Macro-micro interaction mechanism between FRPC pile and sand under horizontal bidirectional load

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ABSTRACT

FRPC pile is a new type of composite pile formed by combining FRP material with traditional material. It has good physical and chemical erosion resistance, light weight, high strength and other advantages. Based on the particle image velocity measurement (PIV) technique, this paper studies the interaction between sand soil and FRPC pile by applying bidirectional horizontal load on the FRPC model pile embedded in sand soil. In the process of loading the FRPC model pile, a CCD high-speed industrial camera is used to take gray image of sand deformation around the test observation surface pile. DH3816 Strain Collecting Instrument was used to collect pile side strain, and image processing software PIVview2C was used to get displacement cloud picture. By analyzing the distribution of total displacement, horizontal displacement and vertical displacement of sandy soil under different loads, the micro mechanism of FRPC pile and sandy soil is clarified. The distribution of pile side moment was studied, and the macro mechanism of FRPC pile and sandy soil is clarified.

Keywords: FRPC pile, PIV (Particle Image Velocimetry) technology, bidirectional horizontal load, macro-micro mechanism

1 INTRODUCTION

With the rapid development of offshore wind power projects, the application of large-diameter single pile foundation is more and more common. The problem of durability is increasingly outstanding for pile with traditional material (steel, concrete, timber) in corrosive environment, which will require high maintenance and rehabilitation cost with high life-cycle cost. Concrete filled in FRP tube pipe pile [1] is a novel composite pile with many advantages such as good resistance to physical and chemical corrosion, light weight and high strength and so on. The application of FRP materials to offshore wind power projects will greatly improve the durability of pile foundation.

The performance of FRP materials is significantly different from that of traditional pile materials. These differences may lead to different interface properties of pile and soil, which play an important role in pile bearing capacity and load transfer. In order to study the bearing capacity of FRPC pile, Pando et al. [2] evaluated the friction between sand and FRP materials by using the interface shear test, and found that the interface friction Angle of FRPC pile depends on relative roughness, relative height and relative spacing. Frost et al. [3] not only studied the three factors mentioned by Pando that affect the interface performance, but also emphasized that the level of normal stress and the initial compactness of sandy soil also have an impact on interface performance. Axial and horizontal load tests on FRPC piles show that [4-6] is bilinear under axial load, and the restraint effect of FRP pipe is obvious. However, under bending load, the restraint effect is not particularly significant, and the ductility of the FRPC pile is improved. Dai guoliang et al. [7] made a preliminary analysis on the calculation method of horizontal bearing capacity of FRP composite cast-in-place pile. And through [8] analyzing the stiffness degradation, ductility and energy dissipation of FRPC pile, PHC pile and PRC pile, the seismic performance of FRPC pile was studied.

In recent years, digital image processing technology has been widely used. As an effective tool, PIV technology can intuitively observe the interface interaction between pile and soil. Zhou Jian et al. [9] carried out the process test of static pressure pile sinking in sandy soil, and studied the variation law of soil displacement field around pile at different stages of pile sinking according to the response mechanism of

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macroscopic mechanics. W et al. [10] developed a set of equipment for measuring soil deformation using PIV technology, and analyzed its feasibility and error. Chen et al. [11] studied the influence of different pile sinking speeds on horizontal and vertical displacement fields of soil around piles based on PIV technology. Wu Yuedong et al. [12] conducted penetration tests of soil tubes based on transparent soil and PIV technology, and obtained the distribution characteristics of soil mass disturbance and deformation field in the process of penetration. Qi et al. [13] studied the compaction effect of TC pile through PIV technology, and studied the deformation law of soil around the pile. Yuan et al. [14] designed a test system for measuring the displacement of soil around a pile with lateral load based on PIV technology to get the displacement field inside the soil and analyze the law of displacement changes inside the soil around a pile. Cao et al. [15-16] analyzed the variation law of displacement field of soil around pile based on transparent soil and PIV technology. With the development of digital image processing technology, particle image velocity measurement technology (PIV) [17] has been rapidly developed in the field of geotechnical engineering due to its characteristics of simple operation, full flow field measurement and non-interference. Three dimensional particle image velocity measurement technology reconstructs three-dimensional displacement field through two-dimensional displacement and camera parameters. Yuan et al. [18-19] studied the influence of lateral loading pile on soil surface settlement by using PIV technology.

Therefore, based on the digital image processing technology, it is an effective method to observe the interface interaction between FRPC pile and soil. Based on the PIV technology, this paper carried out the horizontal bidirectional test of FRPC pile, and measured the development and change of soil displacement field around the pile during the loading process of horizontal loaded pile. The displacement field of soil mass around FRPC pile under horizontal loading is obtained by measuring the displacement field of soil mass at different loading stages, and the law of the interaction between FRPC pile and soil is revealed.

2 TEST SCHEME

2.1 Mechanical properties of materials

The sand used in the test is the natural sand in Nanjing area, with uniform particles, discontinuous particle size and poor gradation. The gradation of granular material is 0.1 ~ 3 mm, the non-uniformity coefficient \( C_u = 3.436 \), the curvature coefficient \( C_s = 0.904 \), and the moisture content is 10.94%. Sandy soil cohesive force \( C = 8 \) kPa, internal friction Angle \( \phi = 320 \), specific weight \( G_s = 2.683 \), relative compactness \( D_r = 0.65 \). In sample preparation, layering is adopted to control the weight of each layer. After reaching the given height, another layer is laid, and the FRPC pile is close to the glass wall to avoid the flow of sand between the FRPC pile and the glass wall, resulting in excessive local displacement and affecting the overall analysis. After the laying is completed, the sand is kept static for 24h to be compacted under the action of dead weight to ensure the uniformity of soil samples in each test, and then the horizontal two-way load test is carried out.

FRP with outer diameter of 70mm, thickness of 7mm and pile length of 100cm were selected for the test. During the test, the FRP pipe was split along the central axis and half of it was filled with C30 concrete.

2.2 Loading device

A bidirectional cyclic load loading device suitable for model pile is designed in this test, and its device is shown in figure 1. The length of the model box is 0.9m, the width is 0.6m, and the depth is 1m. The length of the pile buried in the soil is \( L=0.8m \), and the pile diameter is \( d = 70 \) mm.

Using the elasticity of the spring dynamometer, first put a certain number of mass blocks in the tray, and then pull the spring dynamometer to the maximum load that the pile can bear. Then the model pile is fixed on the steel wire rope connected with the spring dynamometer. In order to take more photos of the interaction between FRPC pile and sand in the loading process, the loaded mass block was selected as 1.5g. 30 mass blocks were added on the tray before the test. Shooting is selected in the initial stage, adding the mass block in the tray, removing the added mass block, and reducing the mass block in the tray, and four pictures are shot in a cycle.

2.3 Test steps

(1) Layered landfill sand soil, The FRPC semi-pile is embedded in the sand;
(2) Add 30 mass blocks to the Tray and fix the model pile on the wire rope connected with the spring dynamometer.
(3) The experiment was carried out in the evening to provide a stable light environment. The camera was fixed on the support.
(4) Turn on the laser, fix the CCD camera on camera bracket, and adjust the camera position and focal length to obtain the appropriate field of view;
(5) Take four pictures in a cycle, and wait for each level to be loaded and stabilized, then take the model images under that level of load;
(6) By processing the images taken before and after loading with PIV software, the displacement field of soil around the pile before and after loading can be obtained.
(7) The strain gauge is attached to the pile body, and the same sand soil, landfill method and loading method are used to measure the strain change data of the pile body. The arrangement of strain gauge is shown in Fig.
2. Starting from 20cm below the pile tip, one strain gauge is pasted every 5cm in the section from 20cm to 90cm, and a total of 28 pieces of symmetrical patches are pasted on both sides.

3 TEST RESULTS AND ANALYSIS

3.1 Load-displacement curve of pile head

Fig. 3 shows the relationship curve between horizontal load $P$ of pile head and pile displacement on soil surface. When $|P|<117.6N$, the pile head displacement increases little with the increase of load; When $|P|<117.6N$, the pile head displacement increases rapidly and the failure curve is of steep drop type, which presents the typical characteristics of dense sand. When $|P|=294N$, the crack shown in Fig. 4 appears on the pile body 0.245 m away from the sand surface, and the through crack appears on the pile body and damages.

3.2 Analysis of PIV processing results

Fig. 5, Fig. 6 and Fig. 7 show the total displacement cloud diagram, horizontal displacement cloud diagram and vertical displacement cloud diagram of FRPC semi-formed pile and soil at different loading stages. As can be seen from the total displacement cloud diagram in Fig.5, when $P=117.6N$, the total displacement of the FRPC semi-formwork pile and soil is small, and the pile rotates around a point on the central axis (the position with the smallest displacement). This is because as the load increases, Semi-pile separates from sand, which is consistent with the phenomenon shown in Fig. 5 (c) and (d). When $P=294N$, the separation between the sand and the FRP pile is more serious. A point on the central axis moves more left and right under the horizontal two-way load, and the total displacement of the upper and lower regions is greater than that of other regions. This phenomenon clarifies that the movement of the rigid pile under horizontal two-way load and the disturbance of pile to sand soil mainly occur at both ends of pile.

As can be seen from the cloud chart of horizontal displacement in Fig. 6, when $P=117.6N$, the horizontal displacement of the FRPC semi-pile and soil is small. Under the action of the FRPC pile, the displacement of sand around the pile is distributed in layers, and gradually increases from left to right, showing obvious stratification.
As can be seen from the vertical displacement cloud diagram in Fig. 7, when \( P=117.6 \) N, the vertical displacement of the FRPC semi-pile and soil is distributed in layers. As the depth increases, the vertical displacement of the sandy soil gradually decreases. This phenomenon shows that the disturbance of the FRPC half-mode under the horizontal two-way load starts from the surface of the sandy soil. When \( P=294 \) N, the stratification phenomenon and vertical displacement of sandy soil around the pile increase more obviously. This indicates that the disturbance of the pile on the sandy soil is stratified from top to bottom and affects the soil outward along the periphery of the pile.

