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Centrifuge test of a clustered bucket foundation for offshore wind towers

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ABSTRACT: This paper reports the results from a series of centrifuge model tests undertaken to provide insight into the behaviour of a clustered suction bucket foundation. Of particular interest was to compare the performance with that of a monopod foundation. The clustered foundation consisted of three buckets, spacing at 1.5 diameters centre to centre, and was fabricated based on the area equivalent principle i.e. the total plan area of the three buckets was approximately equal to the area of the corresponding monopod foundation. Horizontal load, combined with overturning moment load, was applied to simulate a loading condition that offshore wind towers typically withstand. The resisting performances of the clustered and monopod bucket foundations were evaluated and compared. The use of the clustered bucket foundation improved the resistance as much as 58%, with the efficiency decreasing with increasing rotation angle.

1 INTRODUCTION

Bucket foundations (with length to diameter or aspect ratio, $L/D < 1$) are a type of shallow foundations used offshore that comprise a top plate and peripheral skirt and sometimes internal skirts. The skirts confine a plug of soil and are beneficial in transmitting foundation loads below the mudline to deeper and often stronger soil. This enhances the bearing capacity and reduces displacements compared with a surface foundation. The bucket is installed by jacking in or by pumping water from inside the caisson after it is allowed to penetrate under self-weight. For the latter, the difference between the hydrostatic water pressure outside the cylinder and the reduced water pressure inside provides a differential pressure, or suction, that acts as a penetration force (referred to as suction assisted installation).

Bucket foundations are used widely in the oil and gas industry, to support various offshore platforms and subsea structures such as pipeline manifolds. In addition, they are increasingly being considered in the renewable energy industry, to support offshore wind and current turbines (Sparrevik, 2002; Andersen et al., 2005; Houlsby et al., 2005; Gourvenec, 2007; LeBlanc et al., 2009; Zhu et al., 2011; Hung and Kim, 2012). Various factors such as water depth, soil conditions, fabrication facilities, installation equipment, and transport vessels should be taken into account in order to conceive a suitable foundation type. At some sites, bucket foundations may prove more economical. By comparison with traditional foundation systems, such as piles or massive concrete bases, large savings can be made on installation time and materials.

The foundation may be monopod or tripod/quadruped (i.e. may consist of 1~4 individual buckets; Houslby and Byrne, 2000; Byrne and Houslby, 2003). For the former, the overturning load is applied directly to the single large foundation. In this case the bucket may be embedded solely in the sand and the foundation response to an overturning moment will be critical. For the latter, the overturning loads applied by the wind and waves are resisted predominantly by a ‘push-pull’ action, involving equal and opposite vertical loads at foundation level. In this design, the foundations are likely to be embedded in sand, and it will be the response of the foundation to vertical loads that is critical (Byrne and Houslby, 2003). This study has introduced a clustered bucket foundation, which consisted of three individual buckets and was somewhat similar to the conventional tripod one.

Investigation of bucket foundation and suction caisson response on sandy deposits is very sparse. Houlsby et al. (2006) presented records from field trials for suction installation of caissons, cyclic moment loading under both quasi-static and dynamic conditions to simulate the behaviour of a monopod foundation, and cyclic vertical loading and pullout of caissons to simulate one footing in a quadruped foundation. In assessing penetration resistance of bucket foundations during suction installation, Houlsby and Byrne (2005) proposed a design approach. Dyvik et al. (1993) and Anderson et al. (1993) reported results from large scale model tests on a clustered anchor with four buckets installed in clay and subjected to operational static and cyclic inclined loadings. However, no research has been published that investigates the behaviour of clustered bucket foundations installed in sand and subjected to loadings related to an offshore wind tower. This is critical as the bearing behavior of clustered bucket foundations entails higher complexity than the monopod because of the complex configuration of connected short pile-shape buckets.

In this study, an extensive investigation was carried out on the performance of a clustered bucket foundation subjected to operational loadings through centrifuge model tests and numerical analyses. The installation aspect was not explored herein. The results were compared with those of an (area equivalent—discussed later) monopod foundation. The aim was to provide insight into the behavior of a clustered bucket foundation, quantifying the corresponding improvement of geotechnical performance and highlighting the applicability and efficiency of the suction bucket foundation for offshore structures. This paper reports the results from a series of centrifuge model tests. The horizontal load, combined with overturning moment, was applied to simulate a typical loading condition for offshore wind towers. The results from numerical modeling were reported by Kim et al. (2013a).

