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Capacity of Suction Caisson Anchors based on Small Scale Experiments

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ABSTRACT

Wind power presently reflects a very promising source of renewable energy worldwide. The optimal type of foundations for offshore wind turbines may vary with respect to water depth; in very deep water, the floating type is thought to be most cost-effective. The focus of this paper is to investigate the capacity of suction caisson anchors as a holding structure of offshore floating systems. A kaolinite, most tested in geotechnical engineering, was selected as the clay specimen in the model tests. The article discusses the equipment and procedure to estimate the capacity and performance of a model suction caisson anchor. The capacities are evaluated, and the adhesion and reversed end bearing factors are discussed. Sequential plan for anchor tests is addressed.

1. INTRODUCTION

The development of global wind energy production capacity has an average growth of 26.9% from 1995 until 2012 (Wind Energy Association 2013). To meet the new demands for offshore wind energy, the expertise gained in designing offshore oil platforms can be applied to the development of foundations for offshore wind turbines. Currently, the vast majority of foundations for offshore wind turbines are monopoles, fixed in the seabed in shallow water depths of up to ~30 m. In deeper water (i.e., deeper than ~80 m), floating wind turbines are thought to be most cost effective (Musial and Butterfield 2006). Recent research on this type of wind turbine has included analytical studies, model tests, and prototype implementations (Goupee et al. 2012; Cermelli et al. 2012). Floating wind turbines and their foundations in deep water are exposed to extreme environmental and loading conditions, and therefore, the stability

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and performance of these energy infrastructures are of the utmost important to fulfill one of most promising renewable energy resources and to prevent unwanted disaster.

The suction caisson anchor is a viable and one of mostly selected options for holding system of floating platforms offshore (Andersen et al. 2005). Much effort has been invested to experimentally evaluate the capacity of suction anchors in model scale. Few of those examples include (Larsen 1989) who investigated the installation and horizontal pulling capacity of suction anchors in fine-grained soils. In their study, the investigation concluded that the method for installation and horizontal pullout capacity of the anchor is dependent on the variation of load with time. (Rao et al. 1997) examined the relationship of liquidity index of the soil and the pullout uplift capacity using open-top and closed-top suction caisson anchors. They also derived the values of adhesion factors and bearing capacity factors from the experimental results. (Watson and Randolph 1998) studied the performance of bucket foundations in fine-grained calcareous soil under the combined vertical and horizontal loading. (El-Gharbawy 2000) performed tests concerning static and cyclic pullout loading. The research established the significance of the rate of pullout loading to the uplift capacity of the suction anchor. There, however, are only few researches which address the performance and capacity of suction caisson anchors under cyclic load, which can be important particularly when they are installed for floating offshore wind turbines.

This article shows a part of a comprehensive experimental program whose main objective is to investigate the pullout performance and capacity of suction caisson anchors under cyclic loading. Details on the test equipment and procedure will be discussed followed by the preliminary results on the uplift performance and capacity of a suction caisson anchor with a length-to-diameter ratio of 2 under monotonic loading.

2. EXPERIMENTAL PROGRAM

An aluminum body was fabricated to have an external diameter 80 mm and thickness 1.5 mm. The length of the pipe that can be embedded is larger than 160 mm, but in the study 160 mm was installed into soil specimen to fulfill a length-to-diameter ratio of 2. Fig. 1 shows the aluminum suction caisson anchor assembled with the top cap and a thin plate with holes for horizontal load applications. Pad-eye holes were, however, not used in this study.

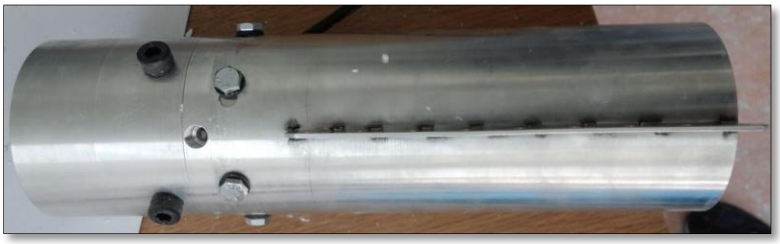

Fig. 1 Suction caisson model

The servo-motor controlled loading machine developed for the suction anchor tests can expose the suction anchor to both horizontal and vertical loading. In this study, only the vertical movement was employed. The maximum displacement that the equipment can provide is around 250 mm. Fig. 2 is an image of the mechanical loading machine used. A load cell was attached to the loading arm to measure the reaction force developed due to the movement of the servo-motor actuator. The load cell has a capacity of 490 N (50 kg) with a resolution of 0.0033% of rated output. Fig. 3 presents the test set-up for monotonic uplift tests. A cable connects the top cap to the load cell, and therefore to the loading system.