### 3.3 Macro analysis

Under the action of external load, the FRP pipe and concrete bond well, and the interface between FRP pipe and concrete will not produce relative displacement. Based on this, the Voigt model for calculating equivalent elastic modulus is established [20]. The Voigt model is used to solve the elastic modulus of FRPC composite pile as follows

\[
E = \lambda_1 E_1 + \lambda_2 E_2
\]  

(1)

Where \( E \), \( E_1 \) and \( E_2 \) are respectively the elastic modulus of FRPC pile, the elastic modulus of FRP and the elastic modulus of concrete. \( \lambda_1 \) and \( \lambda_2 \) are the volume fraction of FRP and concrete, where \( \lambda_1 + \lambda_2 = 1 \).

The outer diameter and wall thickness were selected as 70mm and 7mm respectively, so \( \lambda_2 = 64\% \), \( E_1 = 2.3 \times 10^7 \) kN/m\(^2\), \( E_2 = 3.04 \times 10^7 \) kN/m\(^2\). According to (1) yields

\[
E_p = \lambda_1 E_1 + \lambda_2 E_2 = 2.77 \times 10^7 \text{kN/m}^2
\]  

(2)

According to the model test, the tensile strain \( \varepsilon_+ \) and compressive strain \( \varepsilon_- \) at the measuring points of each section are obtained, and the corresponding bending moment of the section can be calculated according to the bending strain \( \Delta \varepsilon = \varepsilon_+ - \varepsilon_- \) at the section.

According to the theory of material mechanics, \( \sigma = \frac{MY}{I} \) and \( \sigma = \frac{E \varepsilon}{b_0} \), we can give

\[
M = \frac{EI \Delta \varepsilon}{b_0}
\]  

(3)

Where \( M \) is the bending moment of each measuring point of the pile body, \( \varepsilon \) is the measured strain value of each measuring point of the pile body, \( EI \) is the bending stiffness of the pile, and \( b_0 \) is the external radius of the FRP model pile (\( b_0 \) is 35mm).

According to Equation (3), the distribution of pile bending moment under different loads is shown in Fig. 8. It can be found from Fig. 9 that the bending moment of pile body increases first and then decreases along the depth; With the increase of load \( P \), the bending moment of pile increases, and the position producing the maximum bending moment tends to move down with the increase of load. According to Fig. 4, it can be seen that the location of the crack on the pile body is 0.245m away from the ground surface, that is, the crack appears near the position of the maximum bending moment of the pile body when the max horizontal load \( P=294 \) N.

### 4 CONCLUSION

Based on PIV technology, this paper conducts experimental analysis on the displacement field and bending moment distribution of sand around FRPC pile under horizontal two-way load, and obtains the following conclusions:

(1) According to the total displacement cloud diagram, when the horizontal two-way load is small, the total displacement of the FRPC semi-load is small, and the pile rotates around a point on the central
axis, from which point it increases outward. When the load increases to a certain stage, the pile under bi-directional load rotation around the center area, the point on the axis under horizontal bi-directional load around mobile, with the increase of load, sandy soil and FRP piles from much more serious, the point on the axis in horizontal bi-directional load was moving around more, upper and lower regions of the total displacement is larger than in other parts of the displacement; This phenomenon makes it more clear that the FRPC pile rotates around the middle area under the horizontal two-way load, and the soil disturbance mainly occurs at both ends of the pile.

(2) According to the cloud chart of horizontal displacement, it can be found that when the horizontal two-way load is small, the sand displacement around the FRPC pile is distributed in vertical layers and increases gradually from left to right. With the increase of the load, the upper part and the right part produce positive displacement, the lower part and the left part produce negative displacement, and the middle part has the smallest displacement. This phenomenon makes it more clear that the FRPC semi-modular pile rotates around the region with the smallest displacement.

(3) According to vertical displacement contours can be found that when the level of bi-directional load is small, FRPC vertical displacement of soil around pile along the horizontal layers, with the increase of load, the soil of the vertical displacement increases in layers, the increase of the vertical displacement of pile position than others, it shows that the pile of sand disturbance from weeks down into layers, up and down along the pile to outside influence.

(4) According to the bending moment diagram of pile body under different loads, it can be found that with the increase of load, the bending moment of pile body increases, and the position producing the maximum bending moment moves down. By comparing the position where the maximum bending moment of the pile is generated with the position where the pile body is cracked and destroyed, it is found that the crack appears near the position of the maximum bending moment of the pile body when the maximum load is P=294 N.

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