2 BUCKET FOUNDATIONS

A monopod foundation was taken as a reference from a previous work presented by Choo et al. (2012). It was 15.5 m in diameter ($D_m = 15.5$ m) and 10.5 m long and primarily designed for a 3 MW wind turbine. In this study, an equivalent clustered bucket foundation with three individual buckets was fabricated. This means the total area of the three buckets ($3 \times A_c$) were similar to the area of the monopod foundation (A_m). The length of the skirt was same as of the monopod. Three buckets of the equivalent clustered foundation were therefore 8.66 m in diameter ($D_c = 8.66$ m; nearly equal to the area equivalent diameter) and 10.5 m long, spacing centre to centre at $S = 13.0$ m (1.5 D_c). Detailed procedure for calculating an equivalent clustered foundation was presented by Kim et al. (2013a).

Centrifuge model tests were undertaken at 70 g and therefore all prototype dimensions of the foundations were scaled down by 70; i.e. tests were undertaken using 1:70 scale model buckets, with the dimensions given in Table 1. The models were made from steel. The schematic drawings of the foundations and images of the manufactured models are shown in Figure 1.

Table 1. Dimensions of bucket foundations.

Test ID	T1		T2	
Bucket type	Clustered		Monopod	
	Prototype (m)	Model (mm)	Prototype (m)	Model (mm)
Bucket dia. (D)	8.66	123.7	15.5	221.4
Skirt length (L_{em})	10.5	150 (0.68D_c)	10.5	150
Wall thickness (t)	0.07	1	0.07	1
Lid thickness (t_{lid})	0.28	4	0.49	7
Bucket spacing (S)	13.0	186 (1.5D_c)	–	–
	(MN)	(N)	(MN)	(N)
Weight (W)*	22.9	66.7	19.52	56.9

*Including model tower and connecting plate.

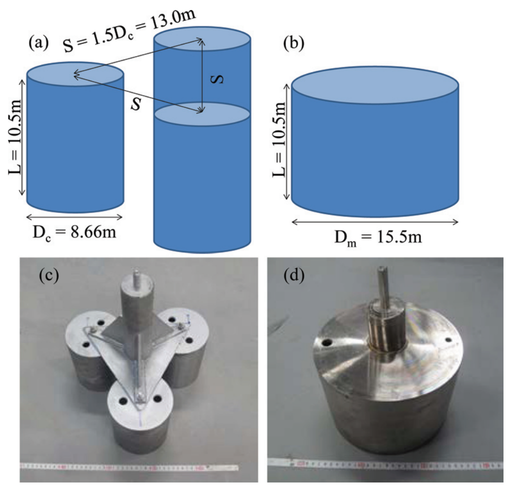

Figure 1. Schematic drawings and pictures of bucket foundations: (a) cluster foundation ($S = 1.5D_c$), (b) monopod, (c) cluster model, and (d) monopod model.

3 CENTRIFUGE MODELING

The experimental program comprised centrifuge modelling of bucket foundations subjected to operational horizontal and moment loadings in a stratified sandy deposit. The work was carried out in the 240 g-ton beam centrifuge at Korea Advanced Institute of Science and Technology (Kim et al., 2013b). It has a swinging platform radius of 5 m with a nominal working radius of 4.7 m. The platform seats cylindrical containers, which have internal dimensions of 900 (diameter) × 700 (depth) mm, representing a prototype test bed of up to 63 m diameter by 49 m deep at 70 g.

3.1 *Preparation of test specimen*

In this study, test specimens were prepared simulating stratification and layer soil properties and geometry similar to a site near the Western coast of Korea, located between Wido and Anma islands. This is because the site is identified as one of the areas with the greatest potential for evolving offshore wind farms in Korea. The seabed profile at the site is stratified and composed of three layers: a silty sand layer from the mudline to GL-11 m, ML and CL layers from GL-11 m to GL-32 m, and a silty sand layer from GL-32 m to the underlying bedrock. A complete report in regards to the seabed conditions was presented by Choo et al. (2012). For the monopod model, two layers were simulated: SM (GL0 m to GL-11 m) and ML (GL-11 m to GL-32 m). For the clustered model, it was simplified as a single (SM) layer deposit, assuming that the influence of the 2nd ML layer on the bearing behavior of the clustered foundation is negligible. Figure 2 shows grain size distribution curves for SM and ML materials used in the model tests. The basic properties of the model soils are presented in Table 2.

