Experiments on loading capability of Inclined Suction Foundation

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Abstract. Suction foundation, as a new type of marine anchoring foundation, has the advantages of reuse, fast construction, and large vertical bearing capacity. In this paper, through a self-developed bearing capacity test device, a series of load-bearing performance tests of the suction foundation are performed to reproduce the bearing characteristics of the suction foundation under the action of the pull-up load. It can be found that bearing capacity of suction foundation increases with the penetration, and the influence of the inclination angle on the bearing capacity of the suction foundation is in a middle value range.

1. Introduction

Nowadays, more and more marine engineering are being applied to suction foundations. However, due to the complexity of the marine environment, the suction foundation is prone to tilt during the penetration process. This is often caused by various factors such as soil inhomogeneity, water flow conditions and so on. To a certain extent, the bearing capacity and service life of the suction foundation are affected in the process, and it is easy to cause offshore platform safety accidents and huge economic losses. Therefore, studying the load-bearing performance of the suction foundation under inclined conditions to provide a reference for engineering applications and developing a method to solve the inclination of the suction foundation during penetration are significant for ensuring the safety of offshore platforms. There are many researches having been done on suction foundations. Bye [1] obtained the relationship between the foundation bearing capacity and the characteristics of the sand and the loading method by tests. Gharbawy [2, 3, 4] and Clustery [5] carried out pull-up tests of bearing capacity in different directions on deep normal consolidated clay grounds in the Gulf of Mexico, and obtained the influencing factors of suction caissons foundations. Narasimha [6] studied the relationship between bearing capacity and penetration depth through suction foundation pull-up tests under different aspect ratios. Fuglsang and Steensen-Bachand [7, 8] carried out pull-out bearing capacity tests in clay and sand, and it was found that the negative pressure in the bucket can improve the foundation load. Allersma [9, 10] performed centrifugal tests on suction anchors under different loads to study the effects of factors such as loading rate and tensile angle. Waston and Randolph [11, 12] studied the load-bearing relationship curve under drainage conditions. However, there are many problems related to vertical installation of suction buckets due to the complex ocean wave current and seabed geological conditions, which may cause the decrease of bearing capacity of the suction buckets after inclined installation [13, 14]. In this paper, through a self-developed bearing capacity test device, a series of load-bearing performance tests of the suction foundation are performed to reproduce the bearing characteristics of the suction foundation under the action of the pull-up load, and the influence of inclination angle and penetration depth on suction foundation bearing capacity is studied.
2. Test equipment and materials

2.1 Test device

The test is carried out in a wave flume of Tongji University Water Conservancy Port Comprehensive Laboratory. The flume is 50 m long, 0.8 m wide and 1.2 m high. There is a soil trough 20m away from the upstream inlet in the water trough, and it is 2.7m long, 0.64m wide and 1m deep. The top of the soil trough is flush with the bottom of the water trough. The test is performed on the soil trough, and the flow rate is controlled by the operating system of the water trough. In order to truly reproduce the pull-up bearing process of the suction foundation in the soil, a special indoor test device (Fig. 1) needs to be developed and manufactured, which can carry out anchor loading tests under different conditions.

![Test device](image1)

The test device consists of four parts:

1. Negative pressure penetrating system. For the penetrating installation of suction foundations, the negative pressure control accuracy needs to be sufficiently high, and it can maintain the negative pressure automatically to meet the penetrating requirements of suction foundations during the test, and ensure the test accuracy.

2. Suction foundation model. Based on the test conditions and the possible application of the engineering, this test uses a suction-based foundation model made of plexiglass. The deformation of the model's own structure is not considered in the test.

3. Loading system. The loading system that used to provide the pull loading must be able to achieve sufficient loading force, and it is convenient to monitor its pull loading displacement and value in real time during the loading process.

4. Data acquisition system. The data acquisition system mainly includes real-time collection of data such as pull loading displacement and value during the loading process, and at the same time, the tensile force measured by the tension sensor can be intuitively displayed on the screen for convenient reading.

2.2 Test preparation

2.2.1 Soil sample preparation. The sandy soil used in this test is processed soil. It has a dry density of 1.56g / cm³, a saturated density of 1.99g / cm³, and a porosity of 0.77. In order to analyze the soil particles, the gradation curve of the soil sample is made by the screening method. The soil sample weigh 504g before the test. After sieving, the weight of the soil samples remaining in the sieve boxes of each specification is recorded. And the gradation curve is drawn according to the data, as shown in Fig. 3. From the grading curve, it can be known that the soil particles are concentrated in the particle size range from 0.1 to 0.25 mm. According to the specifications, the sandy soil is fine sand. The median particle diameter of the soil sample is 0.16 mm, and the soil is homogeneous.
A high-precision permeameter is used to conduct the permeability coefficient test. The permeameter changes the water head to expel the gas in the soil and saturate the soil sample so that the test can be performed. During the experiment, the head height is recorded in different time periods to obtain the penetration speed of the soil sample. The change in head loss is due to osmotic loss. According to the relevant formula, the permeability coefficient of the soil is calculated to be $2.80 \times 10^{-5} \text{ m/s}$.

2.2.2 Test arrangement. Before the test, the sandy soil is laid in layers in a soil trough and submerged with water for at least 48 hours. This is to ensure that the soil is fully saturated. After the soil body saturated, the water trough needs to be flushed again in order to facilitate the observation during the test. This process is to make the water clear, so that the subsequent shooting and viewing test process is more convenient. In consideration of avoiding the influence of the side wall of the soil trough during the test, the suction foundation is placed 50 cm away from the side wall behind the soil trough. The average velocity of the water flow section is measured by propeller flow meter. In order to avoid the measurement errors caused by the presence of soil at soil trough, the propeller flow meter places near upstream. The steel frame is erected above the suction foundation and fixed.

