Experimental Study on Vertical Pullout Cyclic-Loading Behavior of Bucket Foundations

Étude expérimentale sur le comportement de chargement cyclique amovible vertical des fondations à godets

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ABSTRACT: Understanding of the behavior of bucket foundations under cyclic loading is vital for designing offshore wind turbines. The small-scale model tests were conducted to investigate the behaviors of the accumulated vertical pullout displacement and unloading stiffness of the bucket foundation. The model buckets were embedded in saturated sand. The vertical pullout cyclic loading was applied with various load amplitudes up to 10^4 cycles. Test results showed that as the number of load cycles and cyclic load amplitudes increased, the accumulated vertical pullout displacement increased, whereas the unloading stiffness of the bucket foundations decreased. Equations for estimation of the accumulated vertical pullout displacement were proposed based on empirical results, which can be used for the preliminary design of single or tripod bucket foundations.

RÉSUMÉ: La compréhension du comportement des fondations à godets sous charge cyclique est vitale pour la conception d'éoliennes en mer. Les essais sur modèles à petite échelle ont été effectués pour étudier les comportements du déplacement vertical et de la rigidité de déchargement de la fondation à godet accumulés. Les godets modèle étaient encastrés dans du sable saturé. Le chargement cyclique verticale a été appliqué avec des amplitudes de charge variées jusqu'à 10^4 cycles. Les résultats des essais ont montré que lorsque le nombre de cycles de charge et d'amplitudes de charge cyclique augmentait, le déplacement de la traction verticale accumulée augmentait, alors que la rigidité de déchargement des fondations à godet diminuait. Des équations pour estimer le déplacement vertical accumulé ont été proposées sur la base de résultats empiriques qui peuvent être utilisés pour la conception préliminaire de fondations à godets uniques ou tripodes.

KEYWORDS: bucket foundation, cyclic loading, 1*g* model test, vertical pullout, unloading stiffness.

1 INTRODUCTION

Suction bucket foundations have recently been considered as a competitive foundation type for supporting offshore wind turbines. A single bucket foundation consists of a circular surface foundation with a thin skirt around its circumference. Offshore wind turbines with low power rate are installed at shallow water depth. However, these turbines need to be installed at deep water depth because they are subjected to high horizontal load and overturning moments. Thus, tripod bucket foundations may be suited to support offshore wind turbines at deep water depth. The tripod bucket foundation combines three single bucket foundations in a triangle shape.

Previous investigations have stated that the considerable design issues for offshore wind turbines are the accumulated displacement and unloading stiffness of the foundations under cyclic loading (e.g., Zhu et al., 2013; Foglia et al., 2014; Cox et al., 2014). Byrne (2000) performed static and cyclic vertical pullout load tests for a suction bucket in saturated oil sand. Results showed that the accumulated vertical displacement increased with the increase in the number of load cycles. The failure vertical pullout load was relatively independent of the vertical pullout velocity. Kelly et al. (2004) and Kakasoltani et al. (2011) found that the static vertical pullout load-displacement of suction bucket foundations in sand showed softening behavior, and the failure tension load reached at a relatively small displacement.

Houlsby et al. (2005, 2006) presented a simple analytical approach on the tensile bearing capacity of suction caissons under monotonic loading in sand. They considered the bucket foundations under various conditions, including drained and partially drained, as well as the effects of displacement rate. The maximum tensile bearing capacity of suction caissons in sand under rapid loading could be evaluated by adding the suction pressure to the drained tensile bearing capacity. Other studies have observed that the stability of the tripod bucket foundation is mainly governed by the pullout displacement of the upward bucket (Sender, 2009; Kim et al., 2014; Hung et al., 2014).

The behaviors of the tripod bucket foundation can be evaluated through the single bucket foundation under cyclic vertical loads because the upward single bucket governs the stability of the tripod bucket foundation. Thus, this study aims to investigate the accumulated pullout displacements and unloading stiffness of the single bucket foundations in saturated sand. A series of 1*g* experimental tests on two model bucket foundations with embedment ratios of L/D=0.5 and 1, where D is the foundation diameter and L is the skirt length, were carried out. A number of cyclic vertical load cycles N up to 10^4 was applied with varied load amplitudes. The presented results are applicable for the preliminary design of tripod bucket foundations for offshore wind turbines.

2 MODEL TEST PREPARATION

1 .1 *Testing equipment, bucket models, and programs*

Figure 1 shows a schematic diagram of the test equipment used in this study. The loading equipment, which is similar to that presented in LeBlanc et al. (2010), was designed and manufactured. The working mechanism of the test equipment can be briefly described as follows. The weight m_2 at the beginning of a test was equal to the total weight of the driving motor, load lever, steel frame, and weight m_1. The steel frame with the driving motor could be arbitrarily inclined at any angle θ to the horizontal direction, and θ was set at 90° from the beginning of a test, as shown in Fig. 1. The bucket foundation was subjected to the sinusoidal load when the driving motor was rotated because the additional moment would be mobilized in the load lever by the rotation of weight m_1. The sinusoidal load frequency of 0.2 Hz was applied.

