Test study on the load transfer behavior of the composite foundation of pipe-pile with cap & holes

Yongqiang Zou¹, Jinbo Lei*, Xing Zhou¹, Jinyou Yang¹

¹School of Civil Engineering and Architecture, Nanchang Hangkong University, Nanchang, Jiangxi, 330063, China
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Corresponding author’s e-mail: 18979103608@189.cn

Abstract. As the vertical reinforcement of composite foundation, the concrete pipe pile is suitable for the treatment of deep soft foundation engineering. In order to explore the working characteristics of the composite foundation of pipe-pile with cap & holes, the model tests have been carried out between the composite foundation of pipe-pile with cap & non-hole and the composite foundation of pipe-pile with cap & holes, which are three arrangements of holes. The working properties of settlement deformation, load transfer and the pile-soil stress ratio of the composite foundation of all piles have been analyzed. The test results show that: (1) the total settlement of composite foundation of pipe pile with cap & holes is smaller than that of the composite foundation of pipe pile with cap & non-holes, and its settlement curve is relatively gentle.(2) The pile axial force and the pile-soil stress ratio of the composite foundation of pipe-pile with holes is slightly less than that of pipe-pile. (3) The pile side frictional resistance and the soil pressure between two pile caps of the pipe-pile with holes is greater than the pipe-pile with cap & non-holes composite foundation.

1. Introduction

Engineering practice shows that concrete pipe piles have unique advantages for dealing with deep soft soil foundation under the load of embankment[1-6], but the squeezing effect produced by piles will produce different degrees of compression on the soil around the pile, and high excess pore water pressure, which adversely affects the surrounding environment[7-8]. In order to alleviate this adverse effect, it is tried to open the hole in the conventional pipe pile, that is, set some drainage channels so that the pore water in the soil during the construction period of the pipe pile can actively enter the pipe pile cavity through the pile drainage channel, which is known as pipe-pile with holes technology[9-10]. Experimental studies have shown that pipe-pile with holes can accelerate the dissipation of excess pore water pressure in time and space and reduce its peak value, shortening the intermittent pile time[11-12].

In order to explore whether the pipe-pile with holes accelerates the dissipation of excess pore water pressure and reduces the water content of the soil, whether it will change the bearing capacity of the composite foundation of the pipe pile, the model test of the composite foundation with pipe-pile with cap & non-holes and three kinds of pipe-pile with cap & holes with perforated pipe piles is carried out in this paper. The pipe-pile with cap & non-holes and the pipe-pile with cap & holes with different opening methods including the load-settlement curve of the pile composite foundation, the axial force of the pile body, the lateral friction of the pile, the soil pressure around the pile, and the pile-soil stress ratio change the load-bearing behavior are compared and analyzed.
2. Test Overview

2.1. Test Devices and Materials

2.1.1. Soft soil foundation model. The angle steel frame is welded on the 2.0m×2.0m×0.01m steel plate, the four surrounding parts of which are composed of two 1.5m×0.5m×0.01m tempered glass, as shown in Fig. 1(a). The test soft clay is taken from the area along the Yangtze River in Nanchang, transported indoors through air drying, mashing, etc. The soil with a particle size of less than 1 cm is uniformly stirred by adding water to the mixer. The soil moisture content is controlled by more than 40% according to the requirements of reference[13]. According to the method of layered filling, partial compaction and pre-compaction consolidation, the soft soil foundation is prepared as shown in Fig. 1(b). In the layered filling process, the earth pressure box is buried according to the specifications. About physical and mechanical parameters of the prepared soil are shown in Table 1.

![Model box and soft soil foundation](image)

Table 1. Physical and mechanical parameters of soil

|水|空隙比|密度|液限|塑限|塑性指数|渗透性(cm/s) |
|---|---|---|---|---|---|---|
|43.28|1.13|1.82|40.34|21.90|18.44|2.99×10^{-8}|

2.1.2. Model pile. The model pile is made of 800mm long PVC pipe with an outer diameter of 63mm and a wall thickness of 3mm. The pipe-pile with holes is opened in three ways of unidirectional pair holes, bidirectional pair holes and star pair holes, with a hole diameter of 20 mm, as shown in Fig. 2. By being bonded with the pipe pile through super glue, the pile cap is made of 200mm×200mm×15mm plexiglass. It forms three kinds of pipe-pile with cap & holes and pipe-pile with cap & non-holes. The bottom of the pipe-pile is made of transparent thin plates to achieve blocking to avoid the effect of soil plugging during the pile sinking process.

