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Model Tests on Suction Caisson Installation with Soil Plug Removal

T. Zhu, H. Wang, J.-M. Zhang, R. Wang
Department of Hydraulic Engineering, Tsinghua University, Beijing, China, zhutongt@163.com, 332172818@qq.com, zhangjm@tsinghua.edu.cn, wangrui_05@mail.tsinghua.edu.cn

ABSTRACT: Suction caissons are widely used in ocean engineering as an important type of foundation. The formation of soil plugs within the suction caisson, induced by negative pressure during the suction installation process, can impede the penetration of the caisson, consequently reducing its bearing capacity. This study proposes a soil plug removal device for suction caissons that can remove soil plugs during suction installation. The device facilitates the removal of the soil plug within the caisson by employing a fixed frame, a motor system, and a stirring system. The added device does not affect the negative pressure inside the caisson during the suction penetration process via sealing connection with the suction caisson. This newly proposed device and installation procedure provides the benefits of adaptable modification, efficient installation and removal, and reuse of suction caissons. 1g model tests are conducted in this study for suction caisson installation using the proposed device and procedure in sand and clay, comparing the vertical pullout capacity of the caisson with and without the removal of soil plugs. The results show that this installation method can effectively remove soil plugs inside the suction caisson and improve the vertical pullout capacity of the caisson, thereby demonstrating the effectiveness of the device and procedure.

1 INTRODUCTION

Suction caissons are widely used in ocean engineering, which has advantages in terms of time and cost efficiency, transportation convenience, and recycle and reuse potential. However, soil plug formed under the effect of negative pressure during the installation of the suction caisson can result in improper installation and reduced bearing capacity of the suction caisson, which is a critical factor affecting the performance of suction caisson foundations.

In-situ and model tests are important methods for studying the suction caisson response during installation and bearing capacity during operation. Some studies (Hogervorst, 1980; Larsen, 1989; Dyvik et al., 1993; Barusco, 1999; Haland, 2002; Newlin, 2003) have conducted in-situ tests to investigate the formation process of soil plugs during the installation of suction caissons. Some 1 g model tests (Andersen et al., 2005, 2008; Lian et al., 2014; Zhang et al., 2018) and centrifuge model tests (Tran, 2005; Senders and Randolph, 2009; Panagoulias et al., 2017; Kim and Kim, 2020; Ragni et al., 2020; Qu et al. 2021) have demonstrated the effects of soil properties, penetration methods, and installation rates on soil plug height, revealing the role of soil plugs in affecting the penetration resistance and penetration depth of suction caissons. Some researchers (Villalobos and Jara, 2006; Chen and Randolph, 2007; Zhu et al., 2013; Bienen et al., 2018a, 2018b; Wang et al., 2021; Liu et al., 2023) have studied the bearing capacity of suction caissons during operation and revealed that the soil plug can reduce the vertical pullout capacity of the suction caisson. Some researchers (Zhang et al., 2017; Qu et al. 2023; Liu et al., 2025) have proposed methods for removing soil plugs during installation process, such as segregating internal compartments, applying high-pressure flushing, and installing filter layers inside caissons. However, there is limited effective installation methods for suction caissons that can remove soil plugs without affecting the negative pressure inside the caisson.

To address this issue, this study proposes a method that can effectively remove soil plugs during the installation of a suction caisson without affecting the negative pressure inside the suction caisson. A model device is developed, and 1 g model tests are conducted. The effectiveness of this installation method with soil plug removal is demonstrated by measuring the penetration depth of the suction caisson during installation in sand and clay, as well as the vertical pullout capacity during operation.

2 METHOD FOR SOIL PLUG REMOVAL

The conceptual design diagram of the suction caisson soil plug removal device is shown in Figure 1. It mainly consists of three parts: the fixed frame, motor system, and stirring system. The specific devices are as follows.

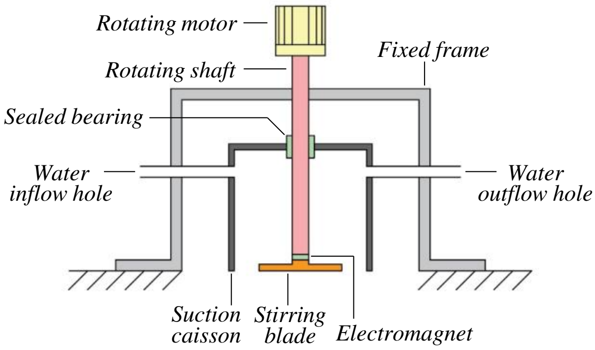

Figure 1. Conceptual design diagram of the suction caisson soil plug removal device.

1) Fixed frame

A fixed frame is used to support the soil plug removal device, and is installed outside the suction caisson. The fixed frame is pre-fitted with water inflow and outflow holes that can connect to the suction caisson via water pipes.

2) Motor system

The motor system mainly includes a rotating motor, a rotating shaft, and a sealed bearing. The rotating motor is installed on the fixed frame, and the rotating shaft passes through the fixed frame, extending into the interior of the suction caisson. The rotating speed and diameter can be adjusted according to the size of the suction caisson. The rotating shaft is connected to the suction caisson via a threaded connection, allowing it to move vertically under the drive of the motor. A sealed bearing is installed at the connection to ensure that the inside of the suction caisson remains sealed during installation, thereby maintaining the negative pressure within the caisson.

3) Stirring system

A 10 mm thick stirring blade is connected to the bottom of the rotating shaft. During the installation of the suction caisson, it rotates and moves vertically under the drive of the rotating motor and rotating shaft, remaining at the surface of the seabed. Consequently, the stirring blade is able to stir the soil plug inside the caisson, mixing the soil plug with the water to form a slurry, which is then extracted outside the caisson. The stirring blade is connected to the rotating shaft via an electromagnet, allowing the stirring blade to detach from the rotating shaft after the installation of the suction caisson, so that all devices except the stirring blade can be recycled.

3 MODEL TEST METHOD

In this section, a model of the device is developed, and tests conditions for the installation and uplift of the suction caisson are presented.

3.1 Test device

The photo and schematic view of the test device are shown in Figure 2. The model container for the tests is 490 mm long, 460 mm wide, and 500 mm high. The suction caisson model has a height of 200 mm, a diameter of 100 mm, and a wall thickness of 1 mm. It is made of a transparent acrylic plate to record the formation process of the soil plug inside the caisson.

In addition to the soil plug removal device, the test device also includes a water inflow and outflow system, and a lifting system. The water inflow and outflow holes are located at the upper part of the suction caisson. The water outflow hole is connected to water tank A via a flexible soft pipe. The other side of water tank A is connected to a vacuum pump. The water tank A is made of a transparent acrylic plate, allowing the observation of the water and slurry extracted during the penetration process of the suction caisson. The water inflow hole is connected to water tank B via a pipe. An electromagnetic valve is installed on the pipe to control the water inflow rate. Sufficient water is supplied into the caisson so that the stirred soil plug can be mix into a slurry.

The lifting system is used to balance the self-weight of the suction caisson and measure the vertical pullout capacity of the caisson after installation. The bottom of the two lifting shafts is connected to the top of the suction caisson, and the top is connected to the counter weights and lifting motors on both sides via fixed pulleys. The counter weights mainly serve to balance the self-weight of the suction caisson, and the lifting motors are used to apply uplift loads on the suction caisson. Force sensors are installed at the top end of the lifting shafts to measure the vertical pullout capacity of the suction caisson under uplift loads.