The bucket foundations used in this study are shown in Fig. 2. The diameter (D) and skirt thickness (t) of the foundations were 150 and 1 mm respectively. Two skirt lengths (L) of 75 and 150 mm were considered. These foundation models were designed to represent prototype bucket foundations for offshore wind turbines at a length scale of 1:100. The prototype steel bucket foundations had an outer diameter of 15 m and a skirt thickness of 33 mm. The Young's modulus of steel was set to 210 GPa. The scaling law was adopted from Wood (2004).

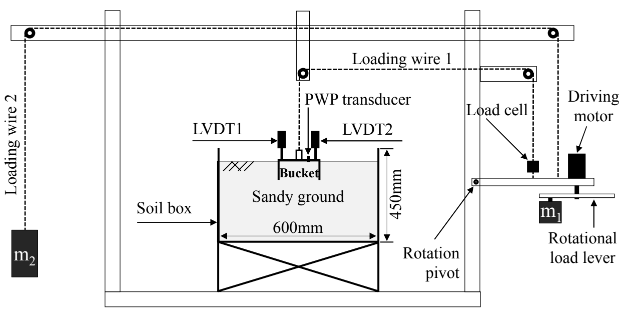


Fig. 1. Schematic diagram of the test equipment

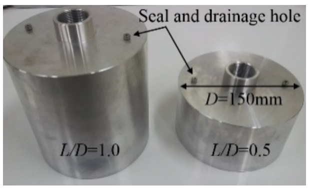


Fig. 2. Photos of bucket foundations used in this study

Eight tests were performed to complete the test program. Two static vertical pullout load tests were first carried out to determine the failure vertical pullout loads (V_{to}) of the bucket foundations. The cyclic vertical load V_{tc} was then determined according to the cyclic load ratio R_c=V_{tc}/V_{to}.

1.2 *Ground preparation and test setup*

Fine silica sand was used in this study. The sand properties are shown in Table 1. This sand had similar properties as the sand in Saemangeum area, where an offshore wind farm will be constructed in the West Sea of South Korea. The cylinder soil box was fabricated with steel with an inner diameter of 600 mm, a height of 450 mm, and a wall thickness of 5 mm. Finite element analysis was performed to determine the dimension of the soil box and minimize the box's boundary effect.

The saturated sand ground was prepared using water sedimentation. The box was first filled with water with a water depth of 400 mm. A large sieve (i.e., sieve No. 40) was then placed above the water surface, and sand particles were dropped on the sieve. Vaid and Negussey (1988) found that the drop velocity of the sand in water is constant, irrespective of the drop height of the sand particle on the sieve. After the preparation of each testing ground for the saturated sand, 10 cm of water was kept above the ground surface for one day for full saturation.

The relative density and unit weight of sands were carefully measured once a test was completed. Small aluminum cans were installed along the depth of the testing grounds during ground preparation. All grounds were relatively uniform. The relative density and unit weight values were about 29% and 17.19 kN/m^3, respectively.

Table 1. Soil properties of sand used in this study and Saemangeum sand

	Soil properties	
	Silica sand	Saemangeum sand
Specific gravity, G_s	2.65	2.67
Maximum unit weight, γ_{max} (kN/m^3)	16.4	16.5
Minimum unit weight, γ_{min} (kN/m^3)	12.6	12.0
Mean grain size, D_{50} (mm)	0.11	0.08

The bucket foundation was installed once the ground preparation was completed. First, the foundation was connected with a circular guide beam and placed at the center of the soil box. The guide beam was restrained to prevent any possible horizontal movement of the foundation during penetration. The foundation was then slowly pushed down by increasing the vertical weight on the top of the vertical guide beam. The drainage holes at the top lid of the foundation were opened for water or air trapped inside the foundation to exhaust during installation. One day was allowed for the full dissipation of possible excess pore water pressure induced inside the bucket during the bucket installation even though the permeability of the sand was high. These holes were closed immediately before the test began.

3 CYCLIC BEHAVIOR OF VERTICAL PULLOUT

3.1 *Vertical pull out failure load*

The foundation was pulled out vertically at a constant velocity of 0.5 mm/s to obtain the static vertical pullout capacity V_{to} of the bucket foundation.

Figure 3(a) shows the static vertical pullout tests for the bucket foundations at L/D = 0.5 and 1. The vertical pullout load increased with the increase in skirt length. V_{to} was considered as the peak point on the load-displacement curve. The V_{to} values were 36.82 and 70.83 N at L/D = 0.5 and 1, respectively. Figure 3(b) illustrates the development of suction pressure inside the bucket during loading, which might be the cause of the softening behavior of the sandy soil in this study.