2.1.3. Cushion. The medium sand is used as the cushion material, and the cushion layer is laid to a thickness of 100 mm.

2.1.4. Bearing plate. The bearing plate is made of square steel plate with a side length of 400 mm and a thickness of 10 mm, and three small holes with a diameter of 10 mm are drilled for the subsidence mark to pass through.
2.2. Measuring Equipment and Measuring Point Arrangement

2.2.1 Earth pressure box. The LY-350 micro strain type earth pressure box is used, and the measuring range vary from 0 to 0.2 MPa. In the soil model, 12 earth pressure boxes are buried, such as m1, m2, ..., m12, etc., and their arrangement is shown in Fig. 3.

2.2.2 Strain gauges. The strain gauge adopts a grid length of 3 mm and a width of 2 mm, a resistance of 120.0 Ω, a sensitivity coefficient of 2.06, and an accuracy class of A. The moisture-proof protection treatment is done when the paste is applied, and the strain gauges are arranged symmetrically along the pile body as shown in Fig. 4.

2.2.3 Settlement Mark and Dial Indicator. Preset 3 subsidence marks, one at the top of the pile and two at the soil between the piles. The corresponding settlement is measured with a dial indicator. The range of the dial gauge is 20mm.

2.2.4 Data Collection System. The earth pressure box and the pile strain gauge data are collected by two DH3818 static strain testers as shown in Fig. 5.
2.3. Experiment Methods

2.3.1. Static pressure pile. In order to ensure uniform vertical pile sinking, the pile body is marked every 10cm, and the speed of the pile sinking is controlled to about 5cm/min. To detect the load on the soil between the pile caps, the pile to the bottom of the pile cap is suspended 10cm away from the soil surface, and the earth pressure box is quickly buried on the soil surface under the pile cap. It continues to sink until the bottom of the pile cap is in contact with the surface of the soil, then lays a cushion on the surface of the soil and the pile cap, and finally places a bearing plate on the cushion for loading, as shown in Fig. 6(a).

2.3.2. Static load test. According to the Technical Specification for Composite Foundation GB/T 50783-2012[14], the static load test is carried out, and the standard weight block (5.1kg per piece, weight about 50N) is used for the pile-up. The graded static pressure stacking method is divided into 8 stages, which respectively are 300 N, 600 N, 900 N, 1200 N, 1500 N, 1800 N, 2100 N and 2400 N loads. The static pressure loading test of composite foundation is shown in Fig. 6(b) is shown.

3. Analysis of Test Results

3.1. Settlement Analysis

Fig. 7(a) to (e) is a comparison of load-settlement Q-S curve and Q-S curve of various pile-type capped pipe pile composite foundation. Fig. 7(f) shows the relationship between settlement difference and load of the bearing plate and pile top of each pile type composite foundation.

It can be seen from Fig 7 that the change law of load settlement curve of composite foundation with pipe-pile with cap & non-holes and three kinds of pipe-pile with cap & holes is basically similar. Comparing the four groups of model test Q-S curves, the total settlement of the pipe-pile with cap & bidirectional holes composite foundation reaches 7.69mm, and the total settlement value of the composite foundation with vented bidirectional pair holes is the smallest, which is 6.63mm. Compared with non-holes pipe piles, the total settlement of unidirectional pair holes, bidirectional pair holes and star pair holes pipe pile composite foundation decreases by 8.32%, 16.64% and 13.78%, respectively. The total settlement of the pipe-pile with cap & holes composite foundation and the settlement difference between the load plate and the pile top are smaller than the composite foundation of the pipe-pile with cap & non-holes. The total settlement of pipe-pile with cap & bidirectional holes composite foundation and the settlement difference between the load plate and the pile top are the smallest, which are respectively 6.41 mm and 0.91 mm. According to the provisions of reference[14] and the variation
Characteristics of each settlement curve, it can be deduced that the bearing capacity of the composite foundation of pipe-pile with cap & non-holes is 9.09 kPa, unidirectional pair holes, bidirectional pair holes and star pair holes. The bearing capacity of the pipe-pile with cap & holes composite foundation in the hole mode is respectively 9.87 kPa, 10.74 kPa, 10.58 kPa. Compared with the pipe-pile with cap & non-holes composite foundation, the improvement rates of the bearing capacity of the composite foundation with three kinds of pipe-pile with cap & holes are respectively 8.58%, 18.15% and 16.39%. From the data, the bearing capacity of the pipe-pile with cap & holes composite foundation with three kinds of opening methods is higher than that of the composite foundation of pipe-pile with cap & non-holes. The load shared by the soil around the pile in the pipe-pile with cap & holes composite foundation is higher than that of the composite foundation of pipe-pile with cap & non-holes. The analysis is due to the excessive pore water pressure generated by the extrusion of the soil during the static pressure pile sinking process, and the drainage channel of the pipe-pile with holes body allows the pore water to actively flow into the lumen, thereby reducing the water content of the soil around the pile. This in turn changes the bearing capacity of the soil, and better plays the role of the soil during the bearing process of the composite foundation.
3.2. Analysis of Axial Force of Pile Body

