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Experimental studies on the anti-uplift behavior of the suction caissons in sand

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A B S T R A C T

A series of model tests was conducted in sand to explore the anti-uplift behavior of suction caissons, considering the effects of aspect ratios, load inclination angles and loading positions. This paper emphasizes on analyzing the deformation characteristic and the mechanism of the suction caissons under various loading conditions. The movement modes of the suction caisson are different when the load inclination angle increases from 0° to 90° corresponding to various mooring positions. The pull-out bearing capacity decreases with load inclination angles increasing. When the load inclination angle changes from 0° to 60°, the bearing capacity reduces more significantly than that between inclination angle of 60° and 90°. While the load inclination angle is relatively small, the pull-out capacity of the suction caisson decreases after reaching the peak as the loading position moves downwards. Moreover, the optimum loading position locates between 2/3 and 3/4 of the caisson length. The optimum loading position is at the bottom of the caisson when the load inclination angle exceeds 60°. However, the influence of the loading position on the pull-out capacity of the caisson can be ignored while the load inclination angle equals to 90°. The pull-out bearing capacity increases as the aspect ratio increases but the aspect ratio has no effect on the deformation characteristic of the suction caisson.

1. Introduction

Suction caisson is a large-diameter steel pipe which has a sealed top equipped with a valve-controlled vent, and an open bottom. Due to the easy construction, reuse and low cost, suction caissons have been widely used in the deep-water offshore engineering such as platforms and wind turbines. The anti-uplift behavior of the suction caisson has attracted more attention because the suction caisson mainly withstands the pull-out load transferred from the upper structures subjected to wind and waves. So far, previous studies have predominately dealt with the anti-uplift behavior of suction caissons in clay [1–5]. The limit analysis method [6,7] and the finite element method [8,9] have also been used to study the bearing characteristics of the suction caissons in clay. However, the anti-uplift behavior of the suction caisson in sand should be further investigated.

Iskander et al. [10] investigated the penetration characteristics and the anti-uplift behavior of the suction caisson in sand under vertical loading through model tests. Bang and Cho [11] proposed the theoretical method of determining the pull-out capacity of horizontal loaded suction caisson, and explored the effects of various aspect ratios, loading positions on bearing capacity. As they concluded, the caisson translates while the horizontal load was exerted on the location of 0.8*L* (the caisson height *L*) and bearing capacity of the caisson increased obviously with the caisson's aspect ratio increasing. Burg and Bang [12] further investigated the effects of the loading position, suction caisson diameter, aspect ratio, and soil strength on the horizontal loading capacity of suction caissons. Allersma et al. [13] carried out the centrifuge tests to explore the influences of various aspect ratios (1, 5/3 and 7/3), loading positions and load inclination angles (10°, 15°, 20° and 25°) on the horizontal bearing capacity of suction piles in sand and clay. The presented results indicate that the pull-out capacity increases obviously for a smaller load inclination angle and the optimum loading position locates in the 2/5 of the caisson height. Bang et al. [14] analyzed the effects of various load inclination angles and loading positions on the bearing capacity of the suction caisson by centrifuge model tests and it was concluded that the optimum loading positions are located between 70% and 75% of the caisson height. In addition, the finite element method [15] and the limit equilibrium method [16] were used to study the pull-out characteristics of the suction caisson.

This paper describes the model test procedures and results, the deformation characteristics and the mechanism interpretation. The main variables included in the study are the load inclination angle, the point of the load application on the suction caisson and the aspect

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Table 1
Test conditions.

Aspect ratios L/D	Loading positions Z/L	Load inclination angles (°)				
	0	0	15	30	60	90
	1/2	0	15	30	60	90
2, 4, 6	2/3	0	15	30	60	90
	3/4	0	15	30	60	90
	1	0	15	30	60	90

Note: Z – the vertical distance from the loading position to the top of the caisson;
L – the length of the suction caisson;
D – the diameter of the caisson.

ratio. Effects of these three parameters on the suction caisson pull-out loading capacity are described and discussed.

2. Experimental setup

To comprehensively investigate the anti-uplift behavior of the suction caisson embedded in sand, seventy-five tests were conducted taking three aspect ratios, five loading positions and five load inclination angles into account. The test conditions are shown in Table 1. The load inclination angle representing the loading direction is measured from the horizontal to the straight wire connected to the suction caisson.

2.1. Model caissons used

As shown in Fig. 1, the three model suction caissons were made of stainless steel tube, with a diameter of 101 mm, thickness of 2.0 mm, and lengths of 202 mm, 404 mm and 606 mm, respectively. The inclined load was applied through a mooring line connected to each of five eye brackets (Figs. 1 and 2). There were four holes on the lid of the suction caissons, two of which were used to fix the inclinometer and the other two were used to let air escape without building any pressure inside the suction caisson during installation.