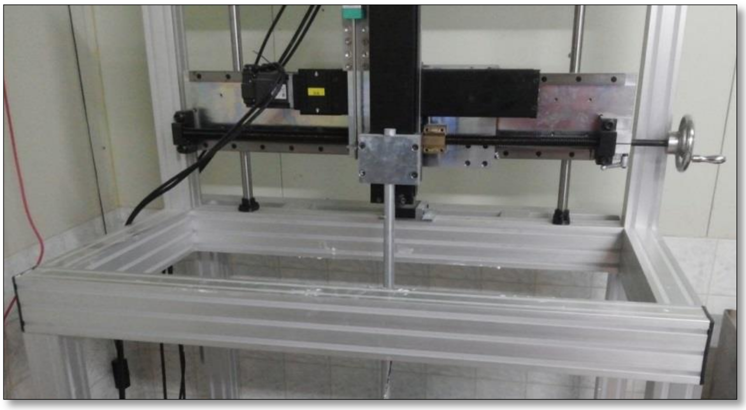

Fig. 2 Mechanical loading machine

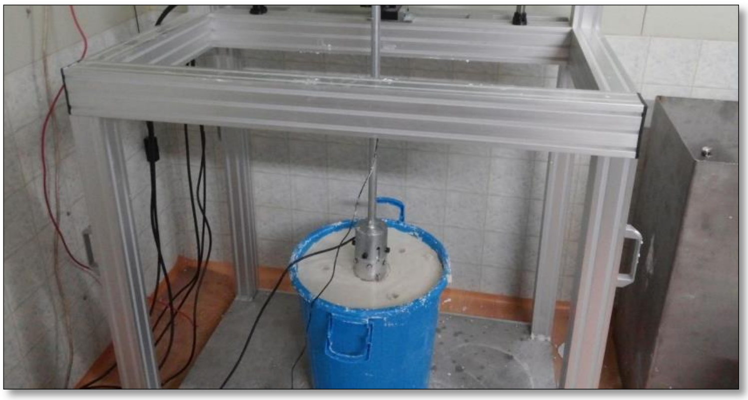

Fig. 3 Experimental set-up of suction anchor static pull-out

The clay was mixed thoroughly by hand with adequate amount of water added to achieve an acceptable uniformity and consistency in soil specimen. The clay mixtures were put in the buckets in succession with small blocks and compacted carefully to avoid unwanted voids and discontinuities. The mixing container and the clay buckets are shown in Fig. 4. After constituting the clay model, water was placed over the mudline to preserve the sample from drying.

Fig. 4 Mixing container and clay buckets

The suction caisson model was unsoiled and cleaned thoroughly before installation to ensure consistent development of friction at the interface of the caisson wall and soil. Industrial grease was applied at assemblage surfaces of the caisson model to guarantee an air-tight assembly when the model was set closed-top.

After completing the assembly, the anchor was attached to loading arm with a steel bar for installation step as presented in Fig. 5(a). It is noted that the anchor was installed with an “open-top”, meaning, the air passage was not closed. The steel bar was replaced by a steel wire to replicate the tension loading applied in the real suction anchor structure Fig. 5(b). The anchor was left for set-up for 30 minutes before pullout tests. Then the anchor was pulled out using a rate of 1.7 mm/s with the reaction force and displacement measured.

(a) (b)

Fig. 5 Model caisson set for (a) installation and (b) pullout

For each soil batch, the undrained shear strength and water content were measured. The undrained shear strength was measured using the vane shear apparatus at three different points for five depths each. The vane shear used and measurement locations are presented in Fig. 6 and 7. Water contents were measured using two points with reference to Layer 1, Layer 2, and Layer 3 of the buckets.