Fig. 8 is a graph showing the axial force versus depth of the pile body of the pipe-pile with cap & non-holes composite foundation and the pipe-pile with cap & bidirectional holes composite foundation. The axial strength values of the other two types of pipe-pile with cap & holes composite foundations are very close to the values of the pipe-pile with cap & bidirectional holes composite foundation, so details will not be further discussed here.

![Curves between pile axial force and depth](image)

From Fig. 8, the axial forces of the piles of each group of composite foundations increase with the increase of the load level, and gradually decrease along the depth direction. At a depth of 0.1 m, the load ratings of 300N, 600N and 900N correspond to the axial forces of the composite foundation of pipe-pile with cap & non-holes respectively being 72.28N, 117.74N and 169.29N, while the axial forces of the pipe-pile with cap & bidirectional holes composite foundation are respectively 71.05N, 111.28N and 151.43N. When load rating is 900N, the axial forces of pipe-pile with cap & non-holes composite foundation at 0.1m, 0.3m, 0.5m and 0.7m depths are 169.29N, 161.64N, 137.47N and 94.41N, while the axial forces of the pipe-pile with cap & bidirectional holes composite foundation are 151.43N, 142.04N, 117.86N and 55.12N. It is not difficult to see that the axial force of the pipe-pile with holes is less than the axial force of the pipe-pile without holes the same depth and the same depth. It can be seen from Fig. 8 that the axial force distribution of the pile-type composite foundation piles decreases with the increase of depth, and the axial force of the pile body increases with the increase of depth in the range of 0.5m–0.7m, which shows that the relative displacement of the pile and soil is large, and the side frictional resistance of the pile is fully exerted. When the load level reaches 1500N, the distribution of the axial force curve of each stage is relatively scattered, and then the axial force variation curve of each stage is concentrated, which indicates that the axial force of the pile increases slowly after each stage of load, and the soil between the piles plays an increasingly obvious role.

3.3. Analysis of Soil Pressure around Pile

The soil pressure between pipe-pile with cap & non-holes composite foundation and pipe-pile with cap & bidirectional holes composite foundation, and curve of soil pressure with load under pile cap are shown in Fig. 9 and Fig. 10.

![Curves of soil pressure between two pile caps](image)
It can be seen from Fig. 9 and Fig. 10 that the change of earth pressure experienced by the soil around the pile occurs within the entire length of the pile, and the earth pressure decreases as the depth deepens. When the load rating is 300N, the soil pressure of the soil with pipe-pile with cap & non-holes composite foundation at a depth of 0.0m~0.1m is close to 1kPa, and the soil pressure of the soil at a depth of 0.3m~0.7m is approximately 0.1kPa. By comparing the curve of soil pressure between pile cap and pile cap, it is not difficult to find that, as the loading grade gradually increases, the surface pressure of the soil between the pile caps is larger than the pressure of the soil under the pile cap, and the soil pressure between the pile caps on the soil surface is larger than the soil pressure under the pile cap. As the depth increases, the difference gradually decreases. This is mainly because under the vertical load, the upper load is transmitted to the cushion through the bearing plate to exert a pressure distribution on the pile cap and the soil between the piles. The pile cap stiffness is much larger than the soil and cushion between the piles, so it bears most of the load. The pile cap load is first transmitted to the deeper soil layer through the pile body. Due to the action of the pile cap and the cushion layer, the soil between the piles can share more loads. Comparing Fig. 9(a) and (b), it can be seen that the earth pressure between the pile cap and the composite foundation pile cap is reduced faster in the depth direction than the pipe-pile with cap & non-holes composite foundation. This feature, which is presented by the pressure distribution around the two types of piles composite foundation, further demonstrates that the pile opening can accelerate the drainage consolidation of the soil around the pile, so that the soil can share more overlying loads, thus better participating in composite foundation bearing.

3.4 Analysis of Pile Side Friction

The relationship between the side friction and the depth of each pile is shown in Fig. 11.