![Particle gradation curve](image1)

**Figure 3.** Particle gradation curve.

![Inclined penetration process](image2)

**Figure 4.** Inclined penetration process.

2.3 Test conditions

In order to investigate the change law of the suction foundation carrying capacity, a total of 9 working conditions for 3 groups of tests are designed (as shown in Table 1). These experiments investigate the effect of the inclination angle and penetration depth on the bearing capacity of the suction foundation. The control group reflects the bearing capacity characteristics of the suction foundation under vertical penetration.

| Group       | Number | Inclination angle (°) | Penetration depth (cm) |
|-------------|--------|-----------------------|------------------------|
| Control Group | 1      |                       | 24                     |
|             | 2      | 0                     | 30                     |
|             | 3      |                       | 36                     |
| Group D.I.A | 4      | 10                    |                        |
|             | 5      | 15                    | 30                     |
|             | 6      | 20                    |                        |
| Group D.P.D | 7      |                       | 24                     |
|             | 8      | 15                    | 30                     |
|             | 9      |                       | 36                     |
3. Test results and analysis

3.1 Analysis of bearing capacity of suction foundation in vertical penetrating

Fig. 5 is the displacement curve of the bearing capacity of the suction foundation under different penetration depths during vertical penetration. It can be seen from the Fig. 5 that the change of the bearing capacity-displacement curve of the suction foundation in the soil is mainly divided into three stages, that is, the fast-rising stage, the gradual-falling stage, and the residual bearing capacity stage. In the fast-rising stage, the bearing capacity of suction foundation under different conditions all rises rapidly in the form of a power function. When the penetration depth increases linearly, the increasing rate of bearing capacity increases accordingly. It can be explained that as the penetration depth of the foundation increases, the peak bearing capacity of the foundation increases. And the increasing trend further increases with the depth. Therefore, this paper uses a linear function to fit the data series, as shown in Fig. 6.

![Figure 5. Bearing capacity-displacement curve in vertical penetrating.](image)

![Figure 6. Relationship between bearing capacity and penetration depth.](image)

3.2 Foundation bearing capacity corresponding to different inclination angles in inclined state

Fig. 7 is the bearing capacity-displacement curve of the suction foundation at the penetration depth of 30cm and the corresponding inclination angles of 10°, 15° and 20°. At this penetration depth, the bearing capacity of suction foundation in vertical penetration is 0.823kN. It can be found that when the degree of inclination is small, the bearing capacity of the suction foundation is about 0.8kN, which is not much different from the bearing capacity in the vertical penetration. As the foundation tilt increases to 15°, the peak bearing capacity is only 0.702kN, which is significantly lower than in the
vertical state. When the foundation continues to tilt to 20°, the peak bearing capacity is 0.628kN, and the gap is even more pronounced. Therefore, it can be concluded that as the inclination angle of the suction foundation increases, the peak bearing capacity will continue to decrease. From the degree of decline, in the early stage of the increase of inclination, the bearing capacity of the suction foundation is weakly affected by the inclination angle. When the inclination angle ranges from 10° to 15°, the bearing capacity is greatly affected by the inclination angle. In the latter stage of the inclination, the influence of the inclination angle on the bearing capacity is between the first two stages. Therefore, the influence of the inclination angle on the bearing capacity of the suction foundation is in a middle value range.

3.3 Foundation bearing capacity corresponding to different penetration depths in inclined state

Fig. 8 is the bearing capacity-displacement curve of the suction foundation at different penetration depths when the inclination angle is 15°. Comparing Fig. 9 and Fig. 6, it can be found that the bearing capacity-displacement curves of the suction foundation rise and fall in the same law during the drawing process. Then from Fig. 9, it can be observed that the bearing capacity of the suction foundation is lower than that in the vertical penetration when it is in the inclined state. Among them, the decrease is the smallest when the penetration depth is 24 cm, followed by the penetration depth of 30 cm, and the bearing capacity decreased the most when the penetration depth is 36 cm. From this, it can be shown that the suction foundation bearing capacity will decrease in an inclined state, and as the penetration depth increases, the decrease of the suction foundation bearing capacity also increases.

4. Conclusions

In this paper, the bearing capacity-displacement curve of the suction foundation at different inclination angles and the bearing performance characteristics during the pull-up process are studied through the self-developed bearing test device. The main conclusions reached are as follows:

(1) During the pull-up process, the bearing capacity-displacement curve of the suction foundation is mainly divided into three stages, namely, the fast-rising stage, the gradual-falling stage, and the residual bearing capacity stage.
(2) After the suction foundation penetrates into the soil, its bearing capacity increases with the penetration depth, and the increase trend is approximately a linear function.

(3) In the inclined state, the bearing capacity of the suction foundation will continue to decrease as the inclination angle increases. When the inclination angle is within 10°, the reduction of the foundation bearing capacity is small. When the inclination angle reaches 10°, the bearing capacity decreases by 5%. The reduction of the foundation bearing capacity begins to increase when the inclination angle is range from 10° to 20°. When the inclination angle reaches 20°, the bearing capacity decreases by 25%.

5. Acknowledgments

This work is financially supported by the National Natural Science Foundation of China [grant 51479137].

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