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RESEARCH ARTICLE

Experimental Studies on Modified Suction Caissons in Fine Sand Subject to Uplift Loading

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Abstract A modified suction caisson (MSC), which was reported by the authors of this paper previously, comprises an external short-skirted structure that is added to a regular suction caisson (RSC). It has been proved that MSCs can improve the lateral bearing capacity and limit the deflection of the caisson compared with RSCs. A series of model tests were conducted to investigate responses of MSCs subject to uplift loading in saturated sand. The effects of external skirt dimensions on the uplift bearing capacity of MSCs were considered. In addition, the influences of the sealed top lid of the skirted structure on the uplift bearing capacity and the resulting passive suction of MSCs were also studied. It was found that the uplift bearing capacities of MSCs are 1.4–1.7 times that of RSCs. Moreover, test results in serviceable conditions show that the sealed external skirted structure of perspex-made suction caissons significantly contributed to the uplift bearing capacity as a result of passive suction.

Keywords Offshore wind turbine · Modified suction caisson · Uplift capacity · Fine sand

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Introduction

A suction caisson is a cylindrical-shaped steel buckets with a top lid containing several valves. Moreover, it has an open bottom end that is used to penetrate the seabed using its own self-weight when all the valves on its lid are open. When penetration by self-weight is complete, all the valves will be closed and the encased water will be pumped out to create suction pressure to penetrate the suction caisson to the desired depth. It has been proved that suction caissons can readily penetrate into fine and medium-coarse sized sands. Penetration of the suction caisson terminates when its lid contacts the soil plug surface. Suction caissons have been widely used in offshore facilities, such as jacket structures, platforms and floating structures, due to their easy installation, reusability, and low construction costs [1–4]. Recently, suction caissons have been increasingly used as foundations for offshore wind turbines. The foundations of offshore wind turbines must be able to resist large lateral and moment loads induced from wind, waves, and currents. Therefore, the design of suction caissons is governed by lateral and moment loads. A modified suction caisson (MSC) (Fig. 1a) was proposed to improve the lateral bearing capacity and limit the lateral deflection of the caisson to meet the requirements of being used as foundations for offshore wind turbines [5]. The design of an MSC is built upon a regular suction caisson (RSC) with the addition of an external skirted structure; the original RSC, which contains a valve on its lid connected to the vacuum pump, becomes an internal compartment of the MSC. There are four open holes on the external skirt lid to minimize the water resistance during installation. These four holes will be closed when the penetration is completed to improve the bearing capacity. Previous studies described the bearing capacity of MSCs under lateral monotonic

