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Model tests of soil heave plug formation in suction caisson

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An experimental study of the formation of the soil heave plug inside a concrete caisson during installation in clay under suction is presented. The soil heave plug, the amount of caisson penetration and the vacuum pressure applied were measured during the model tests. The results show that the soil heave plug can completely fill in the cavity and prevent the caisson from penetrating further. The soil heave plug is affected by the geometry of the caisson. The higher the consolidation stress or the stiffer the soils, the higher is the suction pressure required, and a higher suction will in turn induce a greater soil heave plug. The m value, defined as the ratio of the volume of the soil heave plug to that of the penetrated caisson skirt wall, is adopted to evaluate the soil heave plug. The relationship between the m value and the undrained shear strength of the soil can be used to estimate the amount of soil heave plug and the caisson penetration for a concrete caisson with a wall thickness to external diameter ratio of 5% in normally consolidated clay conditions.

Notation

D_i	internal diameter of caisson
D_o	external diameter of caisson
H_i	internal height of caisson
H_o	external height of caisson
h	penetration depth of caisson
h_p	height of soil heave plug
m	ratio of volume of soil heave plug to volume of penetrated caisson skirt wall
S_u	undrained shear strength
t	caisson wall thickness
σ_c	consolidation pressure

1. Introduction

A suction caisson is a steel or concrete offshore superstructure with an upturned bucket shape penetrated into the seabed soil by self-weight and vacuum suction. The principle of the suction caisson technique is to create a downward net force to sink the caisson into the seabed soil through the application of vacuum suction. The suction is removed after installation is complete. In this way, the foundation to a superstructure can be constructed without treating the soft seabed soil. Most of the suction caisson applications are in deep water. These

include mooring anchors (Andersen and Jostad, 1999, 2002; Andresen *et al.*, 2011; Randolph *et al.*, 2011; Wang *et al.*, 1975), offshore platforms (Zhang and Ding, 2011; Zhang *et al.*, 2007) and foundations for wind turbines (Byrne *et al.*, 2002; Gavin *et al.*, 2011; Houlsby and Byrne, 2000; Houlsby *et al.*, 2005; Whittle *et al.*, 1998). There is also an application of the suction caisson for breakwaters in shallow water; see, for example, Chu *et al.* (2012). The use of suction caissons in shallow water is more challenging because limited downward net force can be applied in the suction caisson.

When a caisson penetrates into clay using suction, soil will be sucked into the open-ended hollow caisson cavity, forming a soil heave plug. An excessive soil heave plug could prevent the target penetration depth being reached because the surface of the soil plug touches the caisson cap and clogs up the inlets; see, for example, Andersen *et al.* (2005), Newlin (2003) and Chen and Randolph (2007). Therefore, a study on the effect of the soil heave plug on the installation of a suction caisson was carried out through the use of model tests.

The soil heave plug has to be taken into consideration particularly when the ratio of the caisson wall thickness to its

diameter is large. One method to evaluate the soil heave plug is to calculate the ratio between the volume of the soil heave plug and that of the penetrated caisson skirt wall (Guo and Chu, 2013). The volume of the soil heave plug can be calculated as $0.2\pi D_i^2 h_p$, where D_i is the internal diameter of the caisson and h_p is the height of the soil heave plug. The volume of the penetrated caisson skirt wall can be defined as $0.25\pi(D_o^2 - D_i^2)h$, where D_o is the external diameter of the caisson and h is its penetration depth. This so-called ratio of soil heave plug, m , can be written as follows

$$1. \quad m = \frac{h_p/h}{D_o^2/D_i^2 - 1}$$

Several field tests, 1g model tests and centrifuge tests have been carried out to investigate the installation procedure for a suction caisson (Andersen *et al.*, 2005; Guo *et al.*, 2012; Houlsby *et al.*, 2005; Tran and Randolph, 2008). The ratios of the soil heave plug from some of the model tests are calculated and summarised in Table 1. It can be seen that, for caissons installed by the self-weight or jacking method, about half of the soil displaced by the caisson tip would flow into the caisson cavity, that is, $m \approx 0.5$. However, for the case of the suction-assisted installation method, m ranges from 0.62 to 4.01 (see Table 1). Furthermore, the ratio of the soil heave plug is significantly influenced by the ratio of caisson wall thickness to the external diameter, t/D_o . Generally, the larger the value of t/D_o , the greater the m value will be. The data

Installation method	m	t/D_o : %	Reference	Note
Self-weight/jack	0.47	0.70	Andersen <i>et al.</i> (2005)	NC clay
	0.48	0.50	Tran and Randolph (2008)	
	0.64	1.67	Chen <i>et al.</i> (2009)	
Suction	0.62	0.27	Houlsby <i>et al.</i> (2005)	NC clay
	1.04	0.70	Andersen <i>et al.</i> (2005)	
	4.01	0.53	Houlsby <i>et al.</i> (2005)	
	2.69	1.00	Tran and Randolph (2008)	Sand
	3.28	2.27	Guo <i>et al.</i> (2012)	

Table 1. Ratio of soil heave plug from different model tests

Figure 1. Model test set-up: (a) sketch of consolidation tank (unit: m); (b) photo of consolidation tank

shown in Table 1 are only for steel suction caissons. However, if the caissons are made of concrete, the ratios of caisson wall thickness to external diameter, t/D_o , will be much higher (Chu *et al.*, 2012). Then the soil heave plug would be more significant when the caisson is installed by suction and thus influence the final penetration depth of the caisson. The concrete caisson also has many advantages over a steel caisson. These include: (a) higher erosion resistance; (b) lower construction cost; and (c) it is easier to make the structure seamless.

In this paper, a study of the soil heave plug in concrete caissons installed by suction in clay consolidated by different consolidation stresses is presented. The major feature of this study as compared with previous model tests is that the suction caisson was installed into soil with the consolidation stress still applied. Thus, the soil heave plug can be studied under the desired vertical overburden stress. The soil heave plug, penetration depth and applied vacuum pressure were measured during the tests. The m value, calculated by the ratio of the volume of the soil heave plug to volume of the penetrated caisson skirt wall, was adopted to evaluate the soil heave plug during the model tests.

2. Model test set-up

2.1 Test set-up

A cylindrical stainless steel tank 1.4 m high and with a diameter of 1.0 m was used to consolidate the soil. The details of the consolidation tank are shown in Figure 1. An internal piston was used at the bottom of the tank to apply vertical consolidation stresses. Kaolin slurry was poured into the cavity on top of the piston. Then compressed air was applied below the piston to move it upward, to apply consolidation pressure to the clay. The water drained to the drainage pipe in the centre of the rod, which was welded to the centre of the piston. The rod was also used to balance the movement of the piston during the consolidation process. A filter layer including two layers of geotextile, fine sand and gravel was laid on top of the piston, as shown in Figure 1(a). A calibration test was carried out before the model test to measure the side friction on the contact edge between the piston and the internal tank walls. The consolidation pressure considered in the following discussion is the net air pressure applied to the soil layers. The settlements of kaolin during consolidation and soil heave plug in the suction caisson during the model test were measured by a Keyence IL series multi-function analogue laser sensor. The laser sensor had a range from 20 mm to 1.0 m and minimum repeatability of 1 μ m. One laser sensor was used to measure settlements of the soil during consolidation by mounting it onto an aluminium angle bar. Four laser sensors were mounted on the top cap to measure the penetration depth of the suction caisson and soil heave plug.

2.2 Clay bed

The soil used for the model tests was consolidated from kaolin slurry. Factory-made kaolin powder was used because of its

high coefficient of consolidation, low compressibility and commercial availability. The kaolin used was supplied by Kaolin Malaysia Sdn Bhd. It has a specific gravity of 2.61, a liquid limit of 61% and a plastic limit of 38%. The kaolin powder was mixed with tap water to form a slurry with water content around 80%. After mixing, the slurry was transferred into the consolidation tank. Then the top cap was mounted onto the cylindrical consolidation tank. Consolidation pressures (σ_c) of 41, 106 and 216 kPa, respectively, were applied to consolidate the slurry into soil for 10 d. The air pressure was maintained during the whole model test to keep the clay in the normally consolidated state. The tested undrained shear strengths (S_u) were measured using the lab shear vane method – see Figure 2(a). It can be seen that the undrained shear strength increased with depth at a constant gradient. Samples of kaolin clay from different depths were taken to measure the water content – see Figure 2(b). It can be seen from the test results that the water content of the kaolin was not uniform.

Figure 2. Basic properties of the consolidated kaolin when consolidated by different consolidation pressures (σ_c): (a) undrained shear strength distribution along depth of clay; (b) water content distribution along depth of clay

Figure 3. Illustration of caisson models (unit: mm): (a) sketch of caisson model; (b) photo of caisson model

Caisson no.	Tip shape	Weight: kg	H_0 : mm	D_0 : mm	t : mm	D_i : mm	H_i : mm	t/D_0 : %
C1	Horizontal	5.85	200	200	10	180	195	5.00
C2	Horizontal	6.87	400	180	10	160	395	5.56

Table 2. Dimensions of test caisson models

Figure 4. Photos of caisson and soil heave plug before and after installation: (a) before installation; (b) after installation; (c) soil heave plug

2.3 Caisson models

Two cylindrical caisson models, C1 and C2, with different height-to-diameter ratios (H_0/D_0) were used for the model tests. The details of the caissons and their dimensions are shown in Figure 3 and Table 2. The skirt wall of model C1 was made completely of concrete with a wall thickness (t) of 10 mm. The height and diameter of model C1 are both 200 mm. The top cap was made of steel plate, which was mounted onto the caisson skirt wall using screws. In order to prevent air seepage, an O-ring was installed between the top cap and the caisson skirt wall. As shown in Figure 3(b), a washer and rod system was mounted on the top cap. An internal polished stainless steel rod could freely move up and down through the washer. The gap between the washer and steel rod or that between washer and top plate was sealed by an O-ring and oil. A 10-cm-dia. plastic plate was mounted on the end of the steel rod to prevent it from penetrating into the clay. The soil heave plug during the installation pushed the steel rod upward. Thus the soil heave plug was monitored through the movement of the rod. Model C2 was designed in the same way as model C1, except its height and diameter were 400 mm and 180 mm, respectively.

3. Model test results and discussion

The model tests were named using a combination of five alphanumeric words. The first two indicate the caisson model number (C1 or C2), and the last three indicate the consolidation pressure used. For example, C1-41 represents a model test carried out using the C1 model and installed into a clay bed consolidated under 41 kPa. The tests were carried out by positioning the caisson on top of the soil and then applying suction pressure to penetrate the caisson.

3.1 Soil heave plug

The soil heave plug has been observed in all the model tests. Photos of a caisson model and soil heave plug during the model test are shown in Figure 4. Before the test, the caisson model C1 was placed on top of the soil surface. As the dead weight of the caisson model was small (5.85 kg), there was little penetration due to self-weight. To prevent tilting of the caisson model during installation, a guide consisting of three metal blocks (Figure 4(a)) was used. After that, a suction pressure was applied. With the increase in suction pressure, the caisson started to penetrate into the clay. The penetration was stopped eventually as shown in Figure 4(b). The termination of the penetration was related to the formation of a full soil plug. In other words, the cavity was filled completely with soil – see Figure 4(c). The depth of caisson penetration against applied suction pressure curves for the three tests, C1-41, C1-106 and C1-206, are plotted in Figure 5(a). For test C1-206, the caisson was jacked 2 cm into the soil first before a vacuum pressure was applied. At the end of the test, the caisson had penetrated 14.2, 11.7 and 10.4 cm for C1-41, C1-106 and C1-206 respectively. Figure 5(a) also shows that the stiffer the soil is, the greater the vacuum pressure that is needed to penetrate the caisson and the

smaller the amount of the penetration. The measured soil heave plug is plotted against the penetration depth of the caisson in Figure 5(b). The soil heave plugs formed in the three tests were 5.2, 6.6 and 8.5 cm, respectively.

3.2 Effect of soil properties

The soil heave plug is affected by the soil properties. The difference between the three model tests shown in Figure 5 is the consolidation stress. It can be seen from Figure 5(b) that the amount of soil heave plug is different. The higher the consolidation stress or, in other words, the stiffer the soil, the greater the amount of soil heave plug. Another observation is that the amount of soil heave plug increases almost linearly with the penetration of the caisson.

The m values for all three tests were calculated using Equation 1 and the m values calculated are 1.64, 2.3 and 3.3 for model

Figure 5. Installation of C1 model in clay: (a) penetration depth of caisson plotted against suction pressure curves; (b) soil heave plug plotted against penetration depth of caisson curves

tests C1-41, C1-106 and C1-206, respectively. The m values are larger than 1.0, which means that extra soil is displaced into the cavity to form the soil heave plug. Using the m values, the soil heave plug plotted against penetration depth of the suction caisson relationships have been calculated and plotted as dashed lines in Figure 5(b). It can be seen that there is a good agreement with the measured curves.

The test results for the three model tests on caisson model C2, C2-41, C2-106 and C2-206, are shown in Figure 6. The soil was consolidated by consolidation pressures of 41, 106 and 206 kPa, respectively. Similar results were obtained as those from caisson model C1. The soil heave plug plotted against penetration depth of suction caisson curve (Figure 6(b)) for test C2-106 is not normal. This was because of a leak of suction pressure at the beginning of the test. The m values are

calculated for the other two tests. The values 1.7 and 2.7 are within the same range as for the tests on caisson C1 as shown in Figure 5(b).

3.3 Effect of caisson height

The influence of the caisson height during the caisson installation tests is discussed in this section. The caisson models C1 and C2 have similar internal diameters of 180 and 160 mm, respectively, and the same caisson wall thickness. However, caisson model C2 is twice the height of model C1. A comparison of the results for the two series of tests is shown in Figure 7. As seen in Figure 7(a), the results of model tests on model C2 have almost the same trends as those on model C1. The suction pressures plotted against penetration depth of the caisson models followed similar trends for the two series

Figure 6. Installation of C2 model in clay: (a) penetration depth of caisson plotted against suction pressure curves; (b) soil heave plug plotted against penetration depth of caisson curves

Figure 7. Comparison of installation test results of C1 and C2 models: (a) penetration depth of caisson plotted against suction pressure curves; (b) soil heave plug plotted against penetration depth of caisson curves

of tests. Take model tests C1-41 and C2-41 for example: the percentage of the amount of penetration for test C1-41 is 71.5% and that for C2-41 is 68.25%. A comparison of the soil heave plug plotted against penetration depth of suction caisson curves is shown in Figure 7(b). It can be seen that the two series of tests follow a similar trend. The m values obtained for tests in soil with the same consolidation pressures are also close, although the m values for model C2 are slightly higher than those for model C1. This is reasonable, as

the proportion of the area of the caisson wall over the cross-section of the caisson for model C2 is larger than that of model C1.

3.4 Water content of clay in soil heave plug

To measure the water content of the clay in the soil heave plug, samples were taken after the tests. The distribution of the water content in the soil heave plug could indicate the flow direction of water and clay under the influence of suction. The

Figure 8. Soil water content distributions before and after caisson installation: (a) model test C1-41; (b) model test C2-41 (w/c indicates clay water content)

Figure 9. Soil water content distributions before and after caisson installation: (a) model test C1-106; (b) model test C2-106

Figure 10. Soil water content distributions before and after caisson installation: (a) model test C1-206; (b) model test C2-206

water content distribution in the soil heave plug after model test C1-41 is shown in Figure 8(a). The water content of the clay before the installation of the suction caisson (or after consolidation) is about 52.5%. After installation, the water content of the clay at the edge of the cross-section is much higher than that at the centre of the soil heave plug. As seen from Figure 8(a), the water content of the clay on top of the soil heave plug is 60.3% in the centre, but 71% at the edge. However, in the middle of the soil heave plug, the water content of the clay is lower than at its top. As seen from Figure 8(a), the water content of the clay in the centre of the cross-section is 55.2%, but that on its edge is 62.6%. This indicates that the pore water in the soil flows from the bottom to the top in the vertical direction, as well as from the centre to the edge in the radial direction. A similar observation is made for test C2-41 and other model tests, as shown in Figures 8(b)–10.

4. Discussion

The m value calculated by the ratio of the volumes of the soil heave plug to that of the penetrated caisson skirt wall was adopted to evaluate the soil heave plug using six small-scale model tests in three soil beds consolidated under three different pressures. Based on the results shown in Figure 5(b) and Figure 6(b), the soil heave plug linearly increases with respect to the penetration depth of the suction caisson. The m values obtained for caissons with different heights do not differ much for the same soil. The m values are also plotted against the undrained shear strength of the soil at the mid-height of the caisson in Figure 11. It can be seen that an almost linear relationship is obtained between the m value and the undrained shear strength of the soil. This relationship can be used to calculate the volume of soil heave plug into the caisson

Figure 11. Relationship between m value and undrained shear strength of soil at mid-height of caisson wall

with $t/D_o = 5\%$ when penetrating in similar soil conditions. For example, if the undrained shear strength of soil at the mid-height is 20 kPa and the concrete suction caisson has an outer diameter of $D_o = 20$ m and a wall thickness of $t = 1$ m or $t/D_o = 5\%$, the m value will be 2.08 using Figure 11. Using Equation 1, the ratio between the soil heave plug and the caisson penetration depth, $h_p/h = 0.488$ can be obtained. Thus the soil heave plug will be $0.488h$ m or 0.488 m for 1 m of caisson penetration into clay. Theoretically, this allows the designer to estimate that the maximum penetration depth of this caisson is 67.2% or $1.0/(1.0 + 0.488)$. However, it should be pointed out that the above estimate is based on an experimental study using a caisson with $t/D_o = 5\%$ tested in the specific soil conditions. Thus, the method may only be applied

for $t/D_o = 5\%$ and similar soil conditions until further verification studies have been made.

5. Conclusions

An experimental study of the behaviour of the soil heave plug in a concrete suction caisson installed in clay for near-shore applications was presented. Model tests were carried out in such a way that the consolidation pressure was maintained throughout the caisson installation phase, so that the behaviour of the soil heave plug could be studied more realistically. The study showed that the consolidation pressure or the vertical overburden stress of soil has a great influence on the soil heave plug. The experimental results also indicate that the soil heave plug is affected by the geometry of the caisson as well. The thicker the caisson wall is, the more soil will be displaced and the larger the soil heave plugs will be. The higher the consolidation stress or the stiffer the soil is, the higher the suction that will be needed to install the caisson and the larger the soil heave plug that will be produced.

The m value calculated by the ratio of the volume of the soil heave plug to the volume of the penetrated caisson skirt wall was adopted in this paper to evaluate the soil heave plug using six small-scale model tests for soil beds consolidated under three different consolidation stresses. The m value obtained for the model test is not much affected by the caisson height. The relationship between the m value and the undrained shear strength of the soil at the mid-height of the caisson is linear. This relationship can be used to estimate the volume of the soil heave plug and penetration depth for concrete suction caissons with $t/D_o = 5\%$ and in similar normally consolidated clay conditions.

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