Suction Caisson Installation in Shallow Water: Model Tests and Prediction

Installation de caissons à succion en eau peu profonde: essais et prédiction

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ABSTRACT: Suction caissons have been used as foundations to support mainly offshore structures such as offshore oil rigs in deep water where a large suction pressure can be generated. Studies have been made recently to use this method for near shore foundations in shallow water where the suction that can be applied is much smaller. In this paper, a study on the installation of suction caissons in clay in shallow water using large scale model tests is presented. The model test setup and test results are discussed. The effects of soil plug and side friction are evaluated. An analytical method proposed by Houlsby and Byrne is adopted to predict the penetration versus time relationship. The analytical solutions agree well with the model test results.

RÉSUMÉ: Les caissons à succion ont été utilisés principalement pour les fondations de structures offshore en eau profonde permettant de générer de fortes pressions de succion. Cet article présente une étude sur une installation de caisson dans de l'argile à faible profondeur en utilisant un modèle à grande échelle. Les résistances d'arrachement et frottements latéraux sont évalués. La méthode analytique proposée par Houlsby et Byrne est adoptée pour prédire la relation pénétration-temps et donne de bons résultats

KEYWORDS: Caisson; Clay; Model Test.

1 INTRODUCTION

A research project to use super-size cylindrical structures to form underwater space and at the same time create land on top is being carried out in Singapore. As the seabed soil is mainly soft clay, suction caissons were considered on possible form of foundations to support form part of the reclaimed land for buildings or other types of structures to be built on top of it, the foundation types for the offshore structures have to be developed using innovative solutions. The most difficult design condition is when the seabed soil is soft. It would be too costly to treat the soft soil offshore. One innovative solution is to use suction caissons.

Normally suction caissons are large, hollow, cylindrical steel or concrete structures in form of upturned bucket shape, and are penetrated into the seafloor bottom sediments by self-weight and suction pressure. The principle of the suction caisson technique is to apply suction inside a sealed cylindrical caisson to create a downward net force to sink the caisson into the seabed soil. After the suction is removed, the foundation is constructed without treating the soft soil. The suction caisson have been successfully employed in recent years in many projects including mooring anchors (Andersen and Jostad, 1999; Andresen et al., 2011; Randolph et al., 2011; Wang et al., 1975), beak water or sea walls (Chu et al., 2012), offshore platforms (Zhang et al., 2007; Zhang and Ding, 2011) and foundation for wind turbine in deep waters (Byrne et al., 2002; Gavin et al., 2011; Houlsby et al., 2005c).

For caissons used in deep water, the hydrostatic water pressure as provided by the water depth can contribute to suction pressure to compress the caisson into seabed. However, in relatively shallow water, there may not be sufficient suction to allow the caisson to penetrate to the required depth. Another factor affecting the penetration of a suction caisson is the soil plug formed inside the caisson. When a caisson is penetrated into clay, soil will go inside the open ended hollow caisson and form soil plug. The soil plug resists the penetration of the caisson. For this purpose and for the development of suitable design methods, model tests and numerical studies were carried out.

Analytical methods for analyzing the installation process of suction caisson have also been proposed (Andersen et al., 2005; Chen et al., 2009; Houlsby and Byrne, 2005a, 2005b; House and Randolph, 2001; House et al., 1999; Tran and Randolph, 2008). In the method by Houlsby and Byrne (2005a, 2005b), a constant penetration velocity was assumed. The driving forces and soil resistance were also assumed to be balanced during the whole installation process. This method was adopted to calculate the amount of penetration of suction caisson subjected to a constant driving force. The solution of this method was compared with those from the model tests and good agreement was achieved. Some of the key design parameters were also evaluated based on the model test results.

2 MODEL TESTS

2.1 *Soil Preparation*

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 into a slurry form with water content of 81.3%. After mixing, the desired slurry was transferred to the consolidation tank as shown in Figure 1. Then the top cap and piston were mounted onto the cylindrical tank. A compressed air pressure of 60*kPa* was applied on top of the piston to consolidate the kaolin slurry for about 10 days. The friction between the piston and the tank wall was 17.35 *kN* measured by a calibration test before the test. Therefore, the effective consolidation pressure was 37.9 *kPa* only.

