Numerical Analysis of Soil Squeezing Effect of Pipe Pile Construction in Deep Silt Site

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Abstract. This article is based on a pile foundation project in Wenzhou City, combined with construction site monitoring data, and established a finite element model to analyze the soil squeezing displacement caused by the construction of PHC pipe piles in deep silt sites, as well as the displacement of different sizes of digged holes on the surface impact. When the distance from the pile position to monitoring point is 35 times of the pile diameter, the field test results show that the horizontal displacement and velocity change of the soil caused by the pile foundation construction decrease with the buried depth, and the main influence range is within the buried depth of 0-14 m. Numerical simulation results show that: (1) without digged hole, the main influence range of the main soil squeezing displacement is about 8 times of pile diameter; (2) the larger the diameter of the digged hole, the smaller the displacement and the influence range of the affected soil on the surface; (3) the ground squeeze displacement caused by the pile construction attenuates in a power function with the distance from the pile position to the measuring point.

Keywords: Pile; Soil squeezing effect; Detection; Numerical simulation; Digged hole.

1. Introduction

During the pipe pile construction in the project, a certain volume of soil will be discharged. If the construction measures are improper, it will affect the nearby buildings. At present, the most commonly used methods to analyze this squeezing effect are the hole expansion method, the strain path method and the finite element method.

Fei Yi (2015)[1] combined with the theory of circular hole expansion, assuming that the plastic failure of the soil obeys Tresca and Mohr-Coulomb criteria, and obtains the radial stress and displacement solution. Pengyuan Zhang, Bing Bai (2016) et al[2] obtained the total stress of the column pore expansion problem in saturated soil, and gave the excess pore water pressure in the elastoplastic zone and the stress field of the soil expansion problem. The circular hole expansion method is simple in form, but it can only analyze radial displacement and radial stress and is not suitable for shallow soils on the surface.

M. M. Baligh[3] proposed a strain path method applied to infinite space soil. After C. Sagaseta[4] used the source method and source sink method to modify it, it was obtained that it can be applied to semi-infinite soil to solve the displacement field of soil squeezing. Zhanyou Luo[5] is based on the theoretical basis of the SPM method. Under the assumption of small strain, the solution is corrected to solve the problem of the free boundary on the surface of the foundation. It is a better way to give the displacement field of the squeezing soil within the entire depth of the pile. However, the strain path method ignores the effect of the pile-soil contact surface and the rotation of the soil element, and the
formula involves multiple integral calculations that are too complicated, especially for large strains, which require numerical integration to complete. Therefore, the application of strain path method to solve pile-soil penetration is rare.

Mingyi Zhang et al.[6] used ANSYS software to realize pile driving by applying displacement, but failed to realize the entire pile driving process. Qun Lu et al.[7] improved the simulation of pile-sinking process by using ANSYS software, and realized the simulation of the whole process of the continuous penetration of statically pressed piles. However, ANSYS software has greater limitations in the choice of soil constitutive model. In contrast, ABAQUS can provide a variety of soil constitutive models[8], which makes it possible to simulate the entire process of pile pressing more comprehensively. Zhanyou Luo combined the ABAQUS software to analyze the soil squeezing effect and various influencing factors during the pile construction process on the basis of considering the pile-soil interaction. Shao Yan[10] performed a numerical simulation of the soil squeezing effect during pile construction and obtained good results.

Based on a pile foundation project in Wenzhou City, this paper uses ABAQUS to analyze the soil squeezing displacement caused by the pile pressing process. At the same time, it briefly analyzes the dug holes that affect the squeezing effect, and the brief relationship between the displacement of the ground surface squeezing soil and the distance from the pile position to the measuring point is discussed.

2. Project Overview

The proposed site is at the Wenzhou Economic and Technological Development Zone, and the landform of the site is similar to the coastal beach landform area of southeastern Zhejiang. The total land area is about 370,000 m². The new factory building is a multi-storey building, mostly steel frame structure or light steel structure, partially reinforced concrete frame structure. The stratum of the proposed site is composed of artificial fill, silted alluvial soft soil, lacustrine and marine general cohesive soil from top to bottom, and is divided into 8 engineering geological layers and 15 sublayers. The buried depth of the groundwater level measured was 1.29~3.21m. The geotechnical parameters of the main soil layers are shown in Table 1.

