loading increases from 26400kN to 35200kN, the lateral friction increases further. It can be seen that the lateral friction is affected by many factors such as the nature of the soil, the depth and the surface load. It is an asynchronous play process.

4.3. Analysis of relative displacement of pile and soil

The relative displacement of the test pile and the around soil is shown in figure 6 when the surface load is 8800kN, 17600kN, 26400kN and 35200kN, respectively. On the whole, with the increment of the load, the relative displacement of pile and soil at pile bottom and pile top show gradually increment trend. When the load is 8800 kN, the relative displacement of pile top was 2.5 mm, while the relative displacement at pile top is zero; when the loading increased to 35200kN, the relative displacement of the pile top reaches 36.5mm, the relative displacement of the pile bottom is 32.5mm. The relative displacement of the pile and soil is proportional to the lateral friction of the pile, in certain range. When the surface load is gradually increase, the lateral friction increases to the limit value, and the relative displacement continues to increase while the lateral friction does not change anymore.
5. Conclusion and Suggestions

Based on the combination of theoretical analysis and site test, regarding to sedimentation problem of super-large tonnage static load test, this paper studies pile sedimentation, lateral friction resistance of pile, pile tip resistance, relative displacement of pile and other physical and mechanical changes characteristics, the study conclusions are as follows:

(1) The finite element analysis model of the large tonnage static load test is established. The nonlinear treatment module of the finite element method in MIDAS software is used to simulate the nonlinear sedimentation of the pile and the surrounding medium. The prediction results are basically the same as those of the on-site monitoring results, and the overall prediction accuracy is 88.79%.

(2) The Q-s curve indicates that the rebound rate of the test pile is 13.83%. Before the load was loaded to 17600kN, the sedimentation of the pile was linearly changed with the pile load. When the load is more than 20000kN, the vertical stiffness (Q/s) of the pile decreases obviously with the increase of the sedimentation of the pile, and the sedimentation increased suddenly, the sedimentation curve has entered the plastic deformation stage, the soil at the end of the pile is gradually compacted.

(3) As the loading of the end increases, the slope of the curve of the axial force of the pile shaft decreases gradually. The soil lateral friction of the silty clay has a greater effect on the pile. With the further increase of the depth, the axial force of the pile is obviously reduced, the decay speed is faster, the pile tip resistance is gradually increased, and the pile shaft exhibits obvious characteristics of the friction pile.

(4) With the increase of the applied load, the lateral friction resistance of the shallow soil decreases gradually when compared with that of the deep soil, and the relative displacement of the pile top and pile bottom increases gradually. Pile tip resistance and pile tip displacement also show a significant proportional relationship.

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