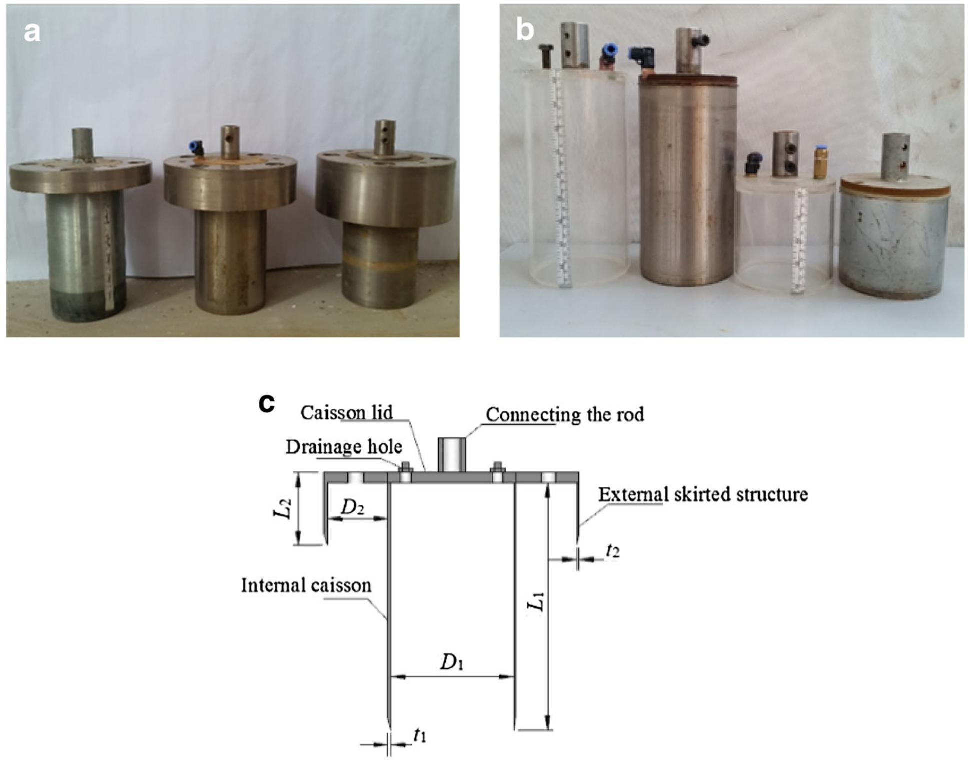

Fig. 1 Models of suction caissons. **a** MSCs (L_1/D_1 = 2.0), **b** RSCs, **c** sketch of MSC

Table 1 Dimensions of RSCs

Suction caisson number	D_1 (mm)	L_1 (mm)	T_1 (mm)	T_2 (mm)
I	120	120	2.0	2.0
II	120	240	2.0	2.0

Table 2 Dimensions and weights of MSCs

MSC number	D_2 (mm)	L_2 (mm)
R3H3	30	30
R3H6	30	60
R3H9	30	90
R3H12	30	120
R5H3	50	30
R5H6	50	60
R5H9	50	90
R5H12	50	120

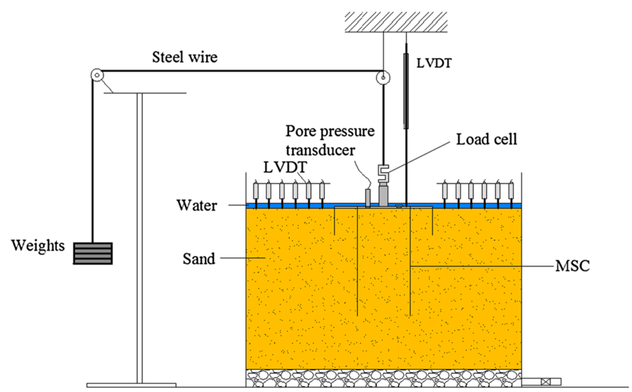

Fig. 2 Schematic of the test setup

loading [6–8]. This paper mainly deals with the behavior of MSCs under uplift loading by performing model tests and comparing results of MSCs to those of RSCs.

The foundation for an offshore wind turbine needs to withstand large overturning moments induced by wind and waves. For wind turbine foundations composed of a tripod of suction caissons, the overturning moment is primarily performed by a "push–pull" action from opposing caissons; therefore, the upwind caisson must resist tensile loads. The uplift capacity of RSCs has attracted more attention [9]. Finn and Byrne [10] were the first to accept the concept of uplift capacity comprising "reverse end bearing capacity" and "passive suction" during the extraction of the suction caisson. The concept of two components of the uplift capacity has been proved by many researchers [11–13]. For example, Luke et al. [14] performed model tests to study the uplift capacity of the suction caisson in clay using a top-cap vented or sealed caisson and taking into consideration the pullout rate. Rao et al. [15] explored the effects of soil cohesive strength, load direction, aspect ratio, and suction caisson embedment depth on the uplift capacity. Gao et al. [16] concluded from

Fig. 3 Procedure of the test. **a** Suction caisson installation, **b** transducers, **c** stepped loading, **d** suction caisson pullout in progress

the test results that the uplift capacity of the suction caisson was dependent on its aspect ratio, loading point position, and loading direction. Mana et al. [17] used finite element method to study the influence of passive suction on the uplift capacity of suction caisson in clay. Mathematical expressions for estimating the average seepage path length as a function of foundation embedment ratios were also proposed. Chen and Randolph [18] investigated the uplift capacity and external radial stress changes by centrifuge tests for suction caissons with sealed top in consolidated clay under both sustained and cyclic loadings.

From the literature, it can be concluded that the uplift bearing capacity of suction caisson in clay consists of reverse end bearing capacity, frictional resistance, and passive suction. The uplift bearing capacity is dependent on aspect ratio, uplift rate, and the soil undrained shear strength. Model tests were performed to investigate the effects of uplift loading rate, aspect ratio of the internal compartment, and the dimensions of external structure on the uplift bearing capacity, and the resulting passive suction of MSCs in saturated fine sand.

Model Tests

Test Instruments

Regular model suction caissons with aspect ratios of 1.0 and 2.0 (Fig. 1b) were made of steel and Perspex, and MSCs (Fig. 1a) were all made of steel. The dimensions of

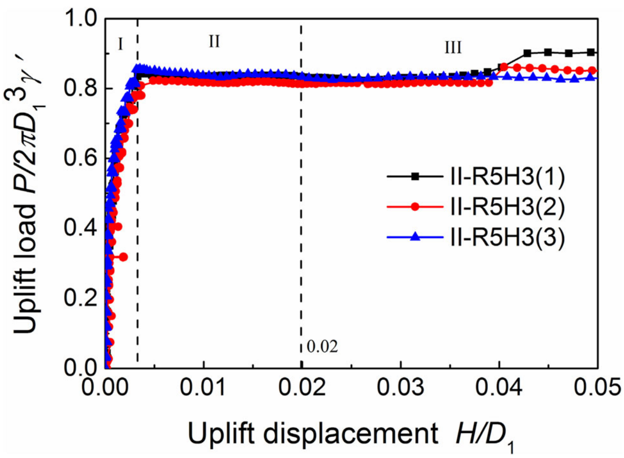

Fig. 4 Uplift load–displacement curves for MSC no. II-R5H3

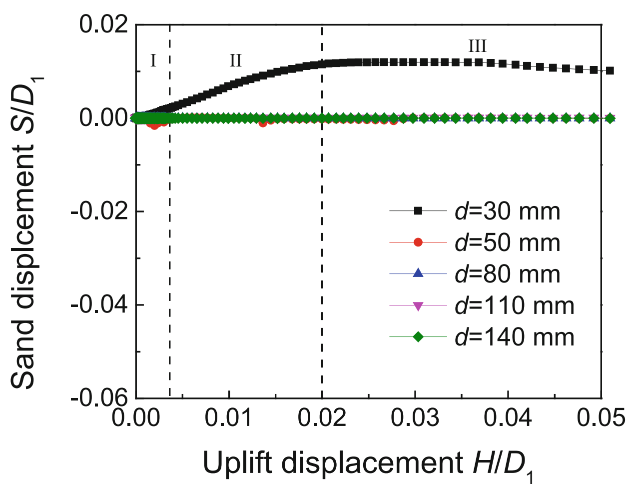

Fig. 5 Curves of sand displacement versus uplift displacement (MSC no. II-R5H3)

RSCs and MSCs are listed in Tables 1 and 2, respectively, and the corresponding dimensional symbols are shown in Fig. 1c. The MSCs are numbered as caisson no. *x*-R*y*H*z*, where *x*, *y*, and *z* are variables. The first variable, *x*, represents an aspect ratio of 1.0 (I) or 2.0 (II) (Table 1), and *y* and *z* denote the width and length of the external structure (Table 2). For example, caisson no. II-R3H9 has an internal compartment aspect ratio of 2.0, and its external skirt width and length are equal to 30 and 90 mm, respectively.

The sand tank (1-m long, 1-m wide, and 0.8-m high) was made large enough to avoid size effects [8]. Suction caissons were installed by a hydraulic jack, and a linear variable differential transformer (LVDT) was placed vertically on the suction caisson lid to measure the uplift displacement. A load cell (range 0–500 N) was used to measure the uplift load. A vacuum gauge (range 0–20 kPa) was connected to the caisson to measure passive suction during uplifting. All the test data were automatically obtained using a data acquisition system.

Sand

Marine fine sand was used in the tests and the sand parameters are as follows: $e_{\max} = 0.903$, $e_{\min} = 0.61$, $e = 0.62$, $D_r = 0.997$, $G_s = 2.69$, $k = 0.00145$ cm/s, $\gamma' = 10.2$ kN/m^3, $c = 0$ kPa, and $\varphi = 34°$.

Test Setup

Figures 2 and 3 show the test setup and the procedure of model test. It is vital to keep the conditions of the test to be constant, especially the relative density for reproducibility. Prior to each test, the sand was loosened to a depth of approximately 1.5 times the length of the internal compartment of the suction caisson being tested to achieve the stress level. Next, the water level was raised to 10 cm above the sand surface and water was allowed to drain through an outlet valve until the water level decreased to 2 cm above the sand surface; this process was repeated twice. Finally, the caisson was left in the sand for 12 h before testing.

The method for installing the suction caisson into the sand was described by Li et al. [7]. The uplift loads were applied gradually in increments of 4.8 N, and each loading step was sustained for 1 min. The uplift bearing capacity is typically determined in terms of failure criteria. The failure criterion of the suction caisson is defined as the uplift displacement of the caisson lid that is 2% of the suction caisson diameter, as stated previously by Byrne and Houlsby [19] and Gourvenec et al. [20].

Test Results and Discussion

Test Results Calibration

When the model suction caisson was completely submerged in water, the uplift load was given directly by the load cell reading. However, if the model suction caisson was partially submerged in water, the uplift load must be calibrated to account for the buoyancy of the suction caisson.

Each test was repeated at least for three times to ensure that the maximum error was within 3%. The load–displacement curves of the MSC no. II-R5H3 are shown in Fig. 4. For this test, the uplift load was normalized to be $P/2\pi D_1^3\gamma'$ [21], where P is uplift force, D_1 is the diameter of the internal compartment, and γ' is the buoyant unit weight of the sand. In addition, the vertical displacement of the

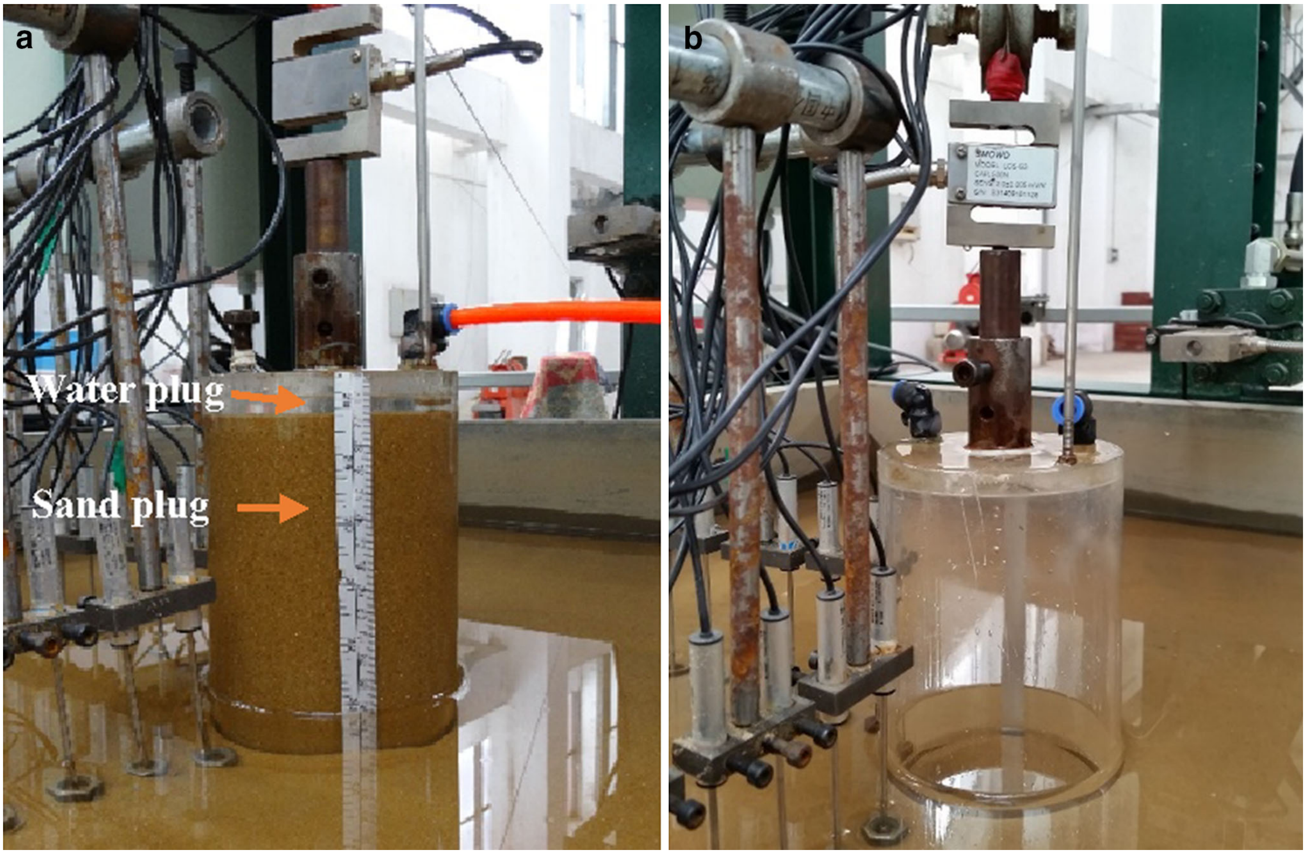

Fig. 6 Uplift failure of RSCs. **a** lid sealed, **b** lid unsealed

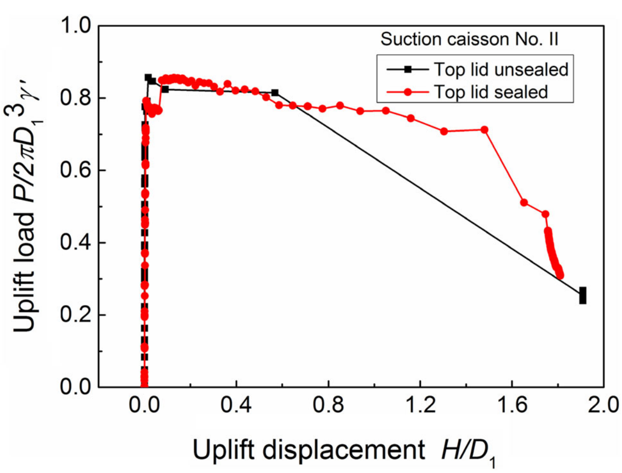

Fig. 7 Uplift load–displacement curves for RSC no. II

Table 3 Average passive suction for RSCs ($H = 0.02\ D_1$)

No. of caisson	Passive suction (kPa)
I-s	−0.507
II-s	−1.33

sand surface is designated as H and given in the dimensionless form of H/D_1 (Fig. 1c).

Uplift load–displacement curves (Fig. 4) can be divided into three phases: quasi-elastic phase (I), plastic phase (II), and failure phase (III). Figure 5 demonstrates the vertical displacement of the sand versus the uplift displacement of the suction caissons during uplifting. As shown in Fig. 5, d represents the distance between the LVDT and the suction caisson's external wall. Moreover, the positive values of vertical displacement represent the sand surface upheaval and the negative value denotes the subsidence of sand surface. In the quasi-elastic phase, the maximum uplift displacements were within 0.005 D_1 for all suction caissons and the uplift displacements of all suction caissons were not significant. However, note that the maximum uplift load in this phase approached the uplift capacity. In the plastic phase, the uplift displacement of the MSC increased from 0.005 D_1 to 0.02 D_1. In the failure phase, the suction caisson was gradually pulled out. Moreover, from Fig. 4, it is observed that the data points become dispersed due to the accelerated uplift displacement.

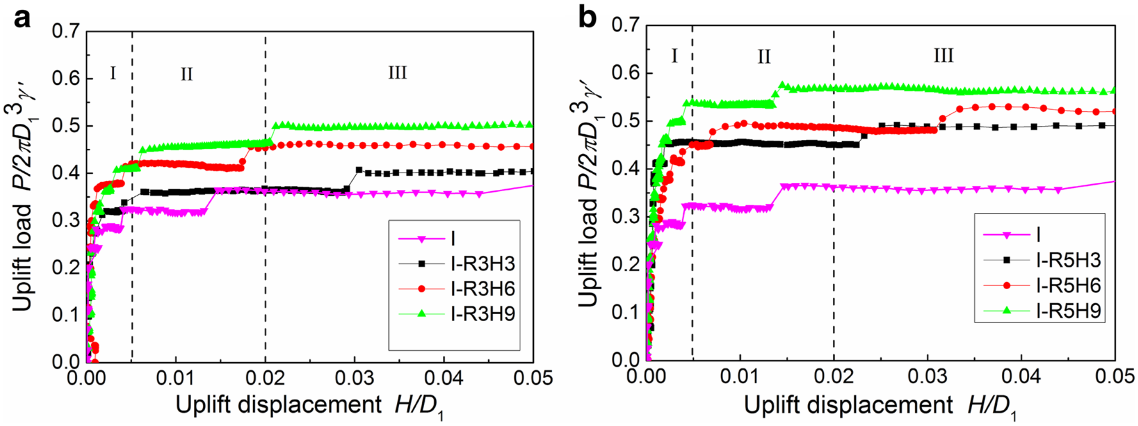

Fig. 8 Uplift load–displacement curves for MSCs (internal caisson no. I). **a** I-R3, **b** I-R5

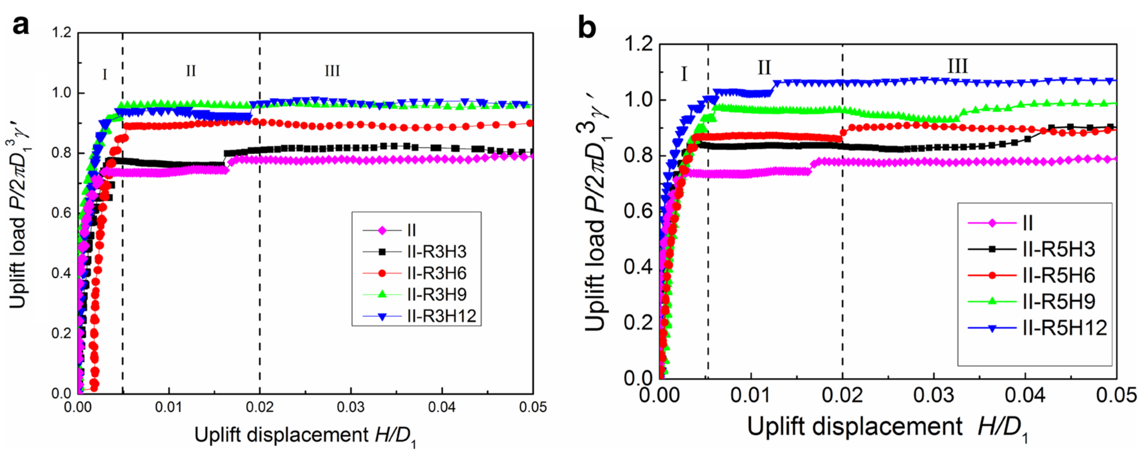

Fig. 9 Uplift load–displacement curves for MSCs (internal caisson no. II). **a** II-R3, **b** II-R5