| Soil | Soil name | Elastic Modulus / mPa | Poisson | Cohesion / kPa | Frictional angle | Height / m |
|------|-----------|----------------------|---------|----------------|-----------------|------------|
| ①2  | Filling   | 7.05                 | 0.38    | 8              | 13.9            | 2.9        |
| ②1  | Silt 1    | 10.92                | 0.35    | 8.1            | 20              | 3.6        |
| ②2  | Silt 2    | 7.5                  | 0.38    | 8              | 16              | 3.8        |
| ②3  | Silt 3    | 10.08                | 0.35    | 8.8            | 20.4            | 2.3        |
| ②4  | Silt 4    | 5.49                 | 0.4     | 10.6           | 9.1             | 13.3       |
| ④2  | Silty Clay| 19.45                | 0.33    | 15.2           | 19.4            | 14.1       |
| ⑤2  | Clay      | 19.45                | 0.33    | 22.8           | 13.9            | 5.9        |
| ⑥1  | Clay      | 30                   | 0.3     | 30.1           | 16.6            | 4.4        |
| ⑥2  | Silty Clay| 20.75                | 0.32    | 20.4           | 17.3            | 15.6       |

The surface of the site is dredger fill, and the bottom is silt and silty soil. The thickness of the soft soil layer is 27.20~33.60 m. The pile foundation layout and measuring point layout of the site are shown in Figure 1.

Figure 1. Monitoring site layout.
Figure 1. It can be seen that the distance between the center point of the pile site constructed on April 6 and the CX3 monitoring point is 35 times of the pile diameter. The pile type adopts PHC prestressed concrete pipe pile with a pile diameter of 500 mm, supported layers is $\textcircled{5}2$ layer of clay, the relative elevation of the pile top is -2.400 m, and the effective pile length is not less than 47 m. Monitoring started on April 4, 2019 and ended on May 4, 2019.

3. Monitoring Results and Analysis

Figure 2 shows the change of displacement of the CX3 measuring point over time. It can be seen from Figure 2 that the horizontal displacement of the soil caused by foundation pile construction in this area decreases with the buried depth. The main impact range is within the buried depth of 0-14 m, the horizontal deformation is 2.56-6.16mm; when the buried depth is below 15 m, the horizontal deformation is less than 1.2 mm.

Figure 3 shows the speed of the change of displacement of soil squeezing at CX3 measuring point with time. As shown in Figure 3, the speed of the change of displacement in the buried depth of 0-14 m is significantly higher than the value whose below 14 m. At this time, the speed of the change of displacement is 0.06mm/d~0.24mm/d, and when the buried depth is below 15m, the speed is not more than 0.05 mm/d.

The changes of the detection data are the consolidation of the soil when the completion of the construction. After April 6 in Figure 2 and Figure 3.

4. Finite Element Numerical Simulation

4.1. Basic Assumptions

Certain assumptions need to be made to establish a numerical model in this paper:
(1) The soil squeezing stress and displacement caused by the foundation pierced by the pile body are axisymmetrical. In order to simplify the calculation, this simulation takes a axisymmetric model;
(2) Compared with the force penetration method of applying load on the pile top, the process of applying displacement to realize the pile pressing process is simpler, so the displacement penetration method is used to realize the pipe pile pressing; the finite deformation theory is used to deal with this problem;
(3) The elastic part of the soil pierced by the simulated pile is treated in accordance with linear elasticity, and the plastic part adopts the Mohr Coulomb failure criterion; the pile is taken as a rigid body, and a 1mm thick pile pipe is established under the tip of the pile to prevent the soil from crossing the axis of symmetry;
(4) The time of penetrating into the soil is short, and the pore water cannot be discharged in time. This model does not consider the consolidation process.
(5) The pile-soil contact surface adopts face-to-face contact, the discrete method is point-to-face discrete, the normal direction of the interaction attribute is hard contact, and the tangential direction adopts the penalty function. The friction coefficient \( \mu = \tan \left( \left( 0.75 - 1 \phi \right) \right) \), where \( \phi \) is the friction angle of the soil; the pile pipe is smooth.

4.2. Calculation Model and Parameter Selection

The elastic modulus of Shanghai soft soil area is 2.5-3.5 times of the compressive modulus\(^\text{[11]}\). After the trial calculations in this paper, the soft soil elastic modulus is taken as 3 times of the compressive modulus. The soil parameters are shown in Table 1. When the pipe pile is pressed into the soil deeper, it will form an occlusion\(^\text{[12]}\), so the model adopts a solid pile for approximate simulation. Figure 4 is a simplified diagram of the finite element model. A axisymmetric model is established with the center of the pile as the axis of symmetry. The pile radius is 250 mm, the pile length is 50 m, the lateral length \( r \) of the soil is 30 m, and the vertical length \( H \) is 70 m. The bottom of the soil has a fixed horizontal and vertical displacement, the right side has a fixed horizontal displacement, and the left side does not need to define boundary conditions due to the existence of a pile pipe; a 50 m displacement load is applied to the pile top to simulate the pile penetration process, and the analysis step time is 2000 s.

