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Characteristic Test Study on Bearing Capacity of Suction Caisson Foundation Under Vertical Load

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Abstract

Suction caisson foundations are often subjected to vertical uplift loads, but there are still no wide and spread engineering specifications on design and calculation method for uplift bearing capacity of suction caisson foundation. So it is important to establish an uplift failure criterion. In order to study the uplift bearing mechanism and failure mode of suction caisson foundation, a series of model tests were carried out considering the effects of aspect ratio, soil permeability and loading mode. Test results indicate that the residual negative pressure at the top of caisson is beneficial to enhance uplift bearing capacity. The smaller the permeability coefficient is, the higher the residual negative pressure will be. And the residual negative pressure is approximately equal to the water head that causes seepage in the caisson. When the load reaches the ultimate bearing capacity, both the top and bottom negative pressures are smaller than S_u and both the top and bottom reverse bearing capacity factors are smaller than 1.0 in soft clay. Combined the uplift bearing characteristics of caisson in sandy soil and soft clay, the bearing capacity composition and the calculation method are proposed. It can provide a reference for the engineering design of suction caisson foundation under vertical load.

Key words: suction caisson foundation, uplift bearing capacity, failure mode, negative pressure, sandy soil, soft clay

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1 Introduction

A suction caisson foundation is a closed-top steel tube that is lowered to the seafloor, allowed to penetrate the bottom sediments under its own weight, and then pushed to full depth with differential pressure produced by pumping water out of the interior. Because of their easy installation, reusability, and low construction costs, suction caissons have been increasingly used in offshore engineering. The compliant offshore structures, such as tension leg platforms, offshore platforms, are usually subjected to considerable uplift forces. For this reason, a lot of studies about this aspect have been done by many researchers, but there are still no wide and spread engineering specifications on design and calculation of uplift bearing capacity for suction caisson foundation. Therefore, the research on the uplift bearing capacity of suction caisson is one of the important issues worth concerning and solving.

Suction caisson foundation always sustains incline or almost vertical loads, which is passed by the attached mooring chain. Therefore, the vertical pullout capacity of caisson should be considered first in order to fulfill the anchoring requirement in engineering design. When suction caisson foundation is subjected to uplift load, the top of caisson will generate negative pressure and it will resist most of the load. Maybe the negative pressure will generate at the bottom of caisson which depends on caisson aspect ratio and loading rate. While under long-term working load, the negative pressure will eventually dissipate. So the maximum uplift loading cannot be taken as the ultimate bearing capacity of suction caisson foundation. Owing to the different permeability characteristics of the soil, the residual negative pressure at the top of caisson is different. The magnitude of the residual negative pressure directly affects the uplift bearing capacity of suction caisson foundation. But the residual negative pressure has not been properly understood and quantified.

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In order to accurately explore the uplift bearing characteristics of suction caisson foundation, many researchers have done a lot of research on the uplift bearing capacity of caisson, such as Byrne and Houlsby (2002), Luke (2002), Chen and Randolph (2007), Rao et al. (1997), Singh et al. (1996), Deng and Carter (2002), Wang et al. (2016), and Li et al. (2019). The uplift bearing capacity of the suction caisson foundation with respect to aspect ratio, uplift rate, types of soil have been investigated in these studies. Zhu et al. (2018), Dai et al. (2019) and Wang (2008) performed theoretical studies on the vertical uplift capacity of suction caisson under undrained pullout load. Jiao et al. (2006), Shi et al. (2003), Mana et al. (2013) and Rao et al. (1997) concluded from the test results that the negative pressure developed at the bottom of the caisson could be taken as part of the uplift bearing capacity. Some researchers (Andersen et al., 1993; El-Gharbawy, 1998; Luke, 2002; Chen and Randolph, 2007) investigated the influences of sustained loadings on the caisson pullout capacity and found that these loadings noticeably reduce the capacity of suction caisson. However, there are few discussions about the failure mode and bearing mechanism for a suction caisson until now. Owing to the large permeable coefficient of sand, the negative pressure is hardly generated to provide the reverse bearing capacity, which is different from the pullout mechanism of suction caisson foundation in soft clay. Iskander et al. (2002) and Bang et al. (2006) carried out model tests to study the pullout behavior of suction caisson foundation in sand. Bang et al. (2011) explored the effects of loading point position and loading direction on the uplift capacity of suction caissons in sand. Houlsby et al. (2006) explored the effect of vertical loads embedded in dense sandy bed by large diameter caisson models in the field. Lu et al. (2005) and Zhang et al. (2005) also investigated the uplift bearing capacity of suction caissons in sand by a series of model tests. Li et al. (2013a, 2013b) analyzed the deformation characteristics and the mechanism of the suction caissons under various loading conditions. Zhu et al. (2011) suggested a calculation method for estimating of the ultimate pullout capacity of caissons under drained and undrained conditions in sand.

The uplift bearing capacity is the key problem to caisson design. However, the above studies on the uplift bearing capacity of suction caisson foundation have not fully revealed the vertical uplift bearing mechanism of the suction caisson foundation. Based on a specially designed experimental system, a series of model tests have been performed to investigate the pullout mechanism of suction caisson foundation in sandy soil and soft clay. The composition of the uplift bearing capacity of the suction caisson foundation is analyzed in detail. It can provide a reference for the engineering design of suction caisson foundation under vertical load.

2 Experimental work

2.1 Tank and soil

A steel tank, which is 1.0 m long, 1.0 m wide, and 1.2 m high, was used to prepare the test bed soil. The soft clay was prepared by mixing several batches of slurry in a small steel barrel and then carefully poured it into the test tank. The initial water content of prepared slurry was about 60%−70%. To accelerate the consolidation of clay slurry, a drainage layer was deployed at the bottom of the tank, and a layer of bricks with an underlying geotextile were placed on the clay surface. When the undrained shear strength of the soil layer reached 6−10 kPa along the depth, the caisson pull-out test was started. The soil parameters measured by the geotechnical test are shown in Table 1.

Table 1 Soil parameters

Type	*w.c.*(%)	Γ(kN/m^3)	w_L(%)	w_p (%)	I_P	S_u (kPa)
Soil 5	40.8	16.8	46.6	28.8	17.8	7.6

Four soils samples with different permeability coefficients were also selected in the experiment. The distribution curves of particle size are shown in Fig. 1. The sand parameters are listed in Table 2. We can know that the permeability coefficient of Soil 1 is larger than that of Soil 4.

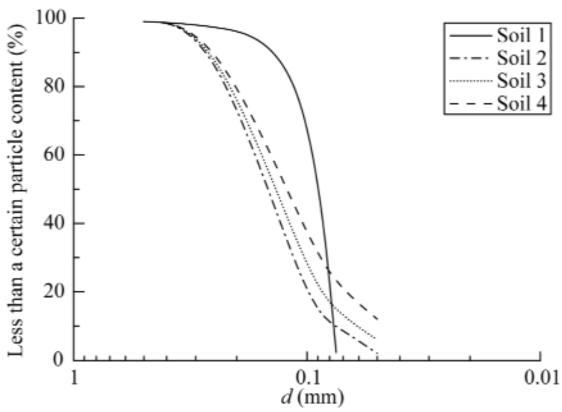


Fig. 1. Grain size distribution curves.