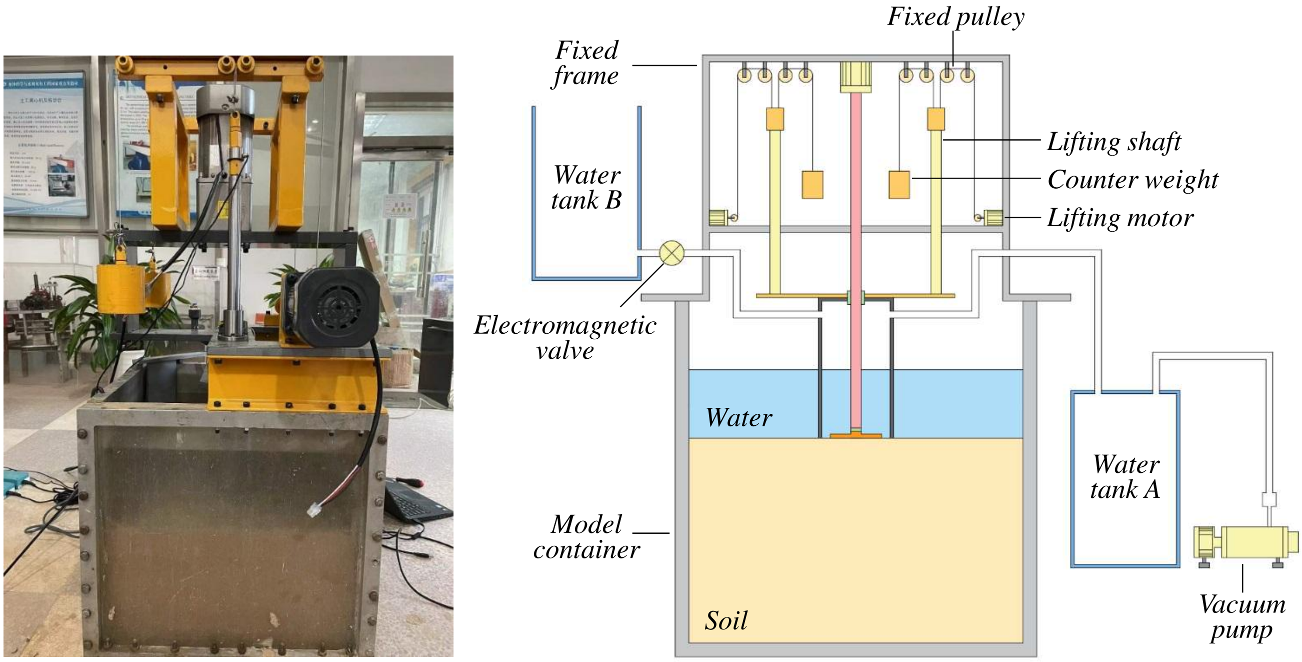

Figure 2. Photo and schematic view of the test device.

3.2 Soil properties

Typical Fujian standard sand and soft clay are used in this study, which have been shown to effectively reproduce the distinct plug formation mechanisms under typical offshore conditions in previous studies (Wang et al. 2021; Qu et al. 2023). Sand with an average particle size d_{50} of 0.085 mm, curvature coefficient C_c of 0.65, and coefficient of nonuniformity C_u of 8.51 is adopted. The clay used in the tests is silty clay. The main soil properties are presented in Table 1.

Table 1. Soil properties.

Sand	
Soil Parameters	Value
Specific weight G_s	2.64
Permeability coefficient k_f (m/s)	2.7×10^{-4}
Peak friction angle φ (°)	35
Maximum dry density ρ_{max} (10^3 kg/m^3)	1.65
Minimum dry density ρ_{min} (10^3 kg/m^3)	1.37
Void ratio e	0.66
Clay	
Soil Parameters	Value
Specific weight G_s	2.7
Permeability coefficient k_f (m/s)	5×10^{-8}
Dry density ρ (10^3 kg/m^3)	1.6
Critical friction angle φ (°)	24
Cohesion c (kPa)	26
Liquid limit w_l	33.5%
Plastic limit w_p	15.5%

3.3 Test conditions and procedures

Four tests are conducted in this study, as shown in Table 2. In Test 1 and 2, the soil is sand, and Test 1 does not apply soil plug removal, while Test 2 does. In Test 3 and 4, the soil is clay, and Test 3 does not apply soil plug removal, while Test 4 does.