Test specimens were prepared in layers off the centrifuge on the laboratory floor. A total of nine layers were deposited and compacted in turn into the container. In order to produce the planned model layers, each layer was controlled at the predetermined relative density. Compaction was carried out by dropping a 13.5 kg circular steel plate from a constant height of 500 mm with a constant number of drops and then applying a static pressure of about 800 kPa. A summary of layers geometry and achieved relative density are given in Table 2. After preparation of a test specimen, saturation was ensured by supplying water very slowly from the bottom of the container. The model buckets were installed and the loading system was set at 1 g. The test specimen was then ramp up and down to enhance the saturation and settlement of the seabed. The ground level of the soil deposit and positions of the model structure and sensors were then measured.

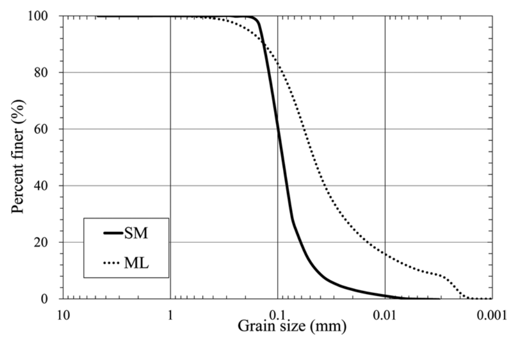

Figure 2. Grain size distributions of model seabed soils.

Table 2. Summary of layer properties and geometry.

Test ID	T1	T2	
Bucket type		Monopod	
Soil layer	Cluster	Layer1	Layer2
Depth	0~−32 m	0~−11 m	−11 m~−32 m
Soil classification	SM	SM	ML
Initial D_r* (%)	70.5	72.4	58.4

*Relative density.

3.2 *Loading equipment*

The foundations were installed at 1 g by jacking in keeping the holes on the lids open. Since the silty sand used in this study is impermeable relative to coarse sand, the drained behavior without any passive suction inside the buckets is a conservative estimate. Thus, the holes on the lids were kept open and operational loadings were applied in-flight after ramping up the centrifuge at 70 g. Offshore wind towers are simultaneously subjected to horizontal and overturning moment loads, which are induced by wind load on the nacelle, blade, and tower and the wave and current loads on the substructure. To apply a horizontal load, horizontal displacement was applied at a predetermined height of a rigid tower mounted firmly at the centre of the triangle plate connecting top lids of individual buckets. The actuator was leveled at 471 mm from the soil surface, simulating an equivalent prototype horizontal loading height of 33 m from the mudline. A full description of this loading system was presented by Choo et al. (2012). Initial loading was applied by moving the actuator to a pre-determined distance so the resulted rotation was about 10°, which was considered to be sufficient to cause failure of the foundation. The actuator was then moved in the reverse direction until the measured load is back to zero. In the next step, reloading was applied until

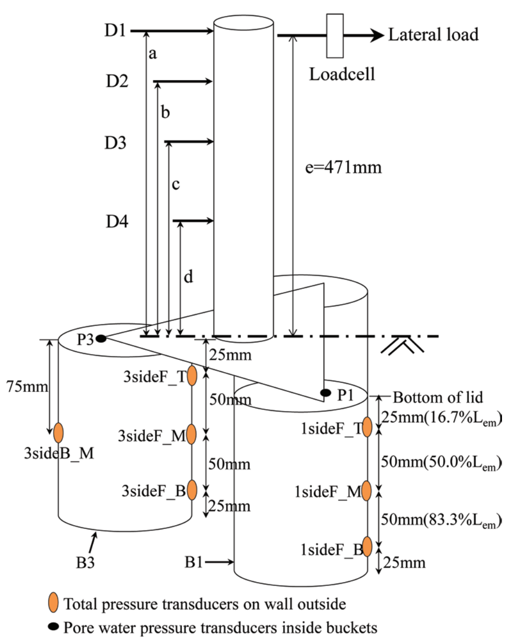

Figure 3. Instrumentation of the cluster bucket model. (a) Displacement measurement, and (b) pore water and total pressure sensors.

Table 3. Locations of displacement measurement.

Test ID	T1 Prototype (m)	T1 Model (mm)	T2 Prototype (m)	T2 Model (mm)
D1 (a)*	33.1	474	33.1	474
D2 (b)*	24.6	352	–	
D3 (c)*	16.2	232	17.2	246
D4 (d)*	8.7	124	8.0	114

*See Figure 3.

the rotation of the bucket foundation exceeded a rotation of 10°.

3.3 *Instrumentation*

The horizontal load was measured by a loadcell installed between the actuator and the tower. The resulted horizontal displacement was measured at multiple locations along the tower to monitor both lateral translation and rotation, with the locations depicted in Figure 3 and tabulated in Table 3. In addition, to measure the soil-structure interactions, Total Pressure Transducers (TPTs) were incorporated on the outer periphery of the skirts of the buckets. The bottom face of the lid of each bucket was equipped with a pore pressure transducer (PPT; labeled as P1 and P3 in Fig. 3) to monitor pressure change developed between the soil surface and base of the bucket.

4 RESULTS AND DISCUSSION

4.1 *Load-displacement relationship*

The load-displacement responses from bucket tests are presented in terms of horizontal load at the loading point, H, as a function of rotation angle, θ. To illustrate the effect of clustering buckets on the form of resistance profile, the results of clustered and monopod foundations (Tests T1 and T2; see Tables 1~3) are shown in Figure 4. The resistance values at different rotation angles are summarised in Table 4. By comparing the results, it can be seen that, using the clustered foundation led to improve the resistance under horizontal loading by 58~19% (reducing with increasing rotation angle). After a rotation of three degrees, the tangential slope of the curve of the clustered foundation decreases gradually and eventually attained to a limiting value.

The clustered foundation effective area for resisting lateral load (projected area = $(S + D_c) \times L_{em}$; see Fig. 1a) was around 40% higher than that of the monopod foundation ($D_m \times L_{em}$). In addition, the

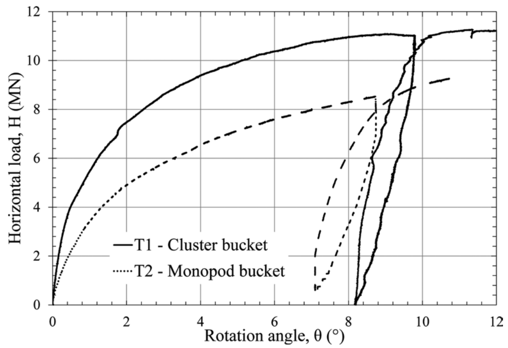

Figure 4. Load-displacement curves of cluster and monopod bucket foundations.

Table 4. Comparison of horizontal resistances at rotation angles of 1°, 2°, 3°, 4°, 5°, 6° and 10° (in prototype scale).

Rotation angle, θ (°)	T1 (MN)	T2 (MN)	$\lambda = T1/T2$
1	5.46	3.44	1.58
2	7.47	4.91	1.52
3	8.62	5.81	1.48
4	9.39	6.54	1.42
5	9.93	7.12	1.39
6	10.4	7.60	1.37
10	10.7	9.00	1.19

skirt surface area of the bucket skirts of the clustered foundation ($3 \times \pi D_c \times 2 \times L_{em}$) was around 68% higher than that of the monopod foundation ($\pi D_m \times 2 \times L_{em}$). With similar volume of the soil trapped inside the skirts and weight of the foundations, the capacity of the clustered foundation possibly improved by the increase in the skirt surface area of the clustered configuration. However, the improvement exactly was not consistent with the difference in the skirt surface area. As such, interaction of individual buckets of the clustered foundation and loss of structural integrity (see Fig. 5b) might have contributed it up to some extent. Furthermore, the significant decrease in the improvement (λ) may be mainly contributed by the loss of structural integrity. Thus, the exposed surface area of the clustered foundation became clearer than that of the monopod and the behavior of the rear bucket transformed from rotation-translation to pullout behavior.

4.2 *Water pressure measurement at top lid*

Figure 6 presents pressure responses of the pore pressure transducers (P1 and P3) attached on the

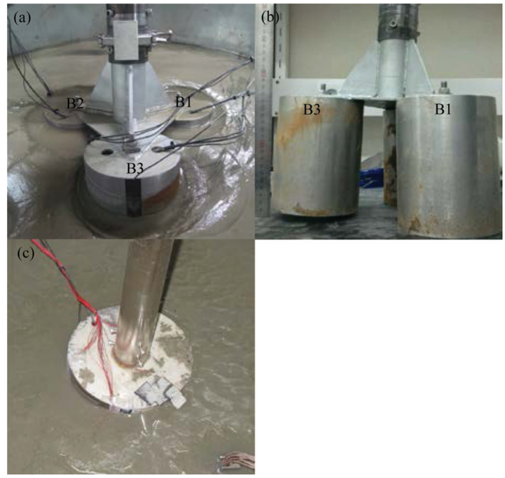

Figure 5. Post observation of the centrifuge model: (a) deformation of the seabed around bucket foundation, (b) deformation of the bucket foundation, and (c) deformation of seabed around the monopod foundation.

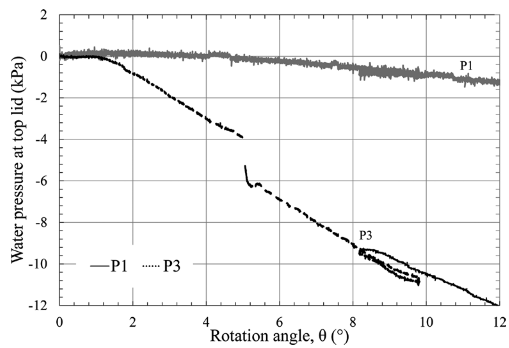

Figure 6. Pressure records of P1 and P3 attached on top lids during the load tests.

bottom face of the top lids. Since the transducers were attached on the inside surface of the top plate and the holes of the lids were open the response of the transducers indicated the up and down movement of the top lids of the buckets. The horizontal load was applied at a slow rate of 0.1 mm/s to simulate drained conditions. The readings were zeroed at the onset of each test. P3 on the rear bucket (B3) showed mainly a bi-linear behavior. The corresponding pressure remained zero until a rotation of 1° and then decreased somewhat linearly to a negative value of −12 kPa. It is inferred that the rear bucket did not move at the beginning of the loading but the front buckets rotated and the connecting triangle plate deformed. The rear bucket then started to be uplifted with the progress of the rotation. This deformation of the connecting plate and the uplift of the rear bucket can be seen in Figure 5.

On the contrary, the pressure at P1 slightly increased at the beginning of the loading and then decreased, meaning the P1 side of the front bucket was initially penetrated, but then slightly lifted up and hence showing a marginal negative value of −1 kPa.

4.3 *Total pressure at skirts*

As noted previously, total pressure transducers were mounted at the front face of one of the front buckets of the clustered foundation and both front and trail faces of the rear bucket (see Fig. 3). Figure 7 shows the histories of total pressures induced by the loading (i.e. measured total pressure during applying horizontal load negating by the initial geostatic pressure at the depth of the corresponding transducer). With the progress of rotation, the total pressure at 1.75 m below the lid of the front bucket (1 sideF_T) increased gradually and reached a plateau. The highest positive pressure was mobilised at that point for $\theta \leq 6°$. For $\theta > 6°$, the pressure at the middle point (1 sideF_M) exceeded that at 1 sideF_T. The bottom point (1 sideF_B) recorded almost constant positive pressure after a rotation of 2.4°.

For the rear bucket, broadly, negative (i.e. reverse direction) or negligible total pressures were measured by the sensors. It can be seen that, the pressure at the front bottom and middle points (3 sideF_B and 3 sideF_M) tended to show a positive value at the onset of loading, but it turned the direction for $\theta \geq 1°$. The front top point (3 sideF_T) recorded a negligible response. The pressure at the rear middle point (3 sideB_M) dropped sharply within $\theta < 1°$ and then remained somewhat constant. The decrease in the initial part reflects the result of rotation.

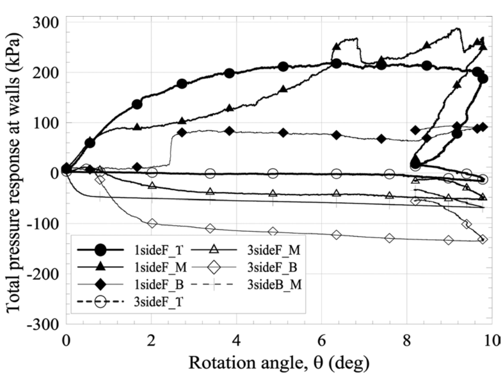

Figure 7. Response of total pressure transducers on bucket skirts.

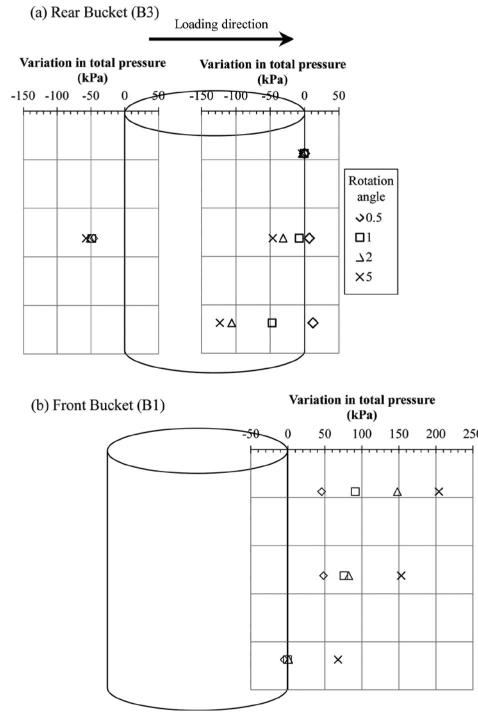

Figure 8. Distributions of total pressure deviations at rotation angles of 0.5°, 1°, 2°, and 5°.

The values of total pressure were picked at four different rotation angles of 0.5°, 1°, 2° and 5° in an attempt to evaluate the distribution of pressure and to make a direct comparison. They are plotted in Figure 8. This presentation is consistent with the behavior of the buckets described previously. It is noteworthy that the pressure readings on the rear bucket (3 sideF_T, 3 sideF_M, and 3 sideF_B in Fig. 8) decreased with the movement of the buckets. Presumably, the inside plug between the surrounding buckets was slightly displaced with the loading and it resulted in a decrease in lateral total pressure on the front of the rear bucket (B3). In addition, the rear bucket (B3) was uplifted as the loading increased, meaning the locations of the pressure transducers moved upward. Therefore, the most decrease in the total pressure occurred for $\theta < 2°$ (which was identified as the beginning of rotation) and afterwards, decreased slightly. This movement also contributed to the decrease in the lateral pressure of the rear side of B3 (3 sideB_M).

5 CONCLUDING REMARKS

This paper has reported results from centrifuge model tests investigating the behavior of a clustered bucket foundation, in comparison with that of a monopod foundation, under horizontal and moment loading. The tests were carried out on silty sand deposit prepared simulating stratification, soil properties and geometries similar to a site with significant potential for future development of offshore wind farms in Korea. The following key conclusions can be drawn from the results presented in the paper.

1. The use of the clustered bucket foundation (D_c = 8.66 m, L_{em} = 10.5 m, and S = 13.0 m) improved the resistance as much as 58% at the most at rotation angle of 1°.
2. For $\theta > 3°$, the tangential slope of the load-displacement curve of the clustered foundation decreased gradually and eventually attained to a limiting value. The significant decrease in the improvement (λ) may be mainly contributed by the loss of structural integrity.
3. The measured total pressure at various locations of both front and rear buckets of the clustered foundation supported the performance discussed previously. The behavior of the front buckets showed a combination of rotation and translation but the rear bucket rotated only at the beginning of loading and then lifted up.

More tests are required to be carried out to develop a failure envelope in V-H-M space. Further investigation is also being undertaken to investigate the behavior of both clustered and monopod bucket foundations during suction installation and under operational cyