Model tests on installation of suction caisson in clay

Essais de modèle sur l'installation et la capacité portante du caisson d'aspiration en argile

Wei GUO, Jian CHU*
School of Civil & Environmental Engineering, Nanyang Technological University, Singapore, * cjchu@ntu.edu.sg
Hailei Kou
College of Engineering, Ocean University of China, Qingdao, China

ABSTRACT: Suction caissons have been used in many offshore projects including mooring anchors, breakwaters, sea walls and foundations for offshore structures. For the suction caissons adopted in deep water, the high hydrostatic pressure will contribute to the suction pressure to sink the caisson into seabed. When concrete caissons with relative thick walls are used in shallow water, there are several technical issues need to be investigated. Model tests were conducted to study the performance of a suction caisson installed in normal consolidated soil. It is observed from the model tests that the suction pressure used for the installation of caisson cannot be too high, but has to be high enough to sink the caisson into seabed. The performance of the suction caisson after installation is also investigated by bearing capacity and pullout tests. The design methods and applications of the suction caissons in offshore projects proposed in the literature are also summarized.

RÉSUMÉ : Caissons d'aspiration ont été utilisés avec succès dans de nombreux projets offshore y compris d'ancrage, les brise-lames, de digues et de fondations pour les structures en mer. Pour les caissons à succion adopté dans l'eau profonde, la pression hydrostatique élevée contribuera à la pression d'aspiration de couler le caisson dans des fonds marins. Lorsque le mur épais de caissons en béton sont utilisés en eau peu profonde, il y a plusieurs problèmes techniques ont besoin d'être explorés. Dans cet article, les méthodes de conception et des applications d'aspiration à caissons dans les projets offshore sont résumés. Model ont été réalisés pour étudier les performances d'un caisson d'aspiration installée dans le sol consolidé normal. Il est observé à partir du modèle tests que la pression d'aspiration utilisé pour l'installation de caisson ne peut pas être trop élevé, mais doit être suffisamment élevé pour couler le caisson dans des fonds marins. Le rendement de l'aspiration après l'installation de caissons est également étudiée par des essais d'arrachement et de capacité portante. L'analyse simplifiée des méthodes basées sur la théorie d'équilibre limite sont également appliqués pour analyser le modèle des résultats de test.

KEYWORDS: Suction Caisson, Suction Anchor, Bucket Foundation.

1 INTRODUCTION

Suction caissons are large, hollow, cylindrical steel or concrete structures in form of upturned bucket shape. The principle of the suction caisson technique is to apply suction pressure inside a sealed cylindrical caisson to create a downward net force to sink the caisson into the seabed soil. After the removal of the suction pressure, the foundation is constructed without the need to treat the soft soil. The suction caisson has also been called suction anchor, suction pile or bucket foundation depending on the usage. Suction caissons have advantage over the traditional underwater foundations because of its relative large bearing and uplift capacity and simplicity in installation. For caissons used in deep water, the high hydrostatic pressure will contribute to the suction pressure that can be used to sink the caisson into seabed. However, in relatively shallow water, there may not be sufficient pressure difference to allow the caisson to penetrate to the required depth. When a caisson is penetrated into clay, soil will go inside the open ended hollow caisson and form a soil plug which will in turn affect the penetration of the suction caisson.

Suction caissons have been successfully employed for in many near shore or offshore projects in recent years (Andersen and Jostad, 1999; Andresen et al., 2011; Randolph et al., 2011) including breakwaters or sea walls (Chu et al., 2012; Guo et al., 2013; Guo and Chu, 2013; Yan et al., 2009), foundations for offshore platforms (Zhang et al., 2007) and wind turbines (Byrne and Houlsby, 2002; Gavin et al., 2011; Houlsby and Byrne, 2000; Houlsby et al., 2005).