The consolidated water was allowed to drain freely through a drainage valve at the bottom of base plate. In order to consolidate the kaolin slurry faster, a filter layer were designed on the bottom of the tank including two layers of geotextile, fine sand and gravel. The movement of piston was monitored by a laser sensor (*Keyence®IL-600*). After the consolidation was completed, the air pressure was reduced to zero and the top cap was removed to allow soil samples to be taken for undrained shear strength and water content tests. The water content of the tested soil was 42.7%. The average undrained shear strength

(S_u) was 13 *kPa* as measured by lab shear vane method along the tank depth.

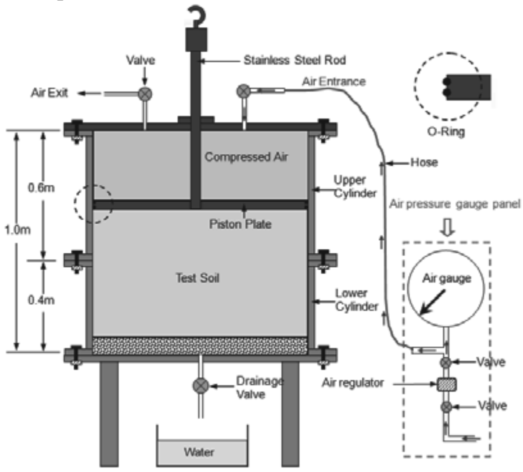


Figure 1 Consolidation procedure of kaolin

2.2 *Caisson Installation*

The caisson was made by an inner steel skirt and covered by a layer of concrete with its total height of 400*mm*, diameter of 205*mm* and wall thickness of 22.5*mm.* The Caisson was assembled with a designed piston which made it possible to monitor the process of soil plug during installation tests. The piston consisted of a 'Teflon' plate and a steel rod. The plate was 25 mm thick and 150 mm in diameter with steel rod mounted in the middle. A crew with a height of 20 mm was used to strengthen the connection of the rod and the plate. Thus the clear internal skirt length of the caisson reduced from 400*mm* to 335 mm. The total weight of caisson and piston was 27.2*kg*.

The vacuum loading system was composed by a vacuum pump (EVISA E25), a vacuum gauge, two bowl vacuum filters, a vacuum tank, and a hose, as illustrate in Figure 2. Note that during suction installation tests, one more absolute pressure transducer was mounted in the caisson cavity to test the vacuum pressure.

The miniature pore water pressure transducers (PPTs) were used in this model test to measure the pore water pressure changes. Such a miniature size was necessary to minimize the influence of the measuring device to the overall soil behavior during model test. Before a model test, all PPTs were calibrated by using water pressure generated in a triaxial cell. The preinstalled positions of the PPTs on the top cap are shown in Figure 2.

The displacement of the piston in the consolidation tank or that of the suction caisson during the model test was measured by laser sensor (KEYENCE IL series) which had an effective measurement range from 20*cm* to 1.0*m*. The displacement of piston rod in caisson was also measure by another laser sensor by mounting an aluminum plate on to the rod. The third laser sensor was mounted on the frame to measure the displacement of suction caisson. Two other laser sensors were used to measure the soil movement on caisson sides as shown in Figure 2. This contact-free displacement measuring method offered both reliability and convenience.

2.3 *Model Test Results*

The model test results of caisson penetrated into the soil bed assisted by vacuum pressure was discussed in this section. Since the self-weight was not able to provide enough penetration force for caisson insertion, the caisson was manually penetrated into soil in a short distance to ensure that the applied suction would not leakage. The applied vacuum pressures in Model Test *No. 1* and *No. 2* during the suction installation are shown in Figure 3. It can be seen that the vacuum pressure increased very slowly till to the largest magnitude of -80*kPa*. The displacements of the caisson and soil plug are shown in Figure 4 and Figure 5, respectively. It can be seen that the soil plug was moving upward throughout the installation procedure. At the beginning, the soil plugs increased nearly linearly with the time. A the time of 81*s* for test *No. 1* and 96*s* for test *No. 2*, there was a sudden jump in the displacement. This happened because the soil plug was broken suddenly. During this period, the caisson had no penetration.