Table 2 Basic parameters of soil

Type	ρ_{dmax} (g/cm^3)	ρ_{dmin} (g/cm^3)	D_r	φ(°)	*k* (cm/s)
Soil 1	1.62	1.281	0.48	36.1	1.2×10^{-3}
Soil 2	1.63	1.285	0.49	35.8	9.1×10^{-4}
Soil 3	1.65	1.298	0.48	34.4	6.4×10^{-4}
Soil 4	1.68	1.302	0.50	33.2	4.2×10^{-4}

2.2 Caisson model

Regular caisson models with aspect ratios of 1.5, 3.0 and 6.0 were made of steel and perspex. Specific parameters of caisson models can be seen in Fig. 2. The caisson model is inserted into the seabed by applying vertical down-

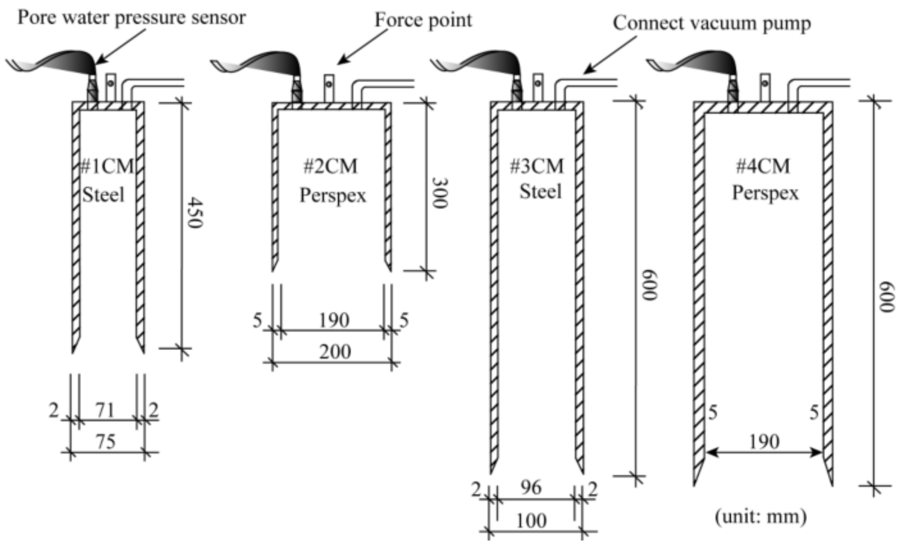


Fig. 2. Suction caisson foundation model.

ward force and suction pressure in sequence. Linear variable differential transformer (LVDT) was placed vertically on the suction caisson lid to measure the uplift displacement. A load cell (range: 500−500 N) was used to measure the uplift load. A vacuum gauge (range: 10−10 kPa) was connected to the caisson to measure negative pressure during uplifting. In order to measure the development of negative pressure during the experimental process, BWMK pore water pressure gauges were arranged at the top and bottom of caisson respectively. The arrangement of the test device and pore water pressure gauge is shown in Fig. 3. All test data were automatically obtained by a data acquisition system.

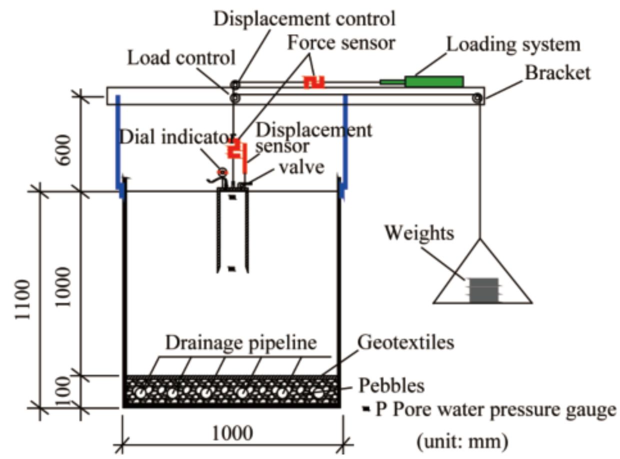


Fig. 3. Sketch of suction caisson foundation test.

2.3 Loading pattern

There are two kinds of load control methods in tests, one is the load control and the other is the displacement control. The test will begin after the pore pressure dissipates completely. In load control tests, each stage load is one tenth of the estimated value of the ultimate bearing capacity. When the displacement of caisson is not stable, stop the tests. The displacement control mainly investigates the influence of the negative pore pressure dissipation on the bearing capacity of the caisson. Plate pull-out test was carried out to measure the external friction of caisson. At the same time, pull-out test of the unsealed suction caisson was carried out to measure the internal friction. The test results are shown in Table 3.

3 Analysis of test results

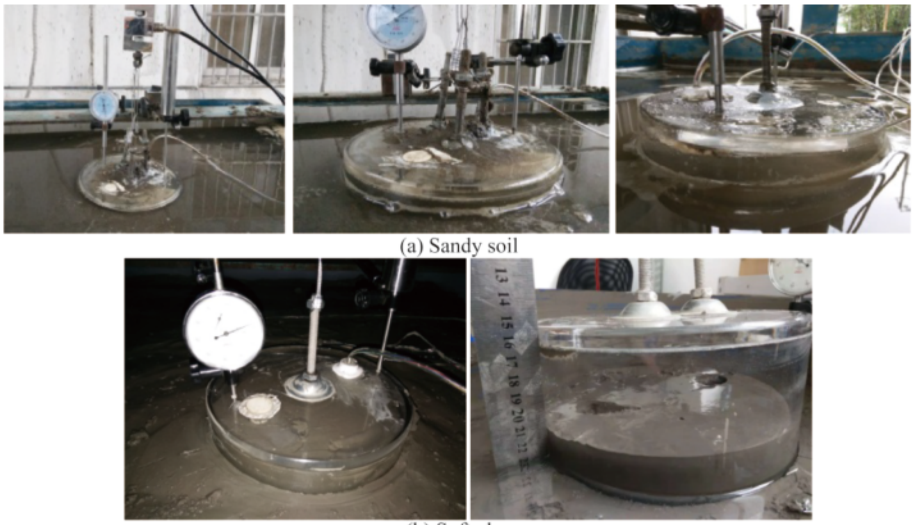
3.1 Load-displacement curve of suction caisson foundation

Fig. 4a shows the test photos of #4CM caisson model in sandy soil. It is found that seepage could happen in the internal caisson. If the permeability coefficient is smaller, the seepage in caisson needs longer time. But in Soil 4, there is

Table 3 Basic parameters of caisson model

No.	Material	D	L/D	W_c	Soil 1		Soil 2		Soil 3		Soil 4		Soil 5	
					F_{ext}	F_{in}	F_{ext}	F_{in}	F_{ext}	F_{in}	F_{ext}	F_{in}	F_{ext}	F_{in}
#1CM	Steel	75	6.0	26	23	19	23.5	20	24	21	24.6	22	32	28
#2CM	Perspex	200	1.5	15	38	35	38.6	34.8	39	37.6	40	38	51	49
#3CM	Steel	100	6.0	65	66	64	67	65	67.8	65	68	65	94	92
#4CM	Perspex	200	3.0	30	82	76	83	76	84	77	85	77.6	101	98

Notes: D−caisson diameter (mm); L− caisson length (mm); W_c−caisson weight (N); F_{ext}−external friction of caisson (N); F_{in}−internal friction of caisson (N).



(a) Sandy soil

(b) Soft clay

Fig. 4. Test photos.

no seepage in #1CM caisson model. And the soil plug moves up with caisson. So the uplift bearing mechanism of suction caisson foundation is different under the effects of caisson aspect ratio and soil permeability.

Fig. 4b shows the test photos of #4CM caisson model in soft clay. It is found that the soil plug moves upward with the caisson. However, once the plug is removed, the bearing capacity of the caisson decreases sharply and the soil plug is observed to drop down from the top of caisson. In contrast, the soil plugs are pulled up with #1CM and #3CM open-top caisson models. So the uplift bearing mechanism of suction caisson foundation is different with the effects of caisson aspect ratio. This phenomenon indicates that the negative pressure at the top of caisson affects the bearing capacity of #2CM and #4CM caisson models and the reaction force at the bottom of caisson affects the bearing capacity of #1CM and #3CM caisson models.

In soft clay, typical plots of the pullout load−displacement behavior of four caisson models are shown in Fig. 5. One can note from the figure that the ultimate bearing capacity of #1CM−#4CM model is 144 N, 221 N, 298 N and 398 N, respectively. Typical plots of the pullout load-displacement behaviors of model open-top caisson are shown in Fig. 6. It can also be noted that the peak failure load of open-top caisson model is achieved at very low displacement in #2CM and #4CM caisson models. On the other hand, pullout load increases with caisson displacement and no distinct failure in #1CM and #3CM caisson models. The difference in the pullout load-displacement behavior of caisson model can be attributed to the difference in the modes of failure. In #2CM and #4CM open-top caisson models, the soil plug does not move with caisson. After the bearing capacity overcomes the friction force, the curve will fall. In #1CM and #3CM open-top caisson models, the soil plug will move upward with the caisson. Both the soil plug and the caisson move together as a single block. So the load-displacement curve does not show a peak failure.

In Soil 1, typical plots of the pullout load-displacement behavior of four caisson models are shown in Fig. 7. One can note from this plot that there are no obvious failure signs on the load-displacement curves under vertical load before the caisson are pulled out. It can be concluded that when the caisson is pulled, the friction of caisson first reverses to resist the pullout force. As the load increases, the friction developes gradually until the displacement of the caisson is not stable. In Soil 4, it can be seen from Fig. 7 that the bearing capacity of caisson is obviously larger than that in Soil 1. It means that the permeability coefficient is smaller, the uplift bearing capacity of suction caisson foundation is larger.

3.2 Composition of uplift bearing capacity

The load and displacement−time curves of #2CM caisson model in soft clay are shown in Fig. 8. When the load is applied to the fifth stage, the uplift bearing capacity of suction caisson foundation is made up of its self-weight and the frictional force. At this time, the caisson did not move but there is negative pressure at the top of the caisson. When the load is applied to the 8th stage, the negative pressure at the top of caisson is 3.2 kPa. The negative pressure at the top of caisson increases gradually with the increase of load. When the load is applied to the 10th stage, the negative pressure at the top of caisson is 5.5 kPa and the displacement of caisson is no longer stable. It was found that the negative pressure at the top of caisson continues developing with the increasing load by other two steps after the breakout loading. The displacement−time plot of model caissons does not show any distinct failure. It can be seen that the negative pressure at the top of caisson affects the uplift bearing capacity of the suction caisson foundation.

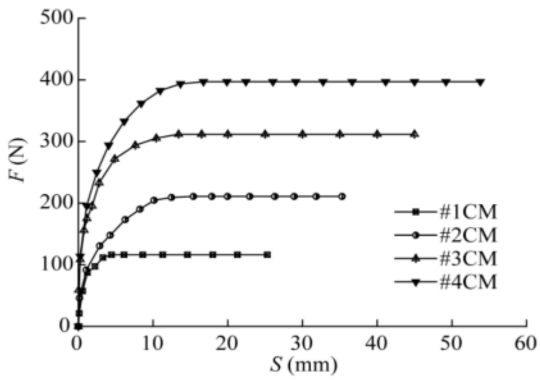


Fig. 5. Load vs. displacement curve.

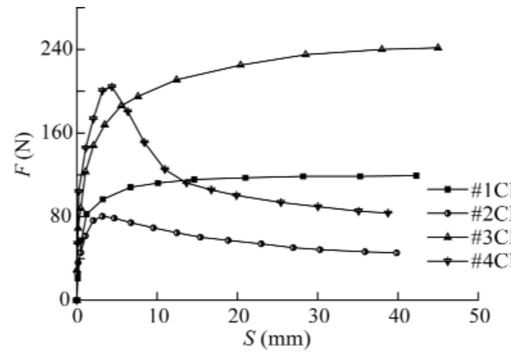


Fig. 6. Load vs. displacement curve of open-top caisson.

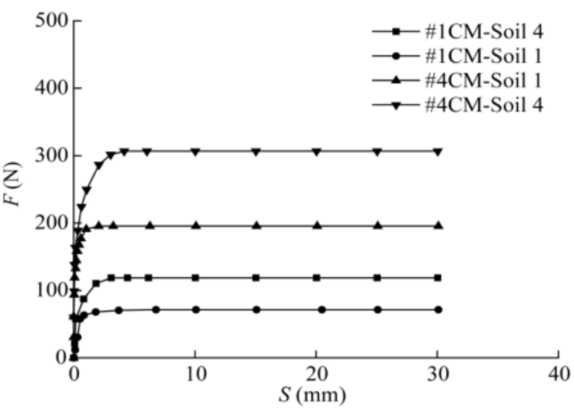


Fig. 7. Load vs. displacement curve.

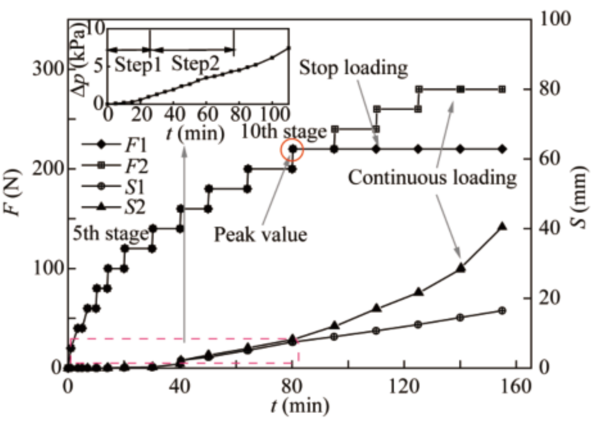


Fig. 8. Load and displacement vs. time curve.

The load, displacement and negative pressure−time curves of #4CM caisson model are shown in Fig. 9a. When the load is applied to the 8th stage in Soil 1, the uplift bearing capacity of the suction caisson foundation is made up of its self-weight and the frictional force. At this time, the caisson did not move but there is negative pressure at the top of the caisson. When the load is applied to the 9th stage in Soil 1, the negative pressure at the top of caisson is −1.57 kPa. Seepage occurs in the caisson and the uplift bearing capacity of the suction caisson foundation reaches its limit value. When the load is applied to the 8th stage in Soil 4, at this time, the caisson did not move but there was negative pressure at the top of the caisson. The negative pressure at the top of the caisson increases gradually with the increase of load. When the load is applied to the 10th stage in Soil 4, the negative pressure is −3.6 kPa and the displacement of caisson is not stable. It was found that the negative pressure at the top of caisson continues developing with the increasing load by other two steps after the breakout loading. The displacement−time curve of model caissons in Soil 4 does not show any distinct failure. It can be seen that the negative pressure at the top of caisson affects the uplift bearing capacity of the suction caisson foundation in Soil 4.

The uplift bearing mechanism is different between #4CM caisson model and #1CM caisson model in Soil 4. The load, displacement and negative pressure−time curves of #1CM caisson model are shown in Fig. 9b. It can be found that the negative pressure at the bottom of caisson developes first and increases with the pullout load. But the negative pressure increment at the top of the caisson is very small. In #1CM caisson model, the soil plug moves upward with the caisson. With the increase of load, the reversed bearing capacity at the bottom caisson increases gradually. The uplift load, displacement and negative pressure−time curves of #3CM caisson model are shown in Fig. 9c. It can be found that the negative pressure at the top of the caisson would transfer to the bottom during the pullout procedure.

From the relationship curves of the three caisson models, there are three main test phenomena in the process of loading.

(1) In sandy soil with high permeability (Soil 1), the negative pressure at the top of the caisson is higher than that at the bottom of the caisson and seepage occurs in the caisson.

(2) In sandy soil with low permeability (Soil 4) or soft clay, the negative pressure at the top of the caisson would transfer to the bottom during the pullout procedure.

(3) It can be found that the negative pressure at the bottom of #1CM caisson model develops first and increases with the pullout load. But the negative pressure increment at the top of the caisson is very small.

In Fig. 10a, the number is the reverse bearing capacity (suction force) at the top of the caisson in Soil 2 and the number is the reverse bearing capacity at the top of the

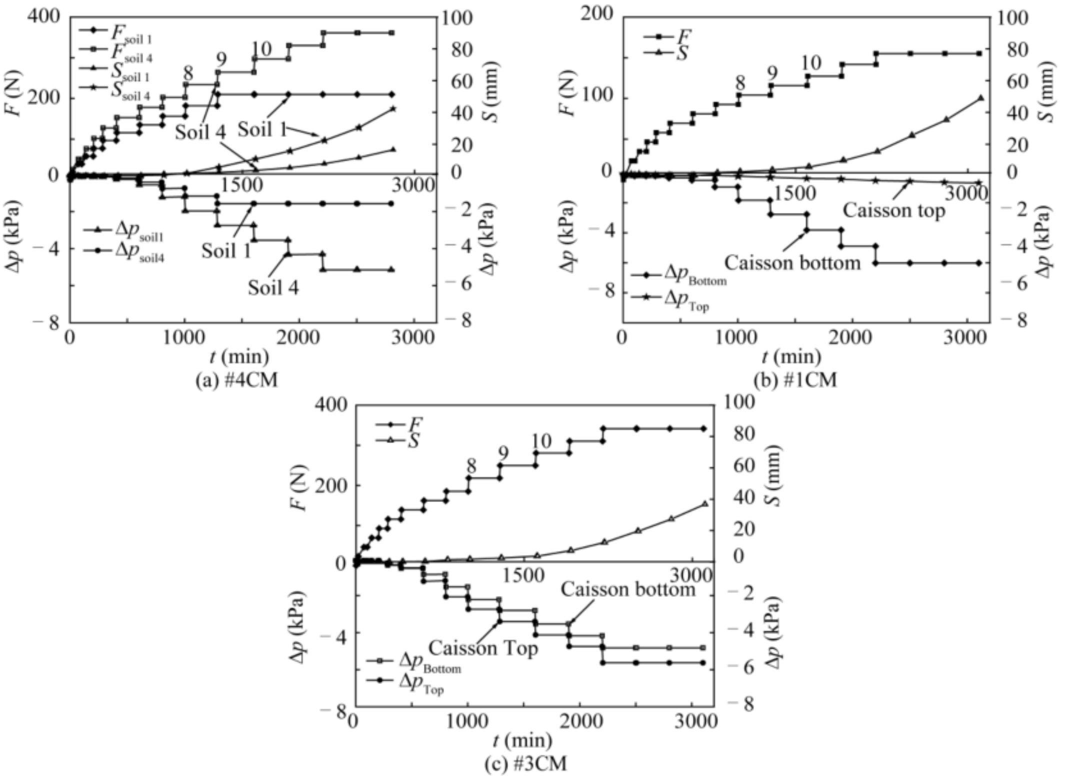


Fig. 9. Load and displacement vs. time curve.

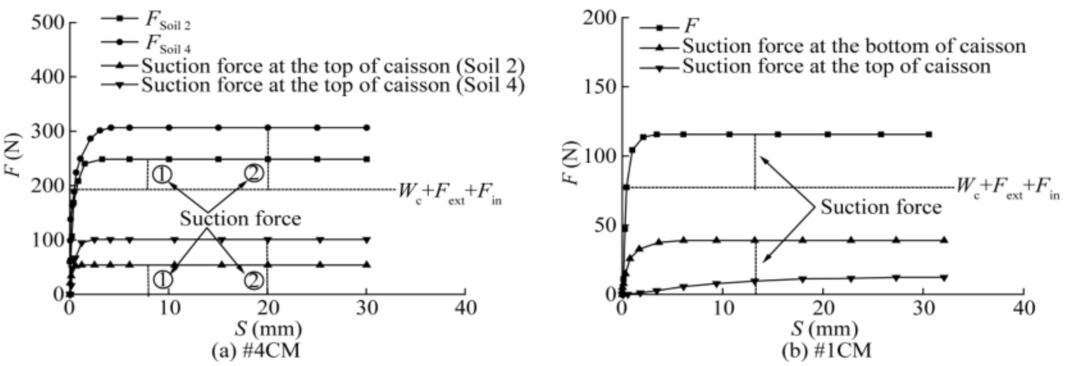


Fig. 10. Load vs. displacement curve.

caisson in Soil 4. It can be found that the uplift bearing capacity of suction caisson foundation is made up of its self-weight, internal and external friction and the reverse bearing capacity at the top of the caisson. It can be seen from Fig. 10b that the uplift bearing capacity of #1CM caisson model in Soil 4 is made up of its self-weight, soil plug weight, external friction and the reverse bearing capacity at the bottom of the caisson.

The composition of the uplift bearing capacity of suction caisson foundation in Soil 5 is shown in Fig. 11a. One can note from this curve that the uplift bearing capacity of suction caisson foundation is made up of its self-weight, the internal and external frictions and the reverse bearing capacity at the top of the caisson. It can be seen from Fig. 11b that the uplift bearing capacity of #3CM caisson model in Soil 5 is made up of its self-weight, soil plug weight, the external friction and the reverse bearing capacity at the bottom of the caisson.

3.3 Negative pressures at the top and bottom of the caisson

Fig. 12a shows a typical plot of change of negative pressures at the top and bottom of #4CM caisson model. It can be found that the negative pressure at the top of the caisson would transfer to the bottom during the pullout procedure in Soil 4. In sandy soil with high permeability, the negative pressure at the top of the caisson is obviously higher than that at the bottom and seepage occurs in the caisson.

Fig. 12b shows the change of negative pressure at the top and bottom of #1CM caisson model. When the uplift load has not overcome the external friction and the self-

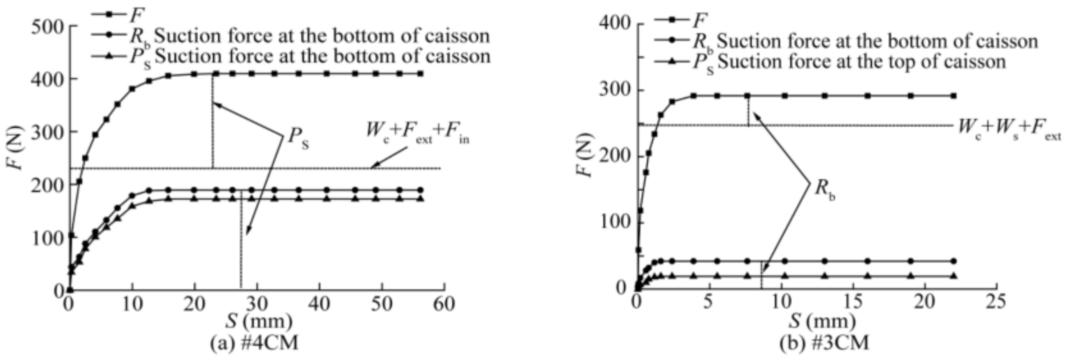


Fig. 11. Load vs. displacement curve.

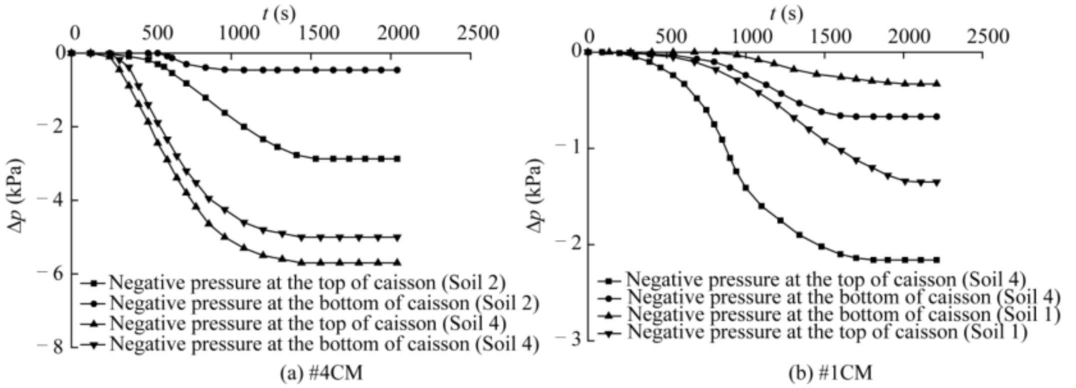


Fig. 12. Negative pressure vs. time curve.

weight of caisson and soil plug, the negative pressure at the bottom of the caisson has not yet developed. Subsequently, it can be seen that the negative pressure increases as the load increases. The negative pressure at the top of the caisson is obviously smaller than that at the bottom of the caisson and the negative pressure at the top of the caisson was smaller than the water head which causes the seepage in the caisson. Therefore, there would be no seepage in the caisson, and the soil plug moved up with the caisson. In sandy soil with high permeability (Soil 1), the negative pore pressure at the top of the caisson is obviously higher than that at the bottom of the caisson, and seepage occurs in caisson.

Fig. 13a shows the change of negative pressure of the #2CM caisson model. It can be found that the negative pressure at the top of the caisson is slightly higher than that at the bottom of the caisson and the negative pressure at the top of the caisson would transfer to the bottom of the caisson during the pullout procedure. Fig. 13b shows the change of negative pressure of #3CM caisson model. When the uplift load has not overcome the external friction and the self-weight of caisson and soil, the negative pressure at the bottom of the caisson has not yet developed. Subsequently, it can be seen that the negative pressure increases as the load increases. The negative pressure at the top of the caisson is obviously smaller than that at the bottom of the caisson and the soil plug moves up with the caisson.

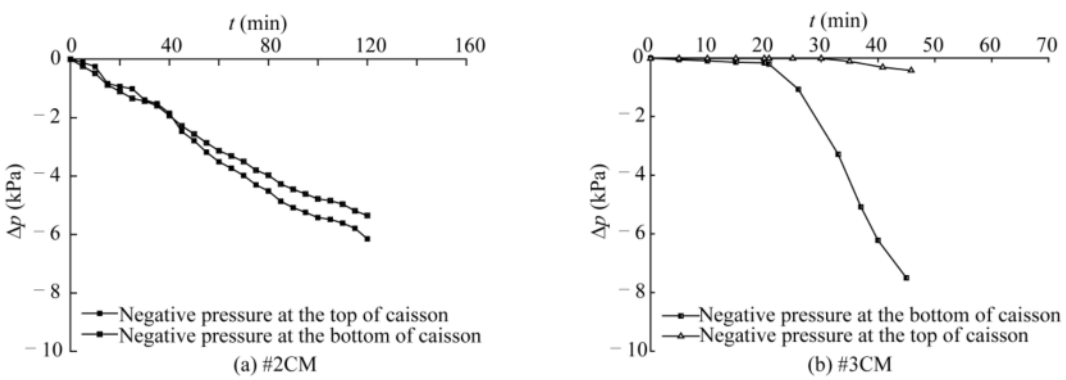


Fig. 13. Negative pressure vs. time curve.

3.4 Bearing capacity of model caisson with displacement control

The following discussion will concentrate on the change of the bearing capacity with the negative pressure dissipation. Zhu et al. (2011) did the same experiment in silt. It was found that the bearing capacity of the suction caisson decreases rapidly with the negative pressure dissipation. At the same time, the bearing capacity is smaller than the actual value. In order to solve the problem, a spring was added between the push rod and the force sensor. The uplift load and negative pressure–time curves of #4CM caisson model are shown in Fig. 14. It can be seen that the bearing capacity of the caisson is close to the actual value by adding a spring device.

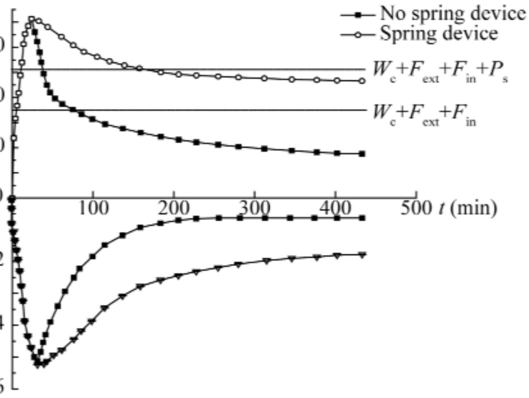


Fig. 14. Load vs. displacement curve.

With the seepage occurrence in the caisson, the caisson is constantly moving upwards. The spring is also shrinking until the tension value tends to be stable. In this case, the tension of spring value is the uplift bearing capacity of caisson. Typical plots of the pullout load–time behavior of caisson model are shown in Fig. 15. Test results indicate that the uplift capacity of caisson tends to decrease with the gradual dissipation of negative pressure. The residual negative pressure at the top of the caisson can sustain much larger uplift loading. This kind of negative pressure is obviously beneficial to the safety of the suction caisson. Therefore, the permeability coefficient is smaller, the negative pressure at the top of the caisson is higher, so the bearing capacity of the caisson is larger.

Fig. 16a shows the development of the negative pressure with time in Soil 1 and Soil 4. It can be seen that the negative pressure at the top of the caisson dissipates quickly in Soil 1. In contrast, the negative pressure at the top of the caisson dissipates slowly in Soil 4. The smaller the permeability coefficient is, the larger the residual suction will be. And the residual negative pressure is approximately equal to the water head that causes seepage in the caisson.

Fig. 16b shows a typical plot of negative pressure dissipation at the top and bottom of #3CM caisson model. It can be found that the negative pressure at the bottom of the caisson dissipate more quickly than that at the bottom of the caisson in Soil 4. On the contrary, the negative pressure at the top of the caisson is obviously higher than that at the bottom of the caisson in Soil 1, and seepage occurs in caisson.

Fig. 16c shows the development of the negative pressure with time in #1CM caisson model. The negative pressure at the bottom of the caisson gradually dissipates with time and the negative pressure value eventually tends to zero. On the contrary, the negative pressure at the top of the caisson is obviously higher than that at the bottom of the caisson in Soil 1, and seepage occurs in caisson.

4 Uplift bearing mechanism of suction caisson foundation

4.1 Uplift bearing mechanism of caisson in soft clay

Two failure modes exist, which are derived by a series of laboratory model tests in soft clay. One is the top tension failure mode and the other is the bottom tension failure mode. The first mode means that the reverse bearing capacity occurs at the top of the caisson and the uplift bearing capacity of suction caisson foundation is made up of its self-weight, the internal and external frictions and the reverse bearing capacity at the top of the caisson. The second mode

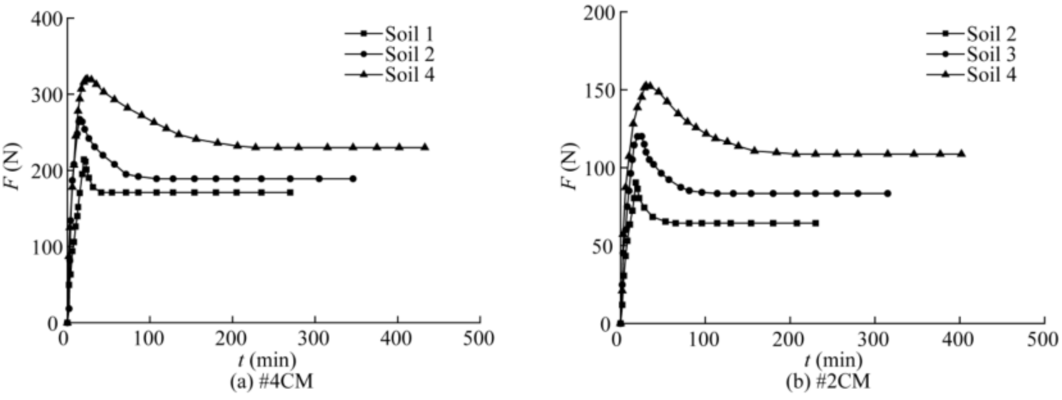


Fig. 15. Load vs. time curve.

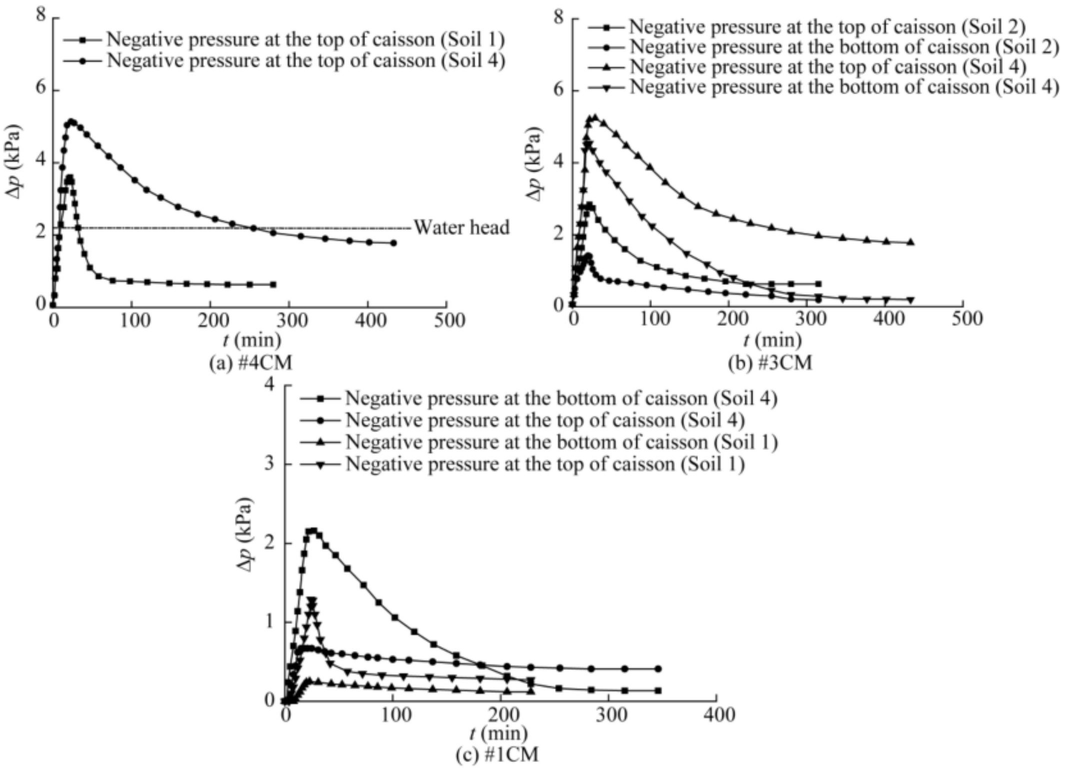


Fig. 16. Negative pressure vs. time curve.

means that the reverse bearing capacity occurs at the bottom of the caisson and the uplift bearing capacity of the suction caisson foundation is made up of its self-weight, soil plug weight, the external friction and reverse bearing capacity at the bottom of the caisson.

For the bottom tension failure mode, the uplift bearing capacity (P_u) of the suction caisson foundation in soft clay may be estimated by the following formula:

$$P_u = F_{ext} + W_c + W_s + R_{b1}, \tag{1}$$

where F_{ext} is the external friction, W_c is the caisson weight, W_s is the soil plug, and R_{b1} is the reverse bearing capacity at the bottom of the caisson.

$$R_{b1} = N_{b1}C_uA_b, \tag{2}$$

where N_{b1} is the bottom reverse factor, C_u is the undrained shear strength, and A_b is the caisson area.

At the same time, Chen and Randolph (2007), Rao et al. (1997), Singh et al. (1996), and Deng and Carter (2002) proposed the following formula according to the balance of soil plug stress. The forces acting on the soil plug are indicated in Fig. 17. When the soil plug moves together with the caissons, the negative pressure at the top of the caisson is obviously smaller than that at the bottom of the caisson. So Eq. (3) proposed by Rao et al. (1997), Singh et al. (1996), Deng and Carter (2002) is not suitable for the analysis of the bottom tension failure mode.

$$R_{b2} = P_s + F_{in} - W_s, \tag{3}$$

where R_{b2} is the bottom reverse bearing capacity, P_s is the reverse bearing capacity at the top of the caisson, and F_{in} is the internal friction.

$$R_{b2} = N_{b2}C_uA_b, \tag{4}$$

where N_{b2} is the bottom reverse factor.

It can be found that the negative pressure at the top of the caisson would transfer to the bottom during the pullout procedure. Rao et al. (1997) and Zhu et al. (2011) demonstrated that the negative pressure at the top of the caisson would transfer to the bottom during the pullout procedure. This test phenomenon also occurs at the top tension failure mode. For the top tension failure mode, the development of the uplift bearing capacity of the suction caisson is divided

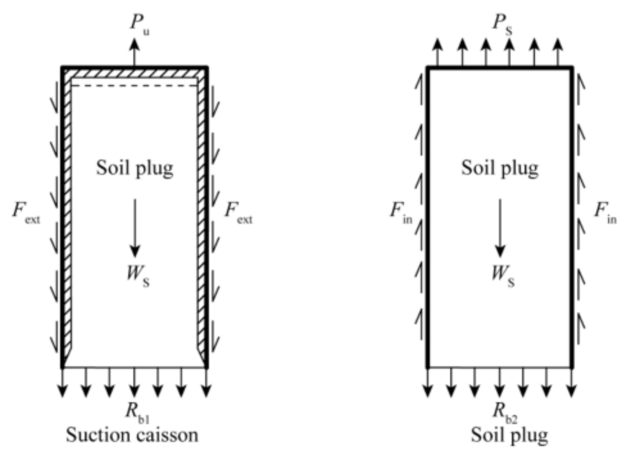


Fig. 17. Force balance relationship of the caisson and soil plug.

into three stages (Fig. 18). When the caisson is pulled, the internal and external frictions resist the uplift load firstly. Then, the reverse bearing capacity at the top of the caisson gradually increases with the uplift load. It can be found that the negative pressure at the top of the caisson would transfer to the bottom during the pullout procedure. In the third stage, as the load increases, the negative pressures at the top of the caisson and the bottom of the caisson gradually increase. Finally, the displacement of the caisson is not stable. The uplift bearing capacity (P) of the suction caisson foundation in soft clay may be estimated by the following formulas:

$$P = F_{\rm ext} + F_{\rm in} + W_{\rm c} + P_{\rm s}; \tag{5}$$

$$P_{\rm s} = N_{\rm b4} C_{\rm u} A_{\rm b}, \tag{6}$$

where $N_{\rm b4}$ is the top reverse factor.

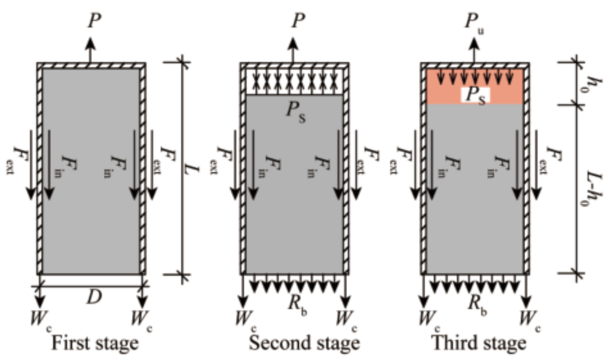


Fig. 18. Development stages of bearing capacity.

Because the suction force at the top of the caisson can balance the part of the soil weight, the failure height of soil can be obtained by the equilibrium equation.

$$h_0 = p_{\rm s}/\gamma. \tag{7}$$

Therefore, the effective friction force in the caisson is

$$F_{\rm in} = \alpha C_{\rm u} \pi D (L - h_0), \tag{8}$$

where α is the friction coefficient between the side wall of the caisson and the soil, which can be calculated by the uplift capacity of the open caisson model.

Table 4 shows the composition of the uplift bearing capacity of the suction caisson foundation. It can be found that the uplift bearing capacity of #1CM and #3CM suction models is made up of its self-weight, soil plug weight, the external friction and the reverse bearing capacity at the bottom of the caisson. The uplift bearing capacity of #2CM and #4CM suction models is made up of its self-weight, the internal and external frictions and the reverse bearing capacity at the top of the caisson. Because the internal and external frictions of the caisson in Table 4 are measured by open caisson model test, the bearing capacity calculated by fully considering the internal friction of caisson is larger than the test value. Table 5 shows the comparison of the uplift bearing capacity between the calculated and test values. When the internal friction of the caisson is calculated by Eq. (8), the calculated results of bearing capacity are close to the test values.

The breakout factors of the reverse bearing capacities at the top and bottom of the caisson are shown in Table 6. Under load control condition, when the load reaches the ultimate bearing capacity, both the top and bottom negative pressures are smaller than $S_{\rm u}$ and both the top and bottom reverse bearing capacity factors are smaller than 1.0 in soft clay.

4.2 Uplift bearing mechanism of caisson in sandy soil

There are also two failure modes in sandy soil as shown in Fig. 19 and Fig. 20. One failure mode is shown in Fig. 19. When the caisson is pulled, the internal and external frictions resist the uplift load firstly. Then, the reverse bearing capacity at the top of the caisson gradually increases with the uplift load. It can be found that the negative pressure at the top of the caisson would transfer to the bottom during the pullout procedure. Finally, the negative pressures at the bottom and top of the caisson gradually dissipate with time. The uplift bearing capacity of suction caisson foundation is supported by the internal and external friction of caisson wall, self-weight of the caisson and residual negative pressure at the top of the caisson. Eq. (9) can be used to calculate the failure mode. Eq. (10) proposed by Zhu et al. (2011) does not consider the negative pressure at the top of the caisson.

$$P_{\rm u} = W_{\rm c} + F_{\rm ext} + F_{\rm in} + P_{\rm s} = W_{\rm c} + \frac{\pi}{2}\gamma' DL^2 (K\tan\delta)_{\rm ext} + \frac{\pi}{2}\gamma' DL^2 (K\tan\delta)_{\rm in} + \frac{\pi}{4} D^2 \Delta p, \tag{9}$$

where, $K_{\rm ext}$ and $K_{\rm in}$ are the horizontal earth pressure coefficients, δ is the friction angle between the caisson and the soil, $P_{\rm s}$ is the reaction force at the top of the caisson, and Δp is the negative pressure at the top of the caisson.

$$P_{\rm u} = W_{\rm c} + F_{\rm ext} + F_{\rm in} = W_{\rm c} + \frac{\pi}{2}\gamma' DL^2 (K\tan\delta)_{\rm ext} + \frac{\pi}{2}\gamma' DL^2 (K\tan\delta)_{\rm in}; \tag{10}$$

Table 4 Composition of caisson bearing capacity

No.	Material	*w.c.* (%)	$P_{\rm u}$ (N)	$W_{\rm s}$ (N)	$W_{\rm c}$ (N)	$F_{\rm ext}$ (N)	$F_{\rm in}$ (N)	$R_{\rm b1}$ (N)	$P_{\rm s}$ (N)
#1	Steel	40.8	144	46	40	45	43	45.6	25.1
#2	Perspex	40.8	221	140	15	51	49	170	172
#3	Steel	40.8	298	92	75	94	92	52.9	19.3
#4	Perspex	40.8	398	280	30	101	98	196	210

Table 5 Comparative analysis of bearing capacity

No.	α	h_0 (m)	P_u (N)	F^a(N)	Diff.	F^b(N)	Diff.
#2	0.034	0.30	221	287	0.29	218	0.01
#4	0.034	0.39	398	439	0.11	375	0.06

F^a is the bearing capacity calculated by fully considering the internal friction of caisson; F^b is the bearing capacity calculated by considering the effective friction force in caisson.

Table 6 Coefficient of reverse bearing capacity

Model	S_u	Δp_{up}	Δp_{down}	N_{b4}	N_{b5}	N_{b1}	N_{b3}
#1CM	7.6	–	6.3	–	–	0.96	0.84
#2CM	7.6	5.7	5.5	0.68	0.76	–	0.73
#3CM	7.6	–	6.6	–	–	0.85	0.88
#4CM	7.6	6.6	6.4	0.85	0.88	–	0.82

N_{b3} is the measured bottom reverse factor, and N_{b5} is the measured top reverse factor.

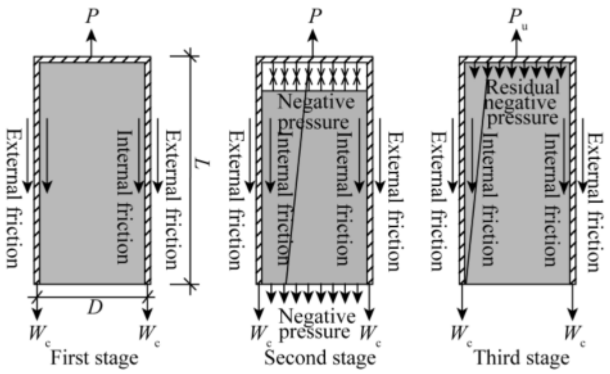


Fig. 19. Development stages of bearing capacity.

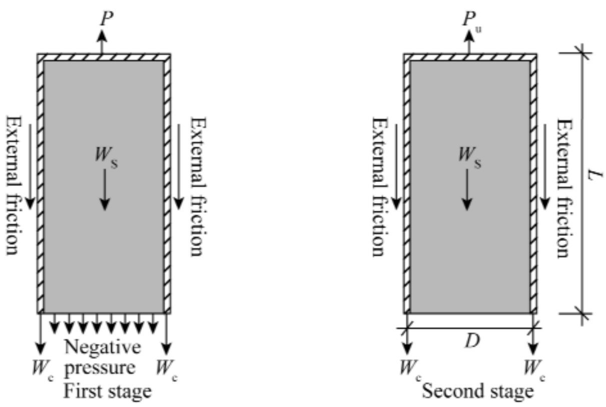


Fig. 20. Development stages of bearing capacity.

$$P_u = W_c + F_{ext} + W_s = W_c + \frac{\pi}{2}\gamma' DL^2 (K\tan\delta)_{ext} + \frac{\pi}{4}\gamma_{sat} D^2 L. \quad (11)$$

When the soil plug moves together with the caisson, the negative pressure at the bottom of the caisson undergoes the process from development to dissipation. For the failure mode, the uplift bearing capacity of the suction caisson foundation is made up of its self-weight, soil plug weight and the external friction. Eq. (11) can be used to calculate this failure mode. The forces acting on the model caisson are illustrated in Fig. 20. The composition of uplift bearing capacity of the suction caisson foundation is shown in Table 7.

Table 8 shows the results of comparative analysis of experimental and calculated values. It can be found from the table that the difference calculated by Eq. (9) is smaller than that calculated by Eq. (10).

Table 7 Composition of caisson bearing capacity

No.	Type	P_s (N)	W_c (N)	F_{ext} (N)	F_{in} (N)	P_u (N)
#1	Soil 1	5	26	23	19	71.4
	Soil 4	0	26	25	22	108.6
#2	Soil 1	2	15	34	32	64.4
	Soil 4	25	15	38	34	97.4
#3	Soil 1	23	65	59	60	194.3
	Soil 4	57	65	62	65	245.2
#4	Soil 1	15	30	78	72	178
	Soil 4	53	30	85	78	230

Table 8 Comparison of bearing capacity

No.	Type	P_u	Eq. (10)	Diff.	Eq. (9)	Diff.
#1	Soil 1	71.4	66.4	0.07	73	−0.02
	Soil 4	108.6	80.6	0.26	101	0.07
#2	Soil 1	64.4	62.4	0.03	83	−0.29
	Soil 4	97.4	72.4	0.26	112	−0.15
#3	Soil 1	194.3	171	0.12	207	−0.07
	Soil 4	245.2	188	0.23	249	−0.02
#4	Soil 1	178	163	0.08	195	−0.10
	Soil 4	230	177	0.23	246	−0.07

5 Conclusions

In order to study the uplift bearing mechanism and failure mode of the suction caisson foundation in sandy soil and soft clay, a series of model tests have been carried out to study the uplift bearing characteristics of the suction caisson foundation with the effects of aspect ratio, soil permeability and loading mode. The main research results are as follows.

(1) In sandy soil with high permeability, seepage will occur in the caisson. The uplift bearing capacity of caisson is composed of its self-weight and internal and external frictions. In sandy soil with low permeability, residual negative pressure will be found at the top of the caisson. The bearing capacity of the caisson is composed of its self-weight, internal and external frictions, and the reverse bearing capacity at the top of the caisson.

(2) In sandy soil, test results indicate that the residual negative pressure at the top of the caisson is beneficial to enhance the uplift bearing capacity. If the permeability coefficient is smaller, the residual suction will be larger. The residual negative pressure is approximately equal to the water head that causes seepage in the caisson.

(3) In soft clay, there are two failure modes. In the top tension failure mode, the uplift bearing capacity of the caisson is made up of its self-weight, the internal and external

frictions, and the reverse bearing capacity at the top of the caisson. In the bottom tension failure mode, the uplift bearing capacity of the suction caisson foundation is made up of its self-weight, soil plug weight, the external friction, and the reverse bearing capacity at the bottom of the caisson.

(4) In the top tension failure mode, the negative pressure at the top of the caisson would transfer to the bottom during the pullout procedure. In the bottom tension failure mode, the negative pressure is only at the bottom of the caisson. When the load reaches the ultimate bearing capacity, both the top and bottom negative pressures are smaller than S_u and both the top and bottom reverse bearing capacity factors are smaller than 1.0 in soft clay.

(5) By combining the uplift bearing characteristics of caisson in sandy soil and soft clay, the bearing capacity composition and the calculation method are proposed to analyze the uplift bearing capacity of suction caisson foundations.

This paper investigates the uplift bearing characteristics of caisson in sandy soil and soft clay, which can provide a reference for the engineering design of suction caisson foundation under vertical load. But this paper only discusses the negative pressure dissipation in sandy soil. Therefore, the long-term uplift bearing capacity of caisson needs further research in soft clay.

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