To develop suitable design methods, model tests were carried out to study the behavior of a concrete suction caisson installed in clay. The displacement of suction caisson and applied vacuum pressure were measured during the model tests. The performance of the caisson after installation is also investigated by carrying out bearing capacity and pullout tests. Simplified analytical studies based on the limit equilibrium method are also applied to analyze the model test results.

2 REVIEW OF DESIGN METHODS

2.1 Installation

A suction caisson is penetrated into soil by its self-weight and suction induced pressure difference. The penetration resistance includes internal and external side frictions (R_{side}) along skirt wall and tip resistance (R_{tip}) which can be estimated by limit equilibrium method as (Andersen & Jostad, 1999),

$$\mathrm{R} = \alpha s_u (A_i + A_e) + (N_c s_{u,tip} + \sigma'_{vo}) A_{tip} \qquad (1)$$

where α is the ratio of side friction, s_u is the average undrained shear strength of soil along the penetration depth, A_i and A_e are the internal and external skin wall areas, respectively, N_c is the bearing capacity factor, $s_{u,tip}$ is the undrained shear strength of soil at the tip of the caisson, σ_{vo}' is the effective vertical pressure on the depth of caisson tip and A_{tip} is the area of caisson tip.

The ratio of side friction α and bearing capacity factor N_c can be back calculated from installation tests. Some typical values from literature are summarized in Table 1. When the penetration depth over diameter ratio (z/D) is in the range from 0 to 4.0, N_c can be calculated as a linear variation from 6.2 at $z/D = 0$ to 9 at $z/D = 4$ (Andersen et al. 2005).

The required vacuum pressure, u_r, is defined as the vacuum pressure to balance the penetration resistance in Eq. (1). If the vacuum pressure is greater than this threshold, the caisson will just about to penetrate into the soil. The required vacuum pressure, u_r, can be written as,

$$u_r = \left[\alpha s_u A_s + \left(N_c s_{u,tip} + \gamma' z\right) A_{tip} - W'\right] / (A - A_{tip}) \qquad (2)$$

where W' denotes the effective weight of caisson and accessory equipment during installation, A is the cross-sectional area of the caisson.

However, a larger vacuum pressure will break the induced soil plug. The maximum vacuum pressure that could avoid the break of soil plug was defined as allowable vacuum pressure, u_a. The allowable vacuum pressure could be calculated as (DNV 2005),

$$u_a = N_c s_{u,tip} + A_i \alpha s_u^{DSS} / (A - A_{tip}) \qquad (3)$$

2.2 Bearing Capacity

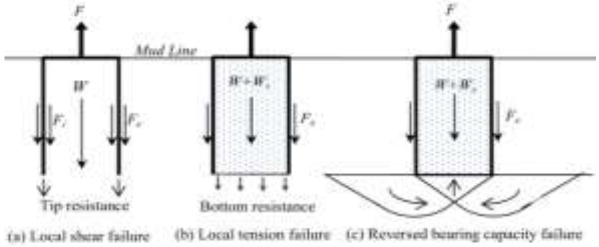
The bearing capacity of a caisson includes the side friction and the end bearing capacity. The side frictions can be calculated using the α-method. The end bearing capacity of the caisson can be calculated using the limit equilibrium theory. For saturated clay in undrained condition, the bearing capacity of caisson can be calculated as,

$$Q_b = \alpha s_u (A_i + A_e) + \left(N_c s_{u,tip} + \sigma'_{vo}\right) A + W' \qquad (4)$$

where N_c is the bearing capacity factor for cohesion which can be referred to Table 1.

2.3 Uplift Capacity

The failure modes of caisson under vertical pullout load depend heavily on the pullout speed because it will generate different degree of passive suction pressure on the caisson bottom. Generally, there are three different failure modes as summarized in Fig. 1 (Randolph and House, 2002).