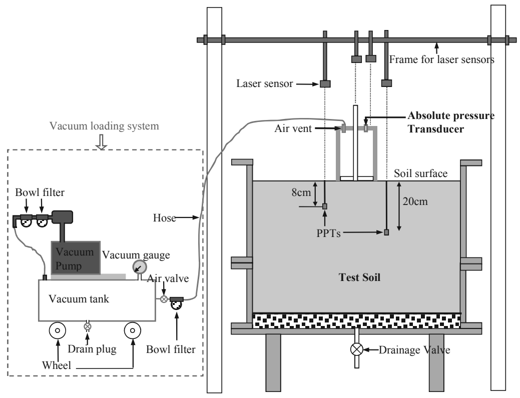


Figure 2 Installation of suction caisson

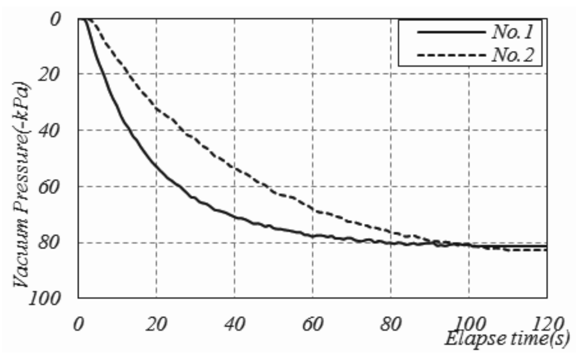


Figure 3 Vacuum pressure vs. time curve

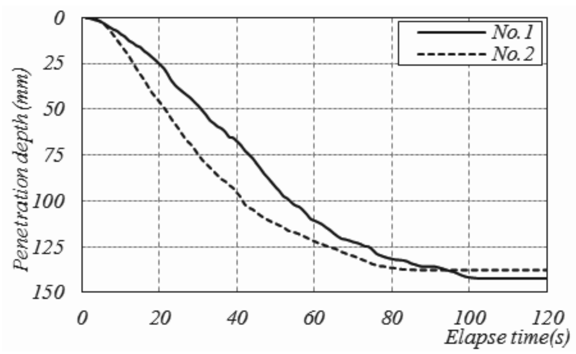


Figure 4 Penetration depth vs. time curve

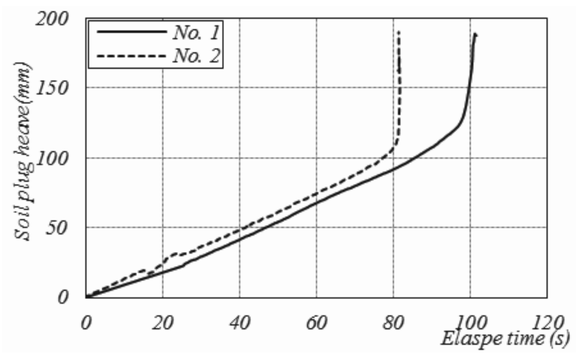


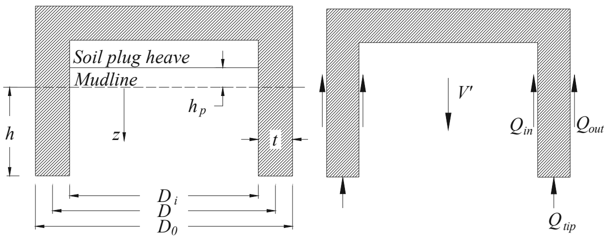
Figure 5 Penetration depth vs. soil plug heave curve

3 ANALYTICAL SOLUTIONS

An analytical method to simulate the penetration procedure for suction caisson in clay has been proposed by Houlsby and Byne (2005b). The friction between internal caisson wall and internal clay and that between external wall and external clay were considered separately by using different friction coefficient (different α value). The self-weight penetration and suction assistant penetration have been made a clear distinction. As the the self-weight penetration is very small in our 1-g model tests, only the suction assistant penetration process is discussed in this paper.

A simplified cross-section of the suction caisson is shown in Figure 6. The vertical coordinates, measured at a depth below the mud line, is set up with z. The inside, outside and average diameters of the caisson are represented by D_i, D_0, D respectively. Therefore, $D_i=D_0-2t$ and $D = (D_i + D_0)/2$ where t is the thickness of the caisson wall. The total height of the caisson is L and height embedment into the seabed is h. The soil plug higher than the mud line inside of the caisson is denoted as h_p. The unit weight of water is γ_w and that of soil is γ.

As illustrated in Figure 6(b), the total effective weight of suction caisson is presented as V'. The side frictions between soil with outside and inside of the caisson are written as Q_{in} and Q_{out}, respectively. The end bearing capacity on the tip of suction caisson is defined as Q_{tip}.



(a) Parameters definition (b) Free body diagram

Figure 6 Cross section of suction caisson (Modified after Houlsby and Byne, 2005b)

When the caisson penetrates into the soil, a bearing capacity failure will occur around the wall tip. It is assumed that the soil plug is mainly due to these displaced soil flow into the caisson. We make the simplifying assumptions that: (a) there is a volume of clay, V_s, flows into the caisson because of the replacement of caisson walls, V_c, and $V_s=mV_c$; (b) the flowed clay does not change the original unit weight of clay within the caisson; and (c) the flowed clay forms the soil plug with its height shown in Eq. (1). These assumptions were especially valid for the suction caisson installed in clay which have already been verified by model test results (Whittle et al., 1998), prototype behavior (Colliat et al., 1996), and finite element analyses (Andersen and Jostad, 2002; Andersen and Jostad, 2004). The values of m will be calculated using the model test results.

$$h_p = m(D_0^2 / D_i^2 - 1)h \tag{1}$$

For the case of suction caisson installation in clay, the calculation neglects the effect of the applied suction pressure and the side frictions along the caisson walls. Then this procedure can be treated as undrained conditions. Therefore, the side frictions are calculated by applying a factor α to the value of the undrained strength (α-method), i.e. $Q_{in} = h\alpha_i s_{ui}(\pi D_i)$ *and* $Q_{out} = h\alpha_0 s_{u0}(\pi D_0)$ where s_{u0} is average undrained strength between mud line and depth h. If the undrained strength of clay increased along depth linearly, i.e. $s_u=s_{u1}+\rho z$, the average undrained strength of soil, s_{u0}, can be calculated as $s_{u0}=s_{u1}+\rho h/2$ where ρ is the coefficient of undrained strength increasing. Similar calculation method can also be applied to the internal undrained strength, s_{ui}. The bearing capacity on the tip is calculated according to the standard bearing capacity calculation, i.e. $\sigma'_{tip} = \gamma' h N_q + s_{u2}N_c$ and $s_{u2}=s_{u0}+\rho h$, where N_c is the capacity factor for a deep strip footing in clay (a typical value of 9 may be adopted) and N_q=1 for undrained analysis. During the suction assisted penetrations, the driving force is the weight of suction caisson and applied suction pressure. The resistance to the caisson is calculated as the sum of the side frictions (Q_{in}+Q_{out}) and the end bearing capacity on the tip (Q_{tip}). The force equilibrium along the vertical direction yields the following equation:

$$V' + s\left(\frac{\pi D_0^2}{4}\right) = h\alpha_0 s_{u0}(\pi D_0) + (h+h_p)\alpha_i s_{ui}(\pi D_i) + (\gamma' h + s_{u2}N_c)(\pi Dt) \tag{2}$$

The internal and external side frictions calculated by $(h+h_p)\alpha_i s_{ui}$ and $hQ_{out}\alpha_0 s_{u0}$ may be assumed to have the same magnitude. This is reasonable as the internally remold clay will have a lower undrained shear strength and a lower coefficient of side friction (Andersen and Jostad, 2004). Then Eq. (2) can be further simplified as follows:

$$V' + s\left(\frac{\pi D_0^2}{4}\right) = 2h\alpha_0 s_{u0}\pi D + (\gamma' h + s_{u2}N_c)(\pi Dt) \tag{3}$$

The penetration depth h can be derived from Eq. (3) and shown as follows:

$$h = \frac{V' + s\left(\frac{\pi D_0^2}{4}\right) - s_{u2}N_c(\pi Dt)}{2\alpha_0 s_{u0}\pi D + \gamma'(\pi Dt)} \tag{4}$$

4 COMPARISON BETWEEN THE TWO METHODS

It should be point out that the analytical method for caisson penetration is only applicable when the caisson is penetrating into clay with a constant velocity. Then the driving forces and resistance forces can be treated as balanced during each calculation step. The results shown in Figure 4, the penetration depth versus time curve is almost in a linear relationship. The comparisons between these two sets of results were made by assuming the caisson was penetrated into the clay in a constant speed or the forces in each calculation step were balanced.

In the following calculation, the tested vacuum pressures were taken as inputs. This procedure maybe not the way for engineering designing but could be used to verify the accuracy of this theoretical method. The comparison could also give a way to evaluate the key design parameters for caisson designing. The average undrained shear strength of soil bed used for calculation was 13*kPa* as discussed in section 2.1. The values of N_c and N_q for undrained analysis were adopted as 9.0 and 1.0, respectively. The average unit weight of soil bed is 12.3kN/m^3 which can easily be derived from *w%* (42.7%) and G_s (2.61). The total weight of concrete caisson is 0.272*kN* (27.2×10*kN*).

The model test results and the analytical results for the displacement of suction caisson are compared in Figure 7. It can be seen that when α=0.72, the two sets of results agree well with each other. The analytical results show that the penetration of suction caisson needs a minimum driving suction pressure. However, the model tests show a much smaller value. Furthermore, the penetration procedure for model No. 2 was delayed (start time of t=25s) comparing to model No. 1 (starting time of t=13s) because the applying speed of vacuum pressure for model No. 2 is lower than that for model No. 1.

The comparison between the theoretical and the model test results regarding the heave of soil plug is shown in Figure 8. The analytical model indicates that a minimum vacuum pressure is required for the soil plug to start to heave as there is no plug movement at the beginning. This is related to the assumption that the heave of soil plug is caused by the penetration of caisson walls. A fitting of the experimental curves using a value of *m*=1.4 was also made. m=1.4 implies that the volume of the soil going into the caisson cavity was 140% of the volume of the soil replaced. This is possible as the additional 40% could come from the expansion of the remolded soil or flow of soil beneath the caisson. As discussed before, the soil plug was broken at the end of the experiments. This aspect could not be modeled by the analytical method.

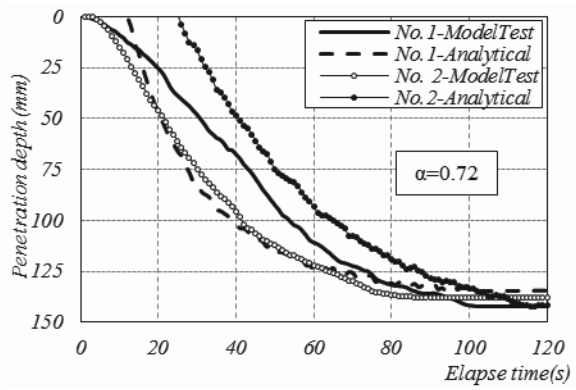


Figure 7 Predicted and measured penetration depth vs. time curves

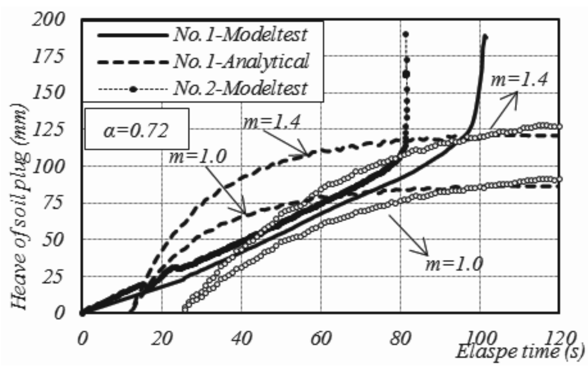


Figure 8 Predicted and measured heave vs. time curves

5 CONCLUSIONS

Suction caissons have been used mainly as foundations to support offshore structures in deep water. Their applications in shallow water are more challenging as the amount of suction that can be applied to install the caissons is much less. Several model tests on the use of suction caisson in clay in shallow water were carried out. The height of soil plug, displacement of the suction caisson and applied vacuum pressure were measured during the model tests. An analytical method proposed by Houlsby and Byrne (2005b) were adopted to simulate the model test results. The analytical results agree well with the model test results with the selection of appropriate parameters.

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