Previous works have shown that the vertical pullout capacity of the foundation can be calculated by considering the skin resistance of the skirt. The equations suggested by Das (1986) and Byrne (2000) are shown in Eqs. (1) and (2) as follows:

$$V_{to} = R_{SO} + R_{SI} \quad (1)$$

$$R_{SO} = R_{SI} = \frac{\gamma' \times L}{2} \times K \times tan(\frac{2\phi'}{3}) \times \pi \times D \times L \quad (2)$$

where R_{SO} is the frictional resistance between the outer surface of the skirt and the surrounding soil, R_{SI} is the frictional resistance between the inner surface of the skirt and the inside soil, and K is the lateral earth pressure coefficient. The K value can be calculated by following the suggestion of Das (1986), or can be simply taken as $K = K_o = 1 - \sin(\phi')$, with ϕ' as the friction angle of sand.

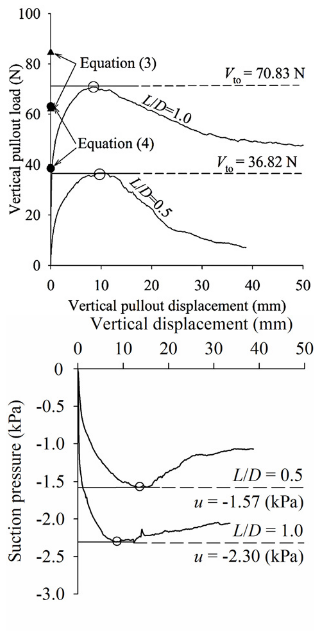
Moreover, Houlsby et al. (2005) experimentally observed that the vertical pullout load of the bucket foundation can be calculated by adding a linear portion of the suction pressure that developed beneath the bucket lid, as shown in Eq. (3):

$$V_{\text{to}} = -u_{\text{suc}}A\left(1 + \frac{2L}{D}(K\tan(\delta))\right) \quad (3)$$

where u_{suc} is the suction pressure beneath the lid of the bucket, A is the cross-sectional area of the foundation, and L is the skirt length embedded in the soil. The friction angle between the foundation and sand in this study is $\delta = 2\phi'/3$.

Equation (1) is also modified by linearly adding a portion of the suction pressure, as shown in Eq. (4).

$$V_{\text{to}} = R_{\text{SO}} + R_{\text{SI}} - u_{\text{suc}}A \quad (4)$$



(a) (b)

Fig. 3. Static vertical pullout test results: (a) load-displacement curves and (b) development of suction pressure

The calculated capacity from the above equations were compared with the measured values shown in Fig. 3(a). The calculation of Eq. (3) overestimated the experimental test results, whereas Eq. (4) yielded values close to that from the experimental tests. The maximum suction pressures of u_{suc} = −1.57 kPa (for L/D = 0.5) and −2.3 kPa (for L/D = 1) were used in Eqs. (3) and (4) respectively. At the maximum suction pressure, the value of term $-u_{\text{suc}} \times A$ corresponded to about 75 % (for L/D = 0.5) and 57 % (for L/D = 1) of the measured V_{to} values. This finding suggested that the vertical pullout capacity of the bucket foundation can be obtained as the sum of the skin resistance and the portion of suction pressure $-u_{\text{suc}} \times A$, as expressed in Eq. (4).

3.2 *Vertical accumulated displacement*

Cyclic vertical pullout tests were carried out by varying the load amplitudes V_{tc} to investigate the cyclic response of the foundations. The V_{tc} values were obtained by assigning different cyclic load ratio R_c values ($R_c = V_{tc}/V_{to}$).

Figure 4 shows the vertical pullout displacement according to various R_c and L/D ratio. The accumulated upward displacement increased with the increase of R_c and N values. The upward displacement of L/D = 1.0 was smaller than that of L/D = 0.5 at the same number of cycles.

Empirical equations were proposed to evaluate the accumulated pullout displacement of the bucket foundations in the saturated sand. The equation consists of the number of load cycles N and the R_c ratio. The form of the proposed equations was derived by referring to those equations proposed by other works for monopiles in sand (i.e., LeBlanc et al., 2010) and for bucket foundations in sand (i.e., Zhu et al., 2013). The equation for the accumulated pullout displacement is expressed in Eq. (5):

$$\frac{w_{\text{N}} - w_{\text{S}}}{w_{\text{S}}} = T_{\text{b}} \times N^{\alpha} \quad (5)$$

where w_N is the accumulated pullout displacement after N cycles, w_S is the static pullout displacement obtained from the first cycle or static load–pullout displacement curve at the same load magnitude of w_N, and T_b is the cyclic load factor that is the function of the R_c ratio. The definitions of w_S and w_N are presented in Fig. 5. The α factor was proposed to consider the effect of the number of cycles N.