(a) Local shear failure (b) Local tension failure (c) Reversed bearing capacity failure

Fig. 1 Failure modes of caisson under pullout load (Modified after Randolph and House, 2002; Cao, 2003)

For the local shear failure as shown in Fig. 1a, the pullout resistance, Q_l, composes by the shearing resistance on the interface between caisson wall and internal (F_i)/external (F_e) soil. The caisson wall tip and weight of caisson (W') also contributes to the uplift capacity.

$$Q_l = \alpha \bar{s}_u (A_i + A_e) + W' + (N_c s_{u,tip} - \sigma'_{vo}) A_{tip} \qquad (5)$$

For the local tension failure in Fig. 1b, the caisson and internal soil plug act as a whole unit. The self-weight includes the weight of caisson (W') and internal soil plug (W_s). The pullout resistance components are same as the local shear failure but without internal side friction. For sealed caissons under long-term or cyclic axial loading, the intermediate mode of failure (Fig. 1b) is suggested because it is difficult to guarantee a good hydraulic seal at the bottom of the caisson subjected to sustain or cyclic (Randolph and House, 2002). The uplift capacity Q can be calculated as,

$$Q_l = \alpha \bar{s}_u A_e + W' + W_s + (A - A_{tip}) \sigma_t \qquad (6)$$

where σ_t is the total tension stress across the base of the soil plug.

For reverse bearing capacity failure as shown in Fig. 1c, the failure mode is similar with local tension failure except a vacuum cavity appears at the bottom of the caisson. Thus the vacuum cavity will heavily increase the uplift capacity. The uplift capacity Q may be estimated as,

$$Q_l = \alpha \bar{s}_u A_e + W' + W_s + (N_c s_{u,tip} - \sigma'_{vo}) A \qquad (7)$$

3 MODEL TESTS AND RESULTS

3.1 Testing setup and installation

A cylindrical stainless steel tank with height of 1.4 m and diameter of 1.0 m was used to consolidate the soil and to carry out suction caisson model tests. The detail of the consolidation tank and testing methods are given in Guo et al. (2015). As shown in Fig. 2, the caisson model was fabricated of a steel inner skirt and covered by a concrete layer with a total skirt wall thickness (t) of 22.5 *mm*, total heights (H) of 400 *mm*, and a diameter of the cross-section (D) of 205 *mm*. The clear skirt length (H_i) is 380 *mm*. A fiberglass was mounted on the top plate to observe soil movement in the caisson cavity. The wall tip of the model was tampered to reduce the penetration resistance during the installation procedure. The slope ratio of the wedge wall tip was 1:2.

The soil used for the model tests was consolidated from kaolin slurry which was supplied by Kaolin Malaysia Sdn. Bhd. The kaolin has a specific gravity of 2.61, a liquid limit of 61%, a plastic limit of 38% and plastic index of 23. The kaolin powder was mixed with tap water into a slurry form with its water content around 80%. After mixing, the slurry was transferred into the consolidation tank. Then the top cap is mounted onto the cylindrical consolidation tank. The air pressures of 106 *kPa* was applied on the cavity below piston to consolidate the slurry for about 10 days. The average water content, unit weight and undrained shear strength of the consolidated kaolin are 46%, 17.2 kN/m^3, and 23 kN, respectively.

Before installation, the caisson model was laid on top of the consolidated kaolin. In order to prevent the caisson model from inclining during the installation period, three narrow plates and three pulleys on their ends were used to hold the caisson model in position as shown in Fig. 2a. As the dead weight of the caisson model was not high (22.25 *kg*), there was little penetration due to its self-weight. The caisson tip end was sealed by kaolin first to prevent the suction pressure from leakage. After that, a suction pressure was applied to suck the caisson into clay.

