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The Centrifuge Model Test on Bearing Characteristics of Suction Pile-Bucket Composite Foundation in Soft Clay

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Abstract: The suction pile-bucket composite foundation, as a new type of offshore wind power foundation, is receiving increasing attention. To study the bearing characteristics of the suction pile-bucket composite foundation under soft clay conditions, this paper conducts small-scale centrifuge model tests on the suction pile-bucket composite foundation under vertical (V) and combined vertical-horizontal (V-H) loading forms. The experimental results indicate that the soil surrounding the foundation subsides significantly after loading. Additionally, the soil opposite to the direction of the foundation's horizontal displacement forms a circular failure surface around the foundation, with the deformation magnitude gradually decreasing outward. The unidirectional load-displacement (F_z-s) curve of the composite foundation in clay conditions is analyzed, and it is found that increasing the length of the suction pile can effectively improve the bearing capacity of the foundation synergy. Finally, the V-H envelope curve of the bearing capacity of the suction pile-bucket composite foundation under soft clay conditions is drawn, which approximately presents a quarter-ellipse shape and shows obvious symmetry.

1. Introduction

Compared with onshore wind farms, offshore wind farms have the advantages of saving land resources, higher and more consistent wind speeds, being unaffected by complex terrain, and minimal impact on the surrounding environment. Therefore, offshore wind power has become a trend in future energy development [1-2]. Taking into account the load characteristics of offshore wind farms and the soil conditions of China's offshore areas, the Offshore Wind Power Research

Group of Tianjin University has developed a suction pile-bucket composite foundation structure [3]. This foundation effectively combines the strong vertical bearing capacity of pile foundations with the excellent resistance to horizontal deformation of bucket foundations, allowing the pile and bucket to work together, minimizing displacement at the pile top and mudline, and fully utilizing their respective bearing capacities [4].

Many scholars have conducted research on the bearing capacity of suction pile-bucket composite foundations using model experiments [5-7]. This study conducts small-scale centrifuge model tests on the suction pile-bucket composite foundation under vertical (V) and combined vertical-horizontal (V-H) loading forms. The experimental results show that the soil around the foundation subsides significantly after loading, and the soil in the opposite direction to the foundation's horizontal displacement forms a circular failure surface around the foundation, with the deformation magnitude decreasing gradually outward. The unidirectional load-displacement (F_z-s) curve of the composite foundation in clay conditions is analyzed, and it is found that increasing the length of the pile can effectively improve the bearing capacity of the foundation synergy. Finally, the V-H envelope curve of the bearing capacity of the suction pile-bucket composite foundation under soft clay conditions is drawn, which approximately presents a quarter-ellipse shape and shows obvious symmetry, providing a certain reference for the vertical bearing capacity design of suction pile-bucket composite foundations in the future.

2. Centrifuge Model Test Schemes

This test was conducted on the TLJ-100A geotechnical centrifuge apparatus at the Geotechnical Engineering Research Institute, School of Civil Engineering, Tianjin University, as shown in Figure 1. A scale ratio of 1:100 was used for this centrifuge test, meaning the test was carried out in a 100g acceleration field. To investigate the bearing characteristics of the suction pile-bucket composite foundation, a small-scale model with a scale ratio of 1:100 was created for the composite foundation on soft clay with D=11m, H=4m, d=4m, and h=6m and 8m (where D is the bucket diameter, H is the suction pile length, d is the suction pile diameter, and h is the bucket height), as shown in Figure 2. The only difference in the model dimensions is the length of the suction pile, designating the shorter pile length as model M-1 and the longer one as model M-2. The test soil was prepared from standard kaolin. In the preparation process, dry kaolin was first poured into a mixer, and then an appropriate amount of water was added and thoroughly mixed to form a slurry with approximately twice the liquid limit. The slurry was then poured into the model box and allowed to consolidate for 30 days, as shown in Figure 3.

The test employs the three-degree-of-freedom loading mechanical arm system at the Geotechnical Institute of Tianjin University (as is shown in Figure 4). This device can apply single-direction loading in the X, Y, and Z directions. According to Xu and Zhang [8], when the shortest distance between the model foundation and the boundary is not less than three times the pile diameter, the boundary effect on the test results can be ignored. Therefore, the test was conducted at the center of the model box to minimize the influence of boundary effects. The foundation was installed under constant acceleration conditions as high acceleration conditions could cause uneven vertical displacement of the soil around the pile under hypergravity, thereby affecting the test results [9].

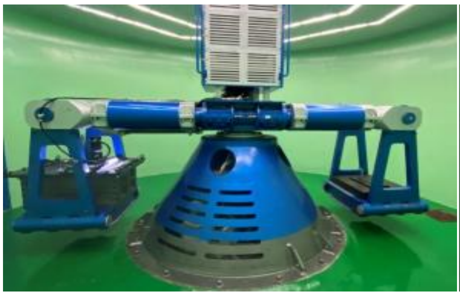


Figure 1: Geotechnical centrifuge

Figure 2: 1:100 Small-scale models

Figure 3: Test clay

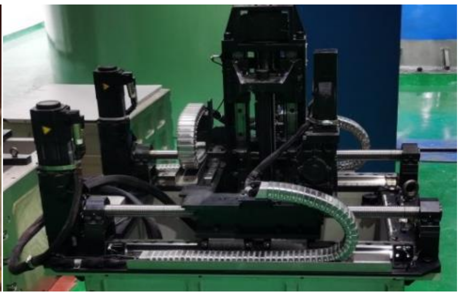


Figure 4: Multi-axis robotic system

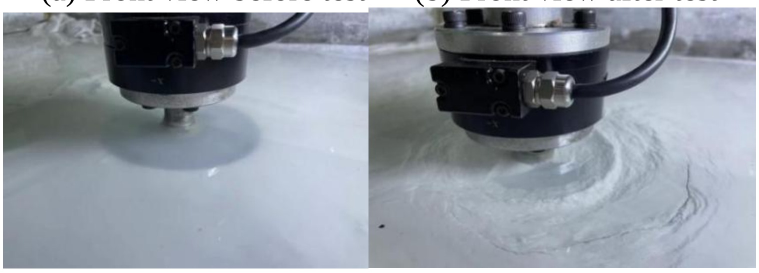
3. Experimental Results and Discussion

During the test, the vertical monotonic loading was applied to the composite foundation at a controlled rate of 1 mm/s as suggested by Stewart and Randolph [10]. Once the vertical loading reached the desired position, it was halted, and horizontal displacement was then applied to the foundation top until it reached the preset position. The horizontal loading speed was controlled at 0.5 mm/s, ensuring the soil remained in an undrained condition throughout the loading process. The changes in the model and soil before and after the test are shown in Figure 5. After the combined load was applied, significant subsidence of the soil around the foundation was observed, with deformation magnitude diminishing outward. The plastic strain was mainly distributed near the pile-soil interface. The foundation tilted slightly in the direction of the horizontal displacement, while a circular failure surface formed around the foundation in the opposite direction.

The vertical loading phase results were analyzed, as shown in Figure 6. The entire bearing capacity curve showed no obvious inflection points, therefore, the vertical ultimate bearing capacity P_u was defined as the bearing capacity corresponding to a vertical displacement of 0.1D for the suction pile-bucket composite foundation on soft clay. The vertical ultimate bearing capacity was 2.01 MN for the M-1 model and 2.11 MN for the M-2 model.

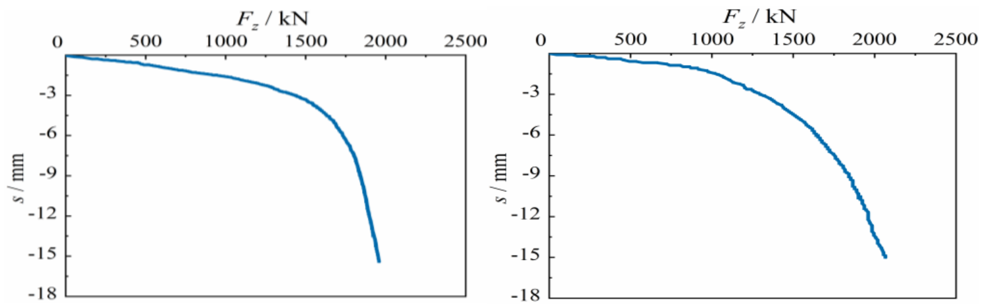
Based on the trend of the envelope curve of the suction pile-tube composite foundation under vertical and horizontal combined loads shown in Figure 7, the unidirectional ultimate bearing capacity of the foundation can be inferred. From the trend line analysis, the vertical ultimate bearing capacity of M-1 is approximately 2 MN, while that of M-2 is approximately 2.2 MN. The inferred values closely match the data measured by centrifugal experiments, confirming their validity. Therefore, it can be inferred that the horizontal ultimate bearing capacity of M-1 is approximately 1.53 MN, and that of M-2 is approximately 1.61 MN.

(a) Front view before test (b) Front view after test



(c) Side view before test (d) Side view after test

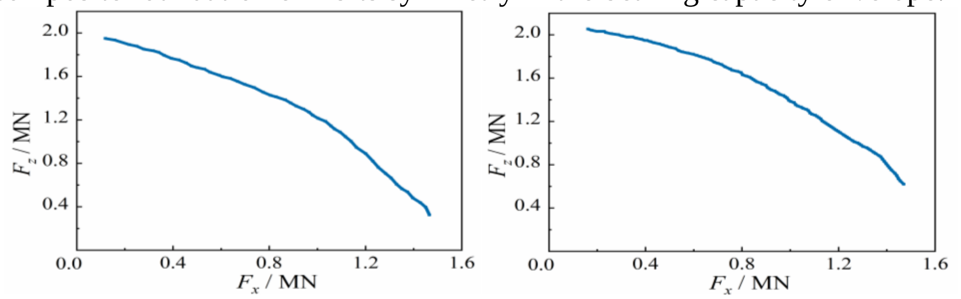
Figure 5: Model and soil before and after test



(a) M-1 (b) M-2

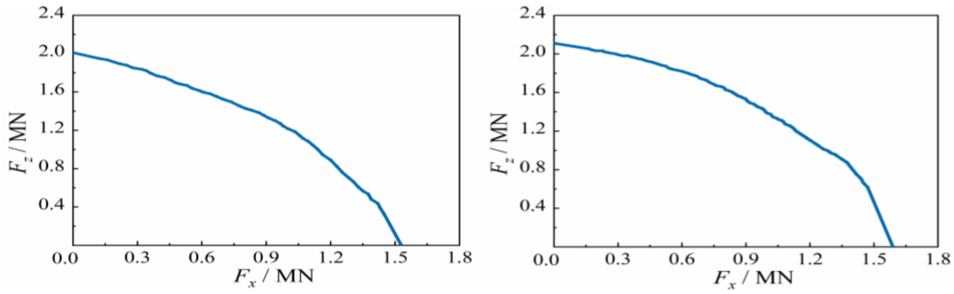
Figure 6: Vertical load-displacement curves

Thus, the complete *V-H* envelope curve for the suction pile-tube composite foundation under soft clay conditions for the M-1 and M-2 models can be illustrated (as shown in Figure 8). The sizes of the envelopes for the two models differ, but their shapes are similar, both roughly presenting a quarter-ellipse shape, indicating that the V-H two-dimensional loading mode of the suction pile-bucket composite foundation exhibits symmetry in the bearing capacity envelope.



(a)M-1 (b)M-2

Figure 7: The partial *V-H* envelope diagram of the composite foundation



(a)M-1 (b)M-2

Figure 8: The *V-H* envelope diagram of the composite foundation

4. Conclusion

This paper conducted a 1:100 small-scale centrifuge model test to study and analyze the bearing capacity Characteristics of the suction pile-bucket composite foundation on soft clay under vertical (*V*) and combined vertical-horizontal (*V-H*) loading conditions. The conclusions are as follows:

(1) After the combined load was applied, significant subsidence of the soil around the foundation was observed, with deformation magnitude diminishing outward. The plastic strain was mainly distributed near the pile-soil interface. The foundation tilted slightly in the direction of the horizontal displacement, while a circular failure surface formed around the foundation in the opposite direction.

(2) The vertical load-displacement (F_z-s) curve of the composite foundation under clay conditions was plotted. The load response of the foundation is linear during the initial loading phase; however, as the loading continues and reaches a certain threshold, further increase in load results in a significant rise in the total displacement of the foundation. The entire bearing capacity curve exhibits no distinct inflection point.

(3) The complete *V-H* envelope curve of the suction pile-bucket composite foundation under soft clay conditions was plotted. The envelope sizes vary but their shapes are similar, roughly forming a quarter-ellipse. It is evident that the bearing capacity envelope of the suction pile-bucket composite foundation exhibits symmetry under the *V-H* two-dimensional loading mode.

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