Table 2. Test conditions.

Test	Soil	Soil Plug Removal
Test 1	Sand	No
Test 2	Sand	Yes
Test 3	Clay	No
Test 4	Clay	Yes

The testing procedure is mainly divided into three steps: 1) Self-weight penetration: An initial self-weight penetration to a depth of 20 mm is first carried out to form a sealed space within the caisson to allow for the application of suction. 2) Suction penetration: After the self-weight penetration, the vacuum pump is turned on to apply suction inside the caisson, causing the suction caisson to penetrate downward. For Test 2 and 4, the rotating motor of the soil plug removal device is turned on during suction penetration. The stirring blade is driven by the rotating motor and shaft to stir the soil plug inside the caisson. Simultaneously, the electromagnetic valve at the water inflow hole is opened to provide sufficient water inside the suction caisson, allowing the soil plug to be thoroughly mixed into a slurry, which is then extracted from the caisson. While for Test 1 and 3, the rotating motor and electromagnetic valve at the water inflow hole remain closed during the process of suction penetration.

3) Lifting process: After suction penetration, the rotating motor and water inflow and outflow system are turned off, and the lifting motor is then turned on. The lifting motor lifts the suction caisson at a constant speed of 0.1 mm/s, and the vertical pullout capacity of the suction caisson is measured using the force sensors on the lifting shafts.

4 TEST RESULTS

This section presents the typical test results, including photos taken during the tests, the final penetration depth, and the vertical pullout capacity of the suction caisson, to demonstrate the effectiveness of the soil plug removal device.

4.1 Soil plug removal

The formation process of the soil plug inside the suction caisson during penetration is recorded using an underwater camera. Figure 3 shows typical photos of the soil plugs inside the suction caisson during the penetration process in the four tests. It is observed that soil plugs with certain heights are formed in both sand and clay during the suction penetration. In Test 2 and 4, where the soil plug removal device is used, once the rotating system of the device is activated, the soil plugs inside the suction caisson became loosened under the action of the stirring blade, subsequently mixing with the water inside the suction caisson to form slurry.

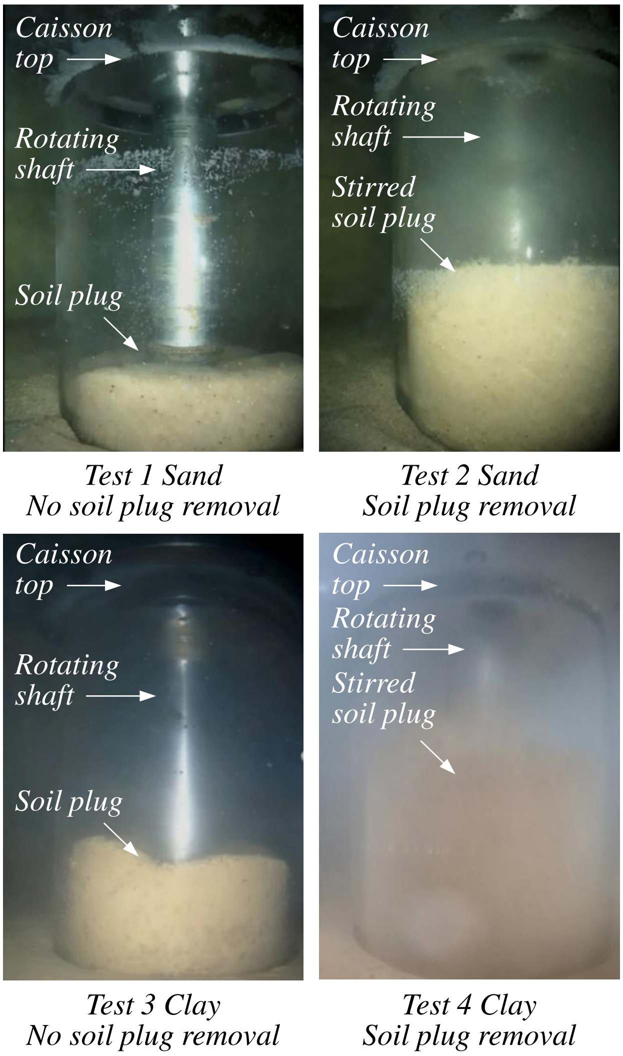

Figure 3. Photos of the soil plugs inside the caisson.

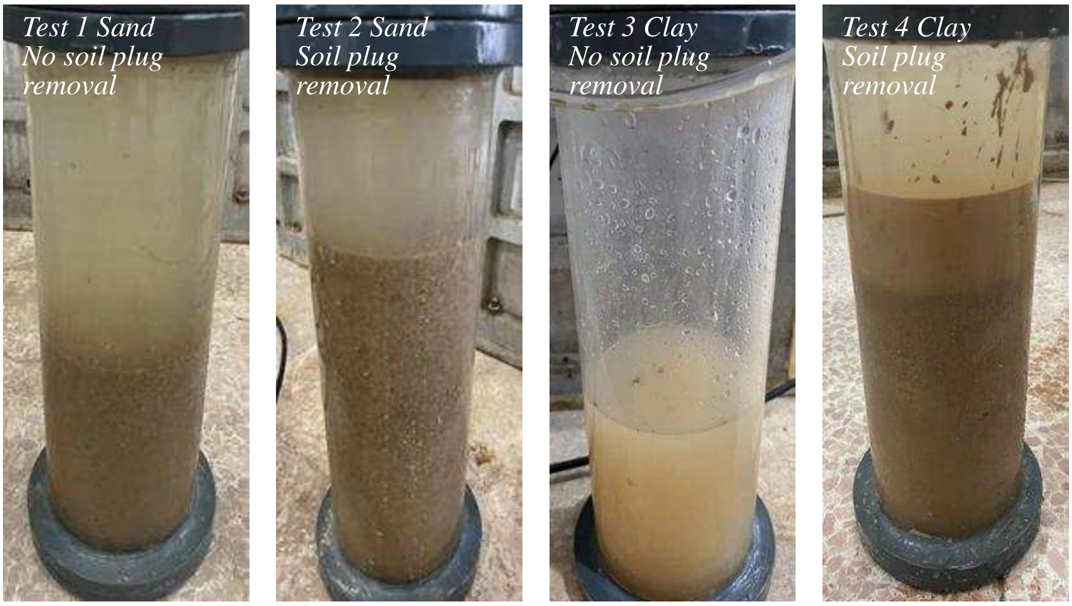

Figure 4. Photos of the soil-water mixture inside the water tank A.

Figure 4 shows the photos of water tank A after the installation of the suction caisson. It can be seen that in all four tests, during the suction penetration process, the soil-water mixture inside the caisson is drawn out. Compared to Test 1 and 3, in Test 2 and 4 where the soil plug removal device is used, there are more soil-water mixture in water tank A, with the liquid being more turbid. This is because the soil plug inside the suction caisson is stirred into a slurry, allowing the vacuum pump to extract it more easily from the suction bucket.

4.2 Penetration depth

Figure 5 shows the maximum penetration depths of the suction caisson in the four tests. It is observed that the soil plug removal method effectively increases the penetration depth of the suction caisson. The target penetration depth is 190 mm. In sand, the maximum penetration depth of the suction caisson in Test 2 is 175 mm, which is 25% greater than that in Test 1. In clay, the maximum penetration depth in Test 4 is 175 mm, which is 40% greater than that in Test 3.