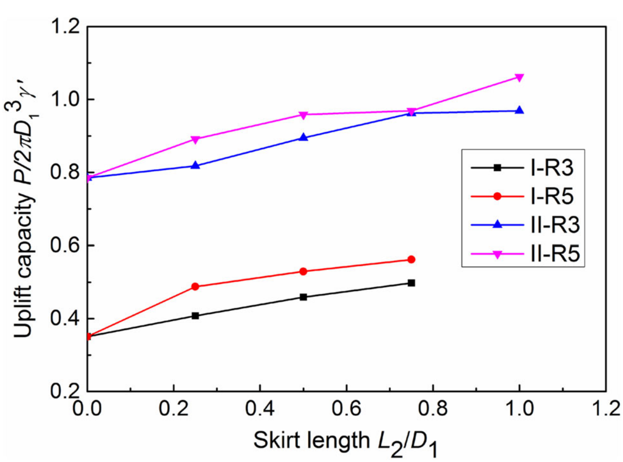

Fig. 10 Influence of external skirted structure on uplift bearing capacity

Effects of Passive Suction

Model tests on perspex-made suction caissons were conducted to study the effect of passive suction on the uplift capacity and to visualize the failure mechanism of the suction caisson under uplift load.

For the RSC with the lid sealed (II-s), the height of the sand plug increased with uplift displacement (Fig. 6a). In contrast, for the unsealed lid (II-u), it was easy to extract the model caisson without sand plug left in the suction caisson (Fig. 6b). The relationships between uplift load and the corresponding displacement for the RSC nos. II can be seen in Fig. 7, which shows that the uplift loading–displacement curve of the sealed lid exhibits a gradual drop, while that of unsealed lid is an abrupt drop. In addition, the uplift capacity increased with the aspect ratio of the suction caisson.

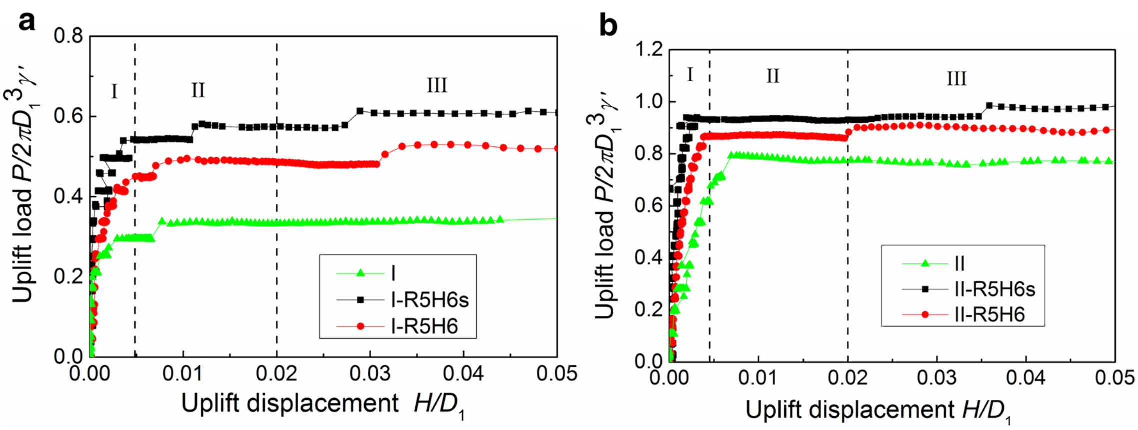

Fig. 11 Uplift load–displacement curves. **a** I-R5, **b** II-R5

Table 4 Uplift capacity of MSCs with different heights of skirts

No. of model caisson	Uplift capacity (N)	Increase of uplift capacity (%)
I	39.19	–
I-R5H6	58.60	49.7
I-R5H6s	67.25	71.6
II	85.75	–
II-R5H6	106.11	23.7
II-R5H6s	108.80	26.9

The passive suction values for RSCs when the uplift displacement (H) of the suction caisson goes up to 0.02 D_1 are listed in Table 3. Note that the passive suction value for a suction caisson with an aspect ratio of 2.0 is 2.6 times larger than that with an aspect ratio of 1.0.

Uplift Model Tests of MSCs

Studies on Aspect Ratio L_2/D_1

Figures 8 and 9 show the uplift load–displacement curves for the MSCs under various aspect ratios L_2/D_1. The uplift capacity of the MSC increased with the increasing width and the length of the external skirted structure.

The uplift bearing capacity of the MSCs with an internal caisson aspect ratio of 1.0 increased by 16% (I-R3H3), 30.9% (I-R3H6), and 42% (I-R3H9), respectively, as shown in Fig. 8. Moreover, the bearing capacities of MSCs with caissons nos. I-R5H3, I-R5H6, and I-R5H9 increased by 39.1, 51.0, and 60.3%, respectively, compared with that of RSCs. Results also show that for the same external skirt length, the uplift bearing capacity of the MSC increased with the external skirt width and external skirt length.

The uplift load–displacement curves for MSCs with an internal compartment aspect ratio of 2 show that there is a positive correlation between the uplift capacity and external skirted structure dimensions, as shown in Fig. 9. Compared with RSCs, the uplift bearing capacities of MSCs containing the internal caisson no. II are increased by 4% (II-R3H3), 14% (II-R3H6), 23% (II-R3H9), and 24% (II-R3H12), respectively. In addition, for caissons nos. II-R5H3, II-R5H6, II-R5H9, and II-R5H12, the bearing capacities are increased by 13.8, 22.4, 23.5, and 35.4%, respectively. The results also show that for the same external skirt dimension, the uplift bearing capacity increased with the internal compartment aspect ratio.

Frictional forces may provide an explanation for the phenomenon regarding the uplift bearing capacity. The frictional forces between the suction caisson wall, sand and the reverse end bearing capacity beneath the skirted structure may increase with the additional surface area provided by the external skirted structure. Moreover, the uplift capacity may also increase with external skirt length and width due to increases in earth pressure resulting from the embedded depth of the suction caisson. In addition, the sand between the external structure and the internal compartment is embraced with the external skirted structure. Therefore, the passive earth pressure would increase with the dimensions of the external skirted structure.

Figure 10 shows the uplift bearing capacities of the MSCs under various MSC dimensions. The MSC considerably increases the uplift bearing capacity depending on the dimensions of the external skirted structure. Moreover, the increase of the dimensions of the external skirted structure is beneficial for the uplift bearing capacity. Therefore, the results demonstrate that MSCs can be applicable to offshore wind turbines.

Effects of Passive Suction for the Modified Skirted Structure

Model tests were also conducted on the MSCs with the external skirt top lid being sealed or unsealed.

The uplift load–displacement relationship of the suction caissons numbered I, II, I-R5H6 and II-R5H6 are shown in Fig. 11. I-R5H6s is the sealed modified skirted structure and is shown in contrast to the unsealed I-R5H6. Note that the uplift capacity of I-R5H6s increased by 14.76% compared with the value for I-R5H6u, while the uplift bearing capacity of II-R5H6s increased by only 2.54% compared with the value for II-R5H6 (Table 4). Furthermore, compared with the bearing capacity of RSCs, the bearing capacities of caisson nos. I-R5H6s and II-R5H6s increased by 71.6 and 26.9%, respectively. It can be concluded that the passive suction in the external skirted structure can significantly improve the uplift bearing capacity of MSCs.

Conclusion

A series of model tests were performed to study the uplift behavior of MSCs in marine fine sand. The following conclusions are obtained.

1. MSCs can provide larger uplift capacity than RSCs; it was found that increasing the aspect ratio of the external skirted structure can significantly improve the uplift capacity. Moreover, the uplift bearing capacities of MSCs are 1.4–1.7 times that of RSCs.
2. MSCs with sealed lids on the external skirted structure can provide a larger uplift capacity compared with MSCs with unsealed lids. The uplift bearing capacity of the MSC with a sealed external skirt top lid increased by 14.76% compared with that of the MSC with an open external skirt top lid.
3. The passive suction increased with the increasing aspect ratio of suction caisson. The maximum passive suction in the suction caisson with an aspect ratio of 2.0 was 2.6 times that with an aspect ratio of 1.0.

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