Table 1 Parameter studies on penetration resistance equation

Year	Reference	Test site	α	N_c	Test type
1986	Tjelta et al (1986)	Gulfaks, North Sea	0.15	9	Field test
1988	Andréasson et al. (1988)	Gothenburg, Sweden	0.2-0.4	7	
1992	Christophersen et al. (1992)	Snorre, North Sea	0.2	-	Field test
1998	Whittle et al. (1998)	MIT	0.26-0.35	16.3	Lab test
1999	Andersen and Jostad (1999)	DNV	0.4-0.5	6.2 - 9	
1999	Randolph et al. (1999)	-	0.3-0.5	7.5	Field test
2001	House and Randolph (2001)	UWA	0.35-0.4	7.5	Centrifuge
2002	Dendani and Colliat (2002)	Girassol, West African	0.2-0.45	-	Field test
2002	Cao et al. (2002)	C-Core	0.25-0.3	9.5	Centrifuge
2003	Huang et al. (2003)	-	0.25-0.3	7.5	-
2003	Luke et al. (2003)	Univ. of Texas, Austin	0.27-0.37	-	Lab test
2003	Newlin (2003a, 2003b)	Gulf of Mexico	0.28-0.43	-	Field test
2004	Chen and Randolph (2004)	UWA	0.35(suction)	7.5	Centrifuge
2007	Chen and Randolph (2007)	UMA	0.77 – 0.88 （NC clay） 0.65-0.92(Sensitive clay)	9 – 12	

(a) Before installation (b) After installation

Fig. 2 Photos of caisson after installation

To investigate the influence of suction pressure on the installation process of suction caisson, two methods were used to install the suction caisson. One was to apply a low suction pressure (- 20 kPa) to achieve a slow penetration rate into clay (Test-1) and another was to apply a high suction pressure (- 90 kPa) to impose a high penetration rate (Test-2).

The displacement of the caisson versus suction pressure curve obtained from Test-1 is shown in Fig. 3. The caisson started to penetrate into clay when the suction pressure reached to -7 *kPa,* but terminated when penetration depth was 0.25 cm. The displacement versus suction pressure curve for Test-2 is also shown in Fig. 3. The final penetration depth for this test was only 42.5% of the caisson height.

The required vacuum pressure u_r was calculated using Eq. (2) and its variation with penetration depth is shown in Fig. 3. In the calculation, α and N_c values were selected as 0.68 and 12.5, respectively. The allowable vacuum pressure u_a was also calculated using Eq. (3) with the same α and N_c values and plotted in Fig. 3. It can be seen from Fig. 3, the applied vacuum pressure in Test-1 was larger than the required vacuum pressure but comparable to the allowable vacuum pressure. This implies that the soil plug did not break during the model test which was also verified by the continuation of the penetration process. The vacuum pressure was maintained at -20 *kPa* which was between the required and allowable vacuum pressure. For Test-2, the applied suction pressure was much higher than the allowable suction pressure. This caused the caisson to penetrate into clay at a higher rate.

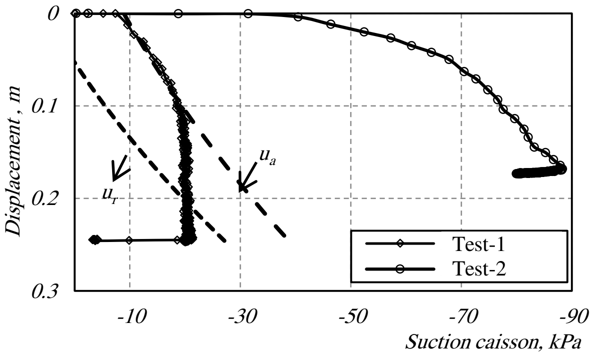


Fig. 3 Comparison of the installation process of the concrete suction caisson in the two model tests (u_a = allowable suction pressure that could avoid the break of soil plug, u_r= required vacuum pressure to installation caisson into clay)

3.2 Uplift capacity

In order to measure the pullout resistance of a suction caisson after installation, a pullout test was conducted. The concrete suction caisson was installed by suction as named as Test-1 in section 4.1. The soil plug in the caisson was removed using high speed water jet through the fiber glass at the top cap of the concrete caisson. The vacuum pressure was applied again till the caisson was fully penetrated into the soil bed as shown in Fig. 4. A load cells were laid between the axial rod and the caisson cap to measure the applied axial forces as shown in Fig. 4a. The pullout speed was controlled as 3.4 cm/min.