![Figure 4. Model simple graph.](image)

![Figure 5. Change of horizontal displacement at Z=-3 m with pile penetrating.](image)
5. Analysis of Numerical Results

5.1. Extrusion Displacement
Figure 5 shows the curve of the horizontal displacement of the reference plane with $Z = -3m$ under the ground surface as a function of pile driving. It can be seen from Figure 5 that the horizontal displacement at the same position increases with the increase of the pile sinking depth.

(1) The pile sinking depth will only produce horizontal displacement when it is close to the reference horizontal plane. For example, when the pile sinking depth $Y = 2.75m$, the maximum horizontal displacement will reach 18 mm; and when the pile tip cannot exceed the reference surface enough depth, the horizontal displacement of shows an upward trend and then a downward trend.

(2) When the pile tip exceeds a sufficient depth of the reference surface, the horizontal displacement decreases like an "inverse function"; at the same time, when the pile sinking depth reaches a certain depth, the horizontal displacement is almost the same. For example, the pile sinking depth $Y$ is 3.75 m and 50 m, the horizontal displacement produced at the time has little change, the maximum horizontal displacement at this time is 250mm, which is the pile radius. The horizontal displacement at 8 times of the pile diameter in the radial direction is 2.1mm, so the radial influence range is about 8 times the pile diameter.

5.2. Variation of Pile Driving Displacement with Different Digged Holes
In order to compare the influence of different sizes of digged holes on the displacement of squeezing soil. When the diameter of the pile is 500 mm and the depth of the lead hole is 30m, the diameter of the lead hole is 300, 350, and 400 mm to analyze the horizontal displacement of the ground. Figure 6 shows the variation curve of the displacement of the ground surface squeezing soil with different sizes of digged holes when the pile sinking is completed.

It can be seen from Fig. 6 that the comparison results of 4 kinds of digged holes show when the digged hole diameter of $D = 400mm$, the value of horizontal displacement is 0.5 times of the digged hole of $D = 300mm$, which is 0.2 times of no digged hole. At the same time, due to the existence of the digged hole, the range of the horizontal displacement is affected radially is reduced by about half.

The horizontal displacement of the ground surface decays in the form of a power function:

$$u_r = ar^{-b}$$  \hspace{1cm} (1)

In the formula, $r$ is the radial distance ($r \geq$ pile diameter); $u_r$ is the horizontal displacement of the soil; $a,b$ is the fitting parameter, seeing in Table 2.

**Table 2.** Fitting parameters of horizontal displacement of ground surface.

| hole/mm | $a$ | $b$ | R-Square |
|---------|-----|-----|----------|
| 0       | 10.47 | 1.48 | 0.99839 |
| 300     | 3.34  | 1.36 | 0.99446 |
| 350     | 1.57  | 1.82 | 0.99847 |
| 400     | 1.24  | 1.83 | 0.99911 |
6. Comparison of Numerical Simulation and Field Test Results

When PHC pipe piles are constructed near the inspection point, the use of dugged holes can reduce the soil squeezing effect. Taking the last 6 piles on April 6 as an example, since the distance between the pile position and the measuring point is greater than 30 times of the pile diameter, it is considered that the horizontal displacement of each pile at the measuring point changes according to formula (1). The horizontal displacement of the measuring point is the sum of the displacements caused by each pile. Figure 7 shows the comparison of the measured displacements and simulation results at each measuring point of the last 6 piles constructed on April 6. It can be seen from Figure 7 that the squeezing effect is significantly reduced after the dugged hole construction is adopted, and it is consistent with the measured results. The relative distance between the monitoring point and the pile position is shown in Figure 8.

7. Conclusion

According to the construction site inspection data and the finite element model simulation results:

(1) The horizontal displacement of the soil caused by the construction of foundation piles on this site decreases with the buried depth, and the main influence is in the range of 0–14m. The horizontal displacement of the ground caused by pile construction and the horizontal distance from the measuring point attenuate according to the power function.
(2) During the construction of PHC pipe piles, the horizontal displacement of a certain horizontal plane shows a trend of increasing with the increase of the pile sinking depth. At the same time, after the pile sinking depth reaches a certain depth, the horizontal displacement is almost the same, and the main influence range of the main soil squeezing displacement is about 8 Times pile diameter.

(3) The influence range of the horizontal displacement of the ground surface and soil squeezing decreases with the increase of the diameter of the digged hole.

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