As shown in Fig. 11, the trend of the lateral frictional resistance of the unit area of the composite foundation of pipe-pile with cap & non-holes and the pipe-pile with cap & bidirectional holes is similar. The change of the lateral frictional resistance per unit area of the piles changes stepwise with the increase of depth. When the loading level is in the range of 300~2100N and the depth is 0.1~0.3m, the frictional resistance per unit area of the composite foundation of pipe-pile with cap & non-holes at the same
position under the same load is higher than the frictional resistance per unit area of the pipe-pile with cap & bidirectional holes composite foundation. When the load rating is 900N, the frictional resistance per unit area of the pipe-pile with cap & bidirectional holes composite foundation is about 0.4kPa, and when the load grade is 1800 N, the frictional resistance per unit area of the corresponding soil reaches 1.6kPa. This is mainly because the cushion layer plays a role in coordinating the relative deformation of the pile and soil. The upper soil settlement is larger than the lower soil, and the pile body stiffness is much larger than the soil body. The pile body itself has less compression deformation, resulting in a larger relative displacement of the lower pile soil. The lateral frictional resistance of the pile body can be fully exerted, which corresponds to the distribution law of the axial force of the pile body with depth in Fig. 8. During the whole loading process, with the increase of the load level, the variation curve of the frictional resistance per unit area of the pipe-pile with cap & non-holes composite foundation is more tightly distributed than that of the pipe-pile with cap & bidirectional holes composite foundation. When the load grade is greater than 1800N, the frictional resistance per unit area of the pipe-pile with cap & non-holes composite foundation is not obvious, while the frictional resistance per unit area of the composite foundation with the pipe-pile with cap & bidirectional holes increases greatly.

3.5. Analysis of Pile-soil Stress Ratio

The pile-soil stress ratio curve of the pipe-pile with cap & non-holes composite foundation and three different opening modes of pipe-pile with cap & holes is shown in Fig. 12. The variation law of the pile-soil stress ratio of each pile-type composite foundation with the increase of load can be obtained from Fig. 12. The pile-soil stress ratio of each pile-type composite foundation shows a small increase and then decrease until it gradually stabilizes with the increase of load. This phenomenon indicates that in the initial stage of loading, the ability of the soil to share the load between the piles is not fully exerted. At this time, the cap pile is mainly used to bear the overlying load. Then, as the load level increases, the soil between the piles begins to gradually play a bearing role. When the value of the load on the pile reaches its limit, the pile-soil stress ratio will drop sharply. In the range of load grade 900N~2100N, the pile-soil stress variation curves of the four pile-type capped pile composite foundations show a downward trend, and the slope of the subsequent change tends to be gentle, indicating that the pile-soil common load-bearing load reaches a stable state. When the load is loaded to 2100N step by step, the pile-soil stress ratios of the four pile-type capped piles with non-holes, unidirectional pair holes and bidirectional pair holes and star pair holes are 3.18, 3.10, 2.83 and 2.74, respectively. It is shown that the pile-soil stress ratio of the composite foundation with capped perforated pipe piles of three kinds of opening methods is smaller than that of the pipe-pile with cap & non-holes composite foundation. The comparison from big to small of the pile-soil stresses in the three kinds of pipe-pile with cap & holes composite foundations is as follows: unidirectional pair holes type, bidirectional pair holes, star pair holes pile type, which shows that the pipe-pile with cap & holes composite foundation can effectively improve the sharing effect of the soil around the pile on the overlying load.

Fig 12. Pile-soil stress ratio of composite foundation
4. Conclusion

1) The opening of the pile body provides a drainage channel for the pore water in the soil surrounding the pile during the static pressure pile sinking process, which accelerates the drainage consolidation of the soil around the pile. This can improve the load-carrying capacity of the surrounding soil in the pipe-pile with cap & holes composite foundation, thereby improving the bearing capacity of the composite foundation and effectively reducing the total settlement of the composite foundation.

2) Compared with the pipe-pile with cap & non-holes composite foundation, the total settlement value of the composite foundation with unidirectional pair holes, bidirectional pair holes and star pair holes pipe pile with cap is respectively reduced by 8.32%, 18.15% and 16.39%. The bearing capacity characteristic values respectively increase by 8.58%, 18.15%, and 16.39%;

3) Under the overlying load, the earth pressure on the soil surface and the lateral friction of the pile between the pile cap and the pipe-pile with cap & holes composite foundation are larger than that of the pipe-pile with cap & non-holes composite foundation. However, the axial force of the pipe-pile with holes body is smaller than that of the pipe-pile without holes body, and the soil load sharing capacity between the pile caps is larger than that of the pile cap.

4) The bearing behavior of pipe-pile with cap & holes composite foundation is affected by the opening method. Therefore, the bidirectional pair holes method has the most obvious advantages of exerting the load on the soil around the pile and reducing the total settlement of the composite foundation. The star pair holes pipe pile with cap comes second.

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