Fig. 6 Vane Shear Apparatus

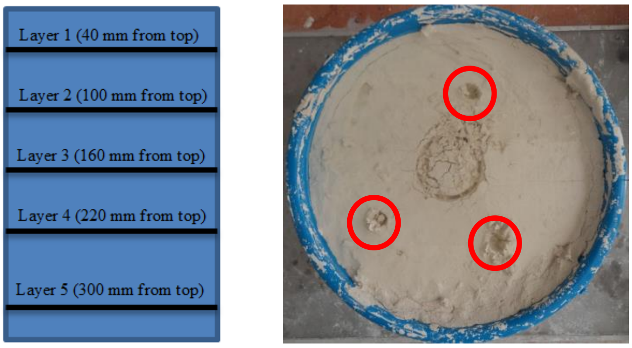

Fig. 7 Locations for vane shear testing

3. UPLIFT CAPACITY AND PARAMETERS

After pulling out the anchor, the modes of failure were documented. For open-top tests, the observed failure was shear pullout without soil plugged inside the anchor (Fig. 8(a)). For suction anchors with closed-top, the soil plugging was observed so that a reversed end bearing failure was witnessed (Fig. 8(b)).

(a) (b)

Fig. 8 Failures with soil (a) unplugged and (b) plugged

Eq. (1) and Eq. (2) are the formulas for the uplift capacity of a suction caisson for unplugged and plugged failure, respectively.

$$Q_{us} = (A_{wall} \cdot \alpha \cdot s_u)_{outer} + (A_{wall} \cdot \alpha \cdot s_u)_{inner} \quad (1)$$

$$Q_{us} = (A_{wall} \cdot \alpha \cdot s_u)_{outer} + (N_c \cdot s_u) \cdot A_{tip} \quad (2)$$

In the equations above, Q_{us} is the ultimate pullout capacity of the suction anchor, A_{wall} is the surface area of the aluminum wall, s_u is the undrained shear strength of the soil, N_c is the reversed end bearing capacity factor, and A_{tip} is the circular cross-sectional area of the caisson. In case of the unplugged failure in Fig. 8(a), the friction in the outer and inner walls are the only sources that resist the uplift load, and therefore Eq. (1) is valid. Fig. 8(b) presents the plugged failure, resulted with closed-top tests, and is in accordance to the suction developed inside the caisson. Eq. (2), with the components of the outer friction and reversed end bearing resistances, can be used to estimate the ultimate uplift capacity in this case. It is noted that the weight of soil plugged in the caisson is neglected in this study.

Fig. 9 shows the force-displacement curves for four open-top tests. The information on the soils tested is in Table 1. The yielding of the system was found at around 10 mm of displacement, and therefore the failure loads were evaluated at that displacement which corresponds to 12% of the anchor diameter.

The failure loads for the open-top experiments and the individual adhesion factors α calculated are shown in Table 2. These failure loads were used to acquire the adhesion factors using Eq. (1). The s_u in the table is the weighted average undrained shear strength within the caisson length of Layers 1, 2, and 3. The average value of the adhesion factors was equal to 0.3.

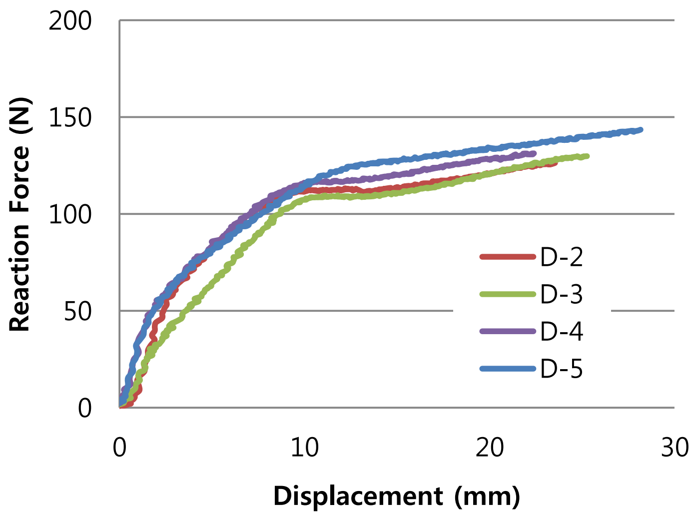

Fig. 9 Force-displacement curves for open-top caissons

Table 1. Undrained shear strength s_u and moisture content ω of soil batches

Test No.	ω (%)	s_u (kPa)				
		Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
D2	69.0	4.3	6.7	7.0	8.3	10.3
D3	68.8	4.0	7.7	8.0	9.3	10.0
D4	66.7	4.3	6.3	7.3	9.0	10.0
D5	67.7	5.0	8.0	7.7	9.0	11.0