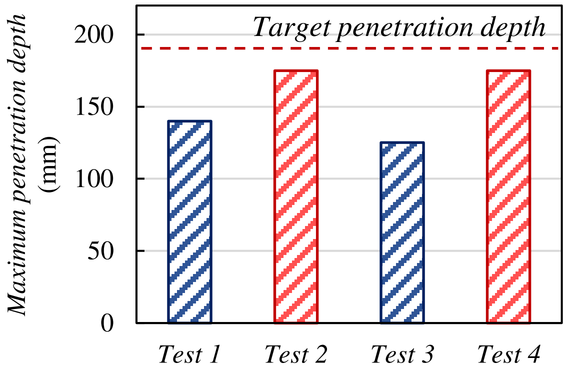

Figure 5. Maximum penetration depth of the suction caisson.

4.3 Uplift capacity

After the suction bucket foundation installation, the lifting motor lifts the suction caisson to test its uplift capacity, as shown in Figure 6. It is observed that the soil plug removal method effectively increases the uplift capacity of the suction caisson in both sand and clay. In sand, using the soil plug removal method in Test 2, the maximum uplift force of the suction caisson is 220 N, which is 34% greater than that in Test 1. In clay, using the soil plug removal method in Test 4, the maximum uplift force of the suction caisson is 214 N, which is 50% greater than that in Test 3. This is mainly due to the increased penetration depth of the suction caisson caused by the soil plug removal.

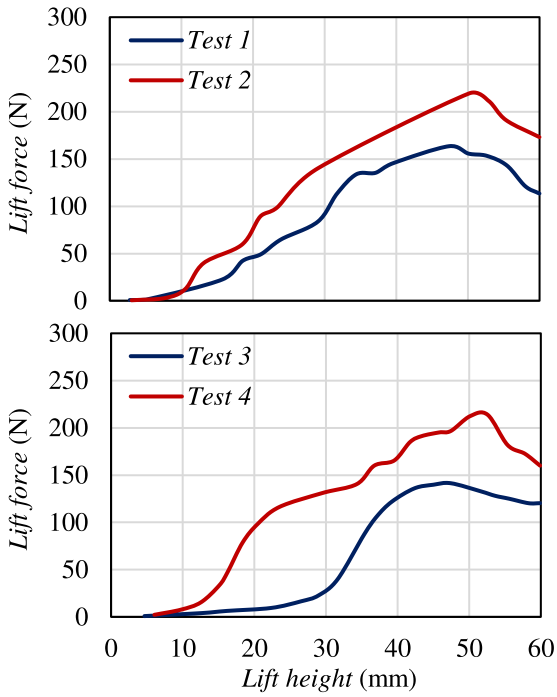

Figure 6. Uplift capacity of the suction caisson.

5 CONCLUSIONS

This study proposes a novel installation method for suction caisson foundations with soil plug removal, and develops a scaled model and testing device. 1 g model tests on suction caisson penetration installation and uplift loading in sand and clay are conducted to verify the effectiveness of the soil plug removal method. The main conclusions are as follows.

1) This soil plug removal device mainly includes a fixed frame, a motor system, and a stirring system, with the following features: a) The stirring blade can effectively remove soil plugs formed inside the suction caisson during penetration. b) The sealing between the rotating shaft and the suction caisson can effectively ensure negative pressure inside the caisson. c) The stirring blade is connected to the rotating shaft via an electromagnet, thereby facilitating extensive reuse of the devices.

2) The effectiveness of the soil plug removal method is demonstrated through 1 g model tests. The proposed soil plug removal method can effectively eliminate the soil plug formed during the suction penetration of caisson foundations in both sand and clay, significantly improving the final penetration depth of the suction caisson and enhancing its uplift capacity.

It should be noted that this experimental study can only qualitatively demonstrate the effectiveness of the proposed soil plug removal method, which provides a concept for the installation method of suction caisson foundations in practical environments. The implementation of the installation method in actual engineering projects requires further in-situ experimental research for validation.

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