(a) Before pullout test (b) After pullout test

Fig. 4 Photos of caisson before and after pullout test

The applied axial pullout force versus pullout displacement of caisson during the model test is shown in Fig. 5. It can be seen that the peak pullout resistance force is 8.4 *kN* at a displacement of 0.05 m. The peak value of the pullout force only balanced the maximum static friction force between the caisson walls and soil bed. After that, the pullout force only has to balance the sliding friction force between caisson skirt wall and surrounding soil. Then Eq. (5) is suggested to be used to calculate the pullout resistance. As shown in Fig. 5, α value of 0.68 agrees well with the model tests results.

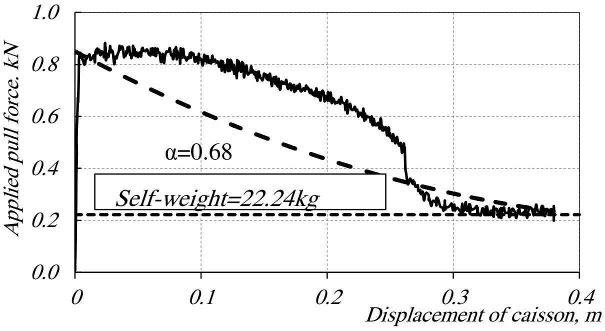


Fig. 5 Applied pullout force versus displacement curve during the pullout test results

3.3 Bearing capacity

Model tests were carried out to test the bearing capacity of caissons after installation. The caisson was penetrated into clay as in Test-2. The soil plug in the caisson was also removed using high speed water jet through the fiber glass at the top cap of the concrete caisson. The vacuum pressure was applied again till the caisson was fully penetrated into the soil bed as shown in Fig. 6. A constant speed of 0.61 cm/min was used to compress the suction caisson model. Two load cells were laid between the axial rod and the caisson cap (see Fig. 6a) to measure the applied axial forces. The displacement of caisson was measured by laser sensors that were mounted on the top cap.

Fig. 7 shows the displacement versus applied axial force curve obtained from the model test. The ultimate bearing capacity of the caisson in this model test can be estimate as 3.3 *kN* through joint points of the two straight lines. Eq. (4) is used to back calculate the ultimate bearing capacity. As seen from

Fig. 7, the results of α=0.68 (from pullout test) and N_c = 12.5 agreed well with the model test results.

(a) before bearing capacity test (b) after bearing capacity test

Fig. 6 Photos of caisson before and after bearing capacity test

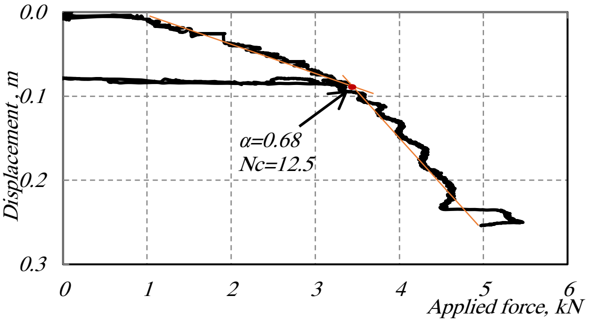


Fig. 7 Applied force versus displacement curve of caisson model during the bearing capacity test

4 CONCLUSIONS

Results of model tests were presented in this paper to study the behaviour of a suction caisson installed in clay. The soil plug heave is not only influenced by the caisson wall thickness but also by the applied vacuum pressure. The suction pressure has to be high enough to induce the required penetration of the caisson. However, the value of suction cannot be too high either because too large a vacuum pressure will induce more soil plug. Simplified analytical equations were used to predict the suction and allowable pressure required. The performance of the caisson after installation was also investigated by bearing capacity and pullout tests. The soil parameter α and N_c value can be estimated based on the model tests.

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