Table 2. Failure loads of open-top caissons and adhesion factors (α)

Test No.	Q_{us} (N)	s_u (kPa)	α
D2	126	5.7	0.3
D3	130	6.1	0.3
D4	131	5.6	0.3
D5	144	6.6	0.3

Fig. 10 shows the load versus displacement graph of the three closed-top suction anchor models. The failure was experienced at displacement of approximately 15% of the diameter of the anchor.

Table 3 presents the undrained shear strength s_u and moisture content ω for the closed-top batches. The failure loads for the closed-top tests are shown in Table 4. With the use of Eq. (2), the average value for the bearing capacity factor N_c was obtained equivalent to 3.7.

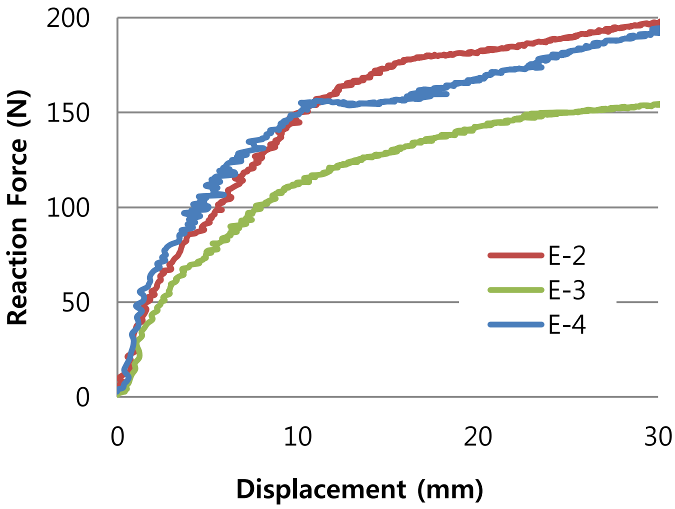

Fig. 10 Force-displacement curves for closed-top caissons

Table 3. Undrained shear strength s_u and moisture content ω of soil batches

Test No.	ω (%)	s_u (kPa)				
		Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
E2	60.4	4.7	5.0	6.3	7.8	9.5
E3	65.3	4.3	5.7	6.8	8.0	10.3
E4	63.8	5.3	7.0	7.7	9.7	10.3

Table 4. Failure loads, s_u, and Nc of closed-top caissons

Test No.	Q_{us} (N)	s_u (kPa)	Nc
E2	210	5.1	4.8
E3	166	5.3	3.1
E4	200	6.4	3.3

In comparison with the adhesion factors obtained by Rao et al. (1997), the values ranged from 0.4 to 0.7 depending on the value of the liquidity index (LI) of the Indian marine clays. The obtained value of adhesion factor α in this article is 0.3 which is lower with respect to the given range in the literature. Concerning the bearing capacity factor N_c, the range of values calculated by Rao et al. (1997) was 2.0 to 5.0. The value of 3.7 from this study falls within the range reported. However, according to the DNV (2005) guide, an adhesion factor between 0.7 to 0.8 is proposed in design. The reversed end bearing capacity factor has a recommended value of 7.6 according to Randolph and Gourvenec (2011). It is therefore necessary to vary the conditions of soil batches and investigate their effect in sequential test program.

4. CONCLUSION

In this article, model tests with open-top and closed-top configurations were investigated. The kaolinite soils used have uniform consolidation period of eight days. The set-up time of the suction caissons after penetration soil was 30 minutes. A total of seven suction caissons were observed, four caissons for open-top tests and three for closed-top tests. The open-top anchor data was used to obtain the adhesion factor equal to 0.3. The reversed end bearing capacity factor was concluded to be 3.7 under given test conditions.

The adhesion factor back-calculated based on the results of model tests was slightly out of the range given by the references. The reversed end bearing factor on the other hand is comparable to the range given. Both values for adhesion and reversed end bearing factors were smaller than the values suggested in design guides. Another set of experiments are planned to investigate the effect of soil conditions and set-up time of the caisson.

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