The centrifuge experiments on influence of inclination on bearing capacity of the suction bucket

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Abstract: To study the mechanism of bearing capacity of a suction bucket, a series of centrifugal tests were designed to investigate the uplift bearing capacity, and the entire dynamic process of pore water pressure were monitored as well. The results show that with the increase of inclined degree of suction foundation, the bearing capacity of suction foundation decreases continuously, and the influence of inclination on the foundation bearing capacity is obvious.

1. Introduction
Suction foundation is an indispensable link in the application of offshore and deep-sea platforms, and its bearing capacity characteristics need to be tested strictly and demonstrated theoretically. At present, the bearing capacity of suction foundation is mainly studied under the vertical state. Jiao B T [1] studied the basic pulling force law of different loading rates and bucket height by conducting a series of experiments on the bucket body drawing. Xu B [2] studied the pull-out resistance of suction foundation under inclined load and vertical load respectively, and obtained the normalized bearing capacity of suction foundation by finite element numerical simulation. Le Chi Hung [3] proposed that vertical bearing capacity increases with the increase of barrel skirt length/barrel diameter. The suction caissons were pulled out under various uplift rate. While horizontal bearing capacity was linear when L/D<0.5, and the rest was non-linear. Li D Y [4] analyzed the relationship between the friction resistance of the barrel wall and the bearing capacity of the barrel tip when the buried depth changed, and proposed an analytical expression to calculate the bearing capacity of the foundation. Li D Y [5] studied the pull-out and load-bearing characteristics of skirt suction foundation in saturated fine sand based on model test, results show that the ultimate uplift bearing capacity increases with the height and width of the skirted structure increasing.

However, in the deep-sea environment, the uncertainty of water flow and the complexity of seabed topography make it difficult to conduct penetration in a completely vertical direction during the suction bucket penetration. At the same time, in the process of inclined penetration of suction bucket, due to the in-fluence of water flow, soil pits caused by water erosion will be formed around the suction bucket. This is bound to lead to a decrease in the carrying capacity of the suction bucket. Therefore, the change of bearing capacity characteristics and the change of ultimate bearing capacity after tilting need further careful study.

Based on this, in this study, aiming at different suction type foundation slope, tests adopt vertical continuous loading method, simulates the corresponding pull-out centrifuge respectively, to get the suction type limited bearing capacity of foundation under different tilt state. Results show that with the tilt increasing in suction type foundation, bearing capacity is reduced, and the influence of inclination on the foundation bearing capacity is obvious.
2. Centrifuge model test design

2.1. Preparation of soil samples
The soil used in this test is processed soil. The particle gradation curve of soil sample is shown in Figure 1, and the physical parameters: The moisture content is 20.6%, the angle of internal friction is 25.8°, and cohesive force is 9.41KPa.

Because the soil particles used in the test are fine and contain some clay particles, if water is added directly, part of the soil will be clumpy, the layered mud mixing method was adopted in this test. The whole test soil was made in three layers, with a total height of 30cm and each layer height of 10cm. Clear water was added in the bucket before sample preparation, and then the dried soil particles were scattered evenly in the bucket, and then stir with an agitator until the mud and water were fully mixed, the last, after the production the mud was poured into the model box evenly. The consolidation process of the mud was completed in the model box.

![Grading curve of the soil used in test.](image)

2.2. Experimental equipment
The static loading centrifuge model test device (Figure 2) was design independently and completed on the basis of the existing geotechnical centrifuge (Figure 3) in Tongji university. The dimensions of the model box (Figure 4) are 700mm long, 500mm wide and 600mm high. The dimensions of the suction bucket model are 100mm in diameter, 100mm in height and 0.5mm in wall thickness. Main parameters of the centrifuge: the maximum load capacity is 150g -t, and the effective radius of the rotating arm is 3.0m. The teleoperation dynamic measurement system can record the change law of mechanical parameters completely in the static loading process through digital camera, camera, pore pressure sensor (1# -3 #).
2.3. Experimental process
The main steps of the test are as follows:

(1) After the model box was installed in place, turned on the camera to keep synchronous monitoring, and then closed the door of the centrifuge laboratory and started the centrifuge dragging device to drive the basket to rotate and increased the centrifugal acceleration to keep it at 50g steadily.

(2) After the hole pressure and soil pressure were stable, the solenoid valve on the water tank was opened, so that the water flow in the water tank can flow into the loading box at a constant speed and stably, and the suction foundation can start to play an anti-pull-out bearing capacity.

(3) When the displacement pointer showed obvious upward displacement and the drawing speed was accelerated obviously on the basis of suction type, the solenoid valve was closed and the inlet process of the loading box was completed. At this time, sensor detection data were recorded.

3. Centrifugal test results and analysis
The test centrifuge kept the centrifugal acceleration at 50 g, aiming at 0 °, 5 °, 15 ° three different suction type base tilt state (Table 1), the centrifugal simulation tests of the corresponding pull-out bearing capacity were carried out respectively. The changes of pore pressure in the process of soil failure were monitored by pore pressure sensors. The vertical continuous loading method (as shown in Figure 2) was adopted in the test to increase the ultimate bearing capacity of the suction foundation in the saturated silty soil foundation. The displacement of the suction foundation in the process of pulling
out was taken as the monitoring variable to test the ultimate bearing capacity of the suction foundation in the saturated silty soil foundation.

Table 1. Test case table.

| Test  | Degree of inclination of suction foundation (°) | Centrifugal acceleration (m·s⁻²) |
|-------|-----------------------------------------------|---------------------------------|
| Test 1| 0                                              | 50                              |
| Test 2| 5                                              | 50                              |
| Test 3| 15                                             | 50                              |

3.1. Analysis of pore pressure change

Three pore water pressure gauges #2, #1, and #3 (Figure 2) were arranged on the left, middle, and right sides of the suction bucket to record the pore water pressure in the soil during the test. It can be seen from the test data that the variation law of pore pressure is similar under three working conditions with different tilt angles relatively. Considered suction type based on the slope of 0° state change of the pore pressure in the process of pulling (Figure 5), when the suction foundation is pulled up, the pore pressure is disturbed, and the most obvious disturbance is the pore pressure of #1. The pore pressure of #2 and #3 drops slightly in 20s-40s, and then continues to rise, this is because the water around the bucket base flows into the bucket during the uplift process, resulting in the rise of water level in the bucket, the decrease of pore volume and the overall upward trend of pore pressure.

Figure 5. The change of pore pressure in the suction foundation.

3.2. Influence of inclination on displacement time curve of suction barrel top

Taking test 1 as an example, the suction foundation rose at a constant speed throughout the drawing resistance process without a large displacement point. However, when the displacement reached 5.1cm, the barrel body has been pulled out, and the load at this time was taken as the ultimate bearing capacity of the suction foundation under this condition.
Figure 6. Curves of versus deflection time of sinking through barrel body at different tilt angles.

Comparing three curves in Figure 6, it can be found that: with the increase of tilt angle, displacement increased faster. When the displacement of the vertically immersed barrel reached 5.1cm, it was pulled out after 45s; Tilt 5° penetration barrel was pulled out when displacement was 5.1 cm, after 32 s; Tilt 15° penetration barrel was pulled out when displacement was 5.1 cm, after 24 s. In the process of bucket foundation pulling, it mainly bore the friction resistance of the side wall and the resistance of the bottom of the bucket. With the increase of tilt angle, the friction resistance of the side wall and the resistance of the bottom of the bucket decreased, and the vertical drawing load was constant, so the barrel body was pulled out quickly.

3.3. Influence of inclination on load displacement curve of suction barrel top

Figure 7. Curves of load versus deflection of the submerged barrel body at different angles.

As far as test 3 concerned, at first the suction type foundation was uniform state in the whole process of pulling, when the barrel moved to 3.9 cm, a horizontal displacement jump points emerged, and with the increase of drawing force, horizontal displacement increased more and more obvious, the suction type foundation with the abrupt change point of the horizontal displacement corresponding drawing force was for ultimate bearing capacity.

Combining Fig.6 with Fig.7, it can be found: with the increase of tilt, suction type foundation suction type foundation bearing capacity decreased. When displacement of vertically immersed barrel reached 5.1cm, it was pulled out, and the load at the time of pulling out was taken as the ultimate bearing capacity of suction foundation under this working condition, that was, 1889kN.; Tilt 5° penetration barrel was pulled out when displacement was 5.1 cm, suction type foundation ultimate bearing capacity was 1746 kN; 15° oblique penetration barrel at first appear horizontal displacement
jump points corresponding to the drawing force as the ultimate bearing capacity of the barrel, was 1463kN.

With the increase of inclination angle, the friction resistance of side wall and bucket bottom decreased, and the bearing capacity of suction foundation decreased. When the tilt is $5^\circ$, suction type foundation bearing capacity was reduced by 7%, when the tilt is $15^\circ$ foundation bearing capacity was reduced by 23%.

4. Conclusion
In this paper, three groups of centrifugal model tests with different inclinations were carried out on the geo centrifugal test platform. The main conclusions can be drawn as follows:

1) In the centrifugal model test, with the increase of tilt, suction type foundation suction type foundation bearing capacity decreases, and when the tilt is $5^\circ$ and suction type foundation bearing capacity reduced by 7%, when the tilt is $15^\circ$ foundation bearing capacity is reduced by 23%. In the field of high-speed centrifugal reduction, the foundation bearing capacity is affected by the gradient greatly.

2) Centrifugal model test results show that suction foundation has two different states in the process of drawing failure: when the inclination degree of suction foundation is small, the suction foundation always keeps a constant rise state; the suction foundation takes the load value at the time of pulling out as the ultimate bearing capacity. When the suction type base tilt is $15^\circ$ and suction type foundation to rise at a constant speed, after arriving at a point, the barrel of the horizontal displacement jump, and with the increase of drawing force, horizontal displacement increase more and more obvious, the suction type foundation with the abrupt change point of the horizontal displacement corresponding drawing force is for ultimate bearing capacity.

3) In the rising process of suction foundation, the pore pressure buried at the left, inside and right positions in the barrel is disturbed, and the disturbance is most obvious at the inside. The pore pressure at the left and right sides is the similar, and the pore pressure at the three positions presents an overall upward trend.

Acknowledgement
This work was financially supported by the Chinese National Natural Science Foundation (No. 51479137).

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