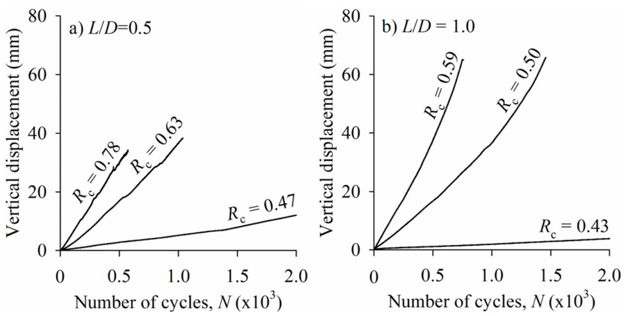


Fig. 4. Accumulated pullout displacement at different cyclic load magnitudes

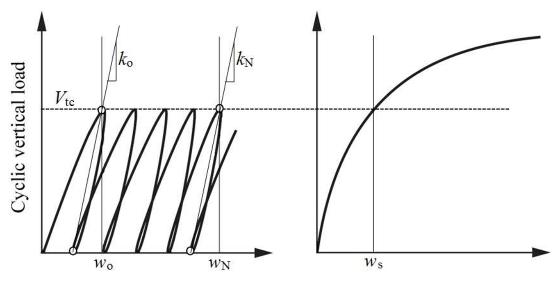


Fig. 5. Definition of accumulated vertical pullout displacement and unloading stiffness

The following analysis steps were carried out to obtain the T_b and α factors. First, the accumulated pullout displacements w_N at N cycles were normalized by the w_S values using the $\frac{w_N - w_S}{w_S}$ ratio. The w_S values were determined from Fig. 3(a). The w_S can be considered the same as w_0 (Zhu et al., 2013). The least square regression analysis was then performed to obtain α and T_b parameters to fit the $\frac{w_N - w_S}{w_S}$ ratios between the experimental tests and Eq. (5). The second step was repeated for each cyclic load magnitude at each L/D ratio.

Figure 6 shows the variation of the T_b parameters with R_c values. Test results showed that the equation for evaluating the T_b parameter can be expressed as the function of R_c values, as shown in Eq. (6).

$$T_b = 1.2 \times R_c^{4.6} \quad (6)$$

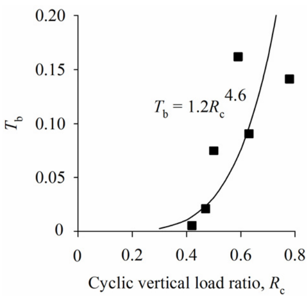


Fig. 6. Variation of T_b parameters at different R_c values for saturated sand

3.3 *Variation of the unloading stiffness*

The unloading stiffness ($k = V_{tc}/\Delta w_N$) of the bucket foundation has been defined in Fig. 5. The unloading stiffness for the bucket foundation slightly decreased with the increase in the number of load cycles, as shown in Fig. 7. The reduction of unloading stiffness might be caused by the gap created between the foundation and surrounding soil.

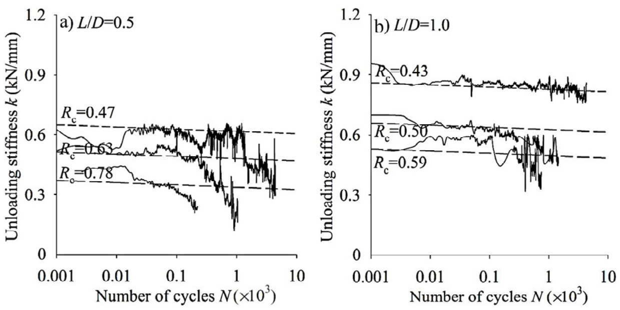


Fig. 7. Unloading stiffness at different load magnitudes

4 CONCLUSION

This study investigated the accumulated displacement and unloading stiffness of the bucket foundations in saturated sands under vertical pullout cyclic loading. A series of 1*g* model tests were carried out. Single bucket foundations at embedment ratios of L/D = 0.5 and 1 were considered. The following conclusions can be drawn based on the test results.

(1) The vertical pullout capacity of the bucket foundation can be evaluated as the sum of the skin resistance of the bucket skirt and the suction force developed inside the bucket lid. The accumulated vertical pullout displacement under cyclic load increased with the increase in load cycles and load magnitude. The unloading stiffness decreased with the increase in the number of load cycles N and load magnitude.

(2) Empirical equations were proposed based on the test results to evaluate the accumulated vertical pullout displacement of the bucket foundation in saturated sand. These equations can be used for the primary design of single or tripod bucket foundations for offshore wind turbines.

5 ACKNOWLEDGEMENTS

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