2.2. Sand used

The particle size distribution curve is shown in Fig. 3. The sand used is poorly graded, with the diameters of all particles less than 1.0 mm and greater than 0.075 mm. The minimum and maximum dry densities of the sand are 1.29 g/cm^3 and 1.64 g/cm^3, respectively. The sand used in the model tests has a dry density of 1.44 g/cm^3, a relative density of 0.49 and an effective internal friction angle of 36.8°.

2.3. Test setup

The model tests container has dimensions of 6 m × 1 m × 3 m in length, width and height. At the height of 80 mm from the bottom of the container, two galvanized pipes with a diameter of 25 mm were installed to let water enter to saturate the sand. On one wall of the test container, a steel structure called crossbeam was fixed by bolts, as shown in Fig. 4. To investigate the effects of various loading angles on the inclined pull-out loading capacity, many specific holes were needed to set on the vertical part of the crossbeam. However, because the spacing of the holes was too small, a chute was a good choice to fasten pulleys. By connecting the caisson with the pulley in different positions of the chute, various loading angles can be obtained, except the conditions of top loading and vertical loading.

The stainless steel wire with a diameter of 2.0 mm was selected as the mooring line connected to the suction caisson. The diameter

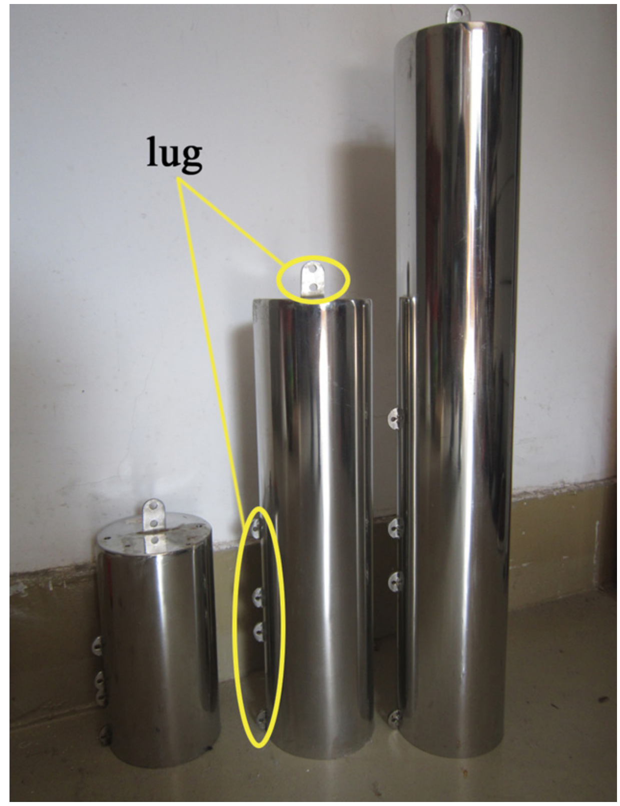

Fig. 1. Photograph of model suction caissons.

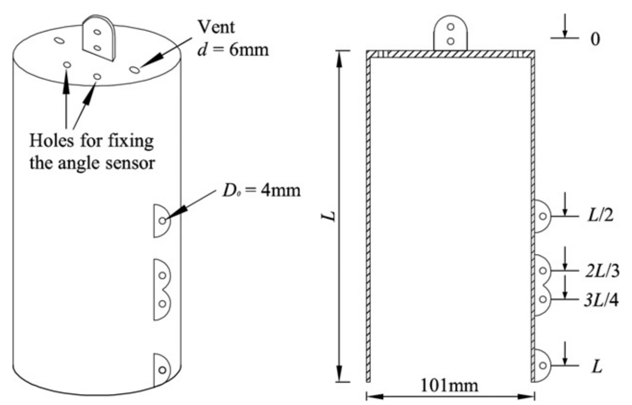

Fig. 2. Schematic showing the detailed vents distribution on top of the model suction caisson.

of the selected wire is the smallest that can resist the maximum test load without breaking. The mooring line was connected to the model suction caisson through an eye bracket welded to a special point as shown in Fig. 2.

During the tests, the inclinometer shown in Fig. 5 was used to measure the rotation angle of the model suction caisson. The inclinometer has a range of −30° to 30° and the accuracy of 0.2°. Prior to caisson installation, the inclinometer was fixed on the top surface of the suction caisson, except the condition of top loading. After installation, the inclinometer was linked to personal computer before loading and the rotation angle of the suction caisson could easily be obtained. A self-made steel ruler was used to measure the horizontal and vertical displacements of the top lug on the model suction caisson, see Fig. 5. The operational principle of the self-made ruler is similar to the calipers. A small hammer was connected with the two sliders on the ruler by string. Prior to loading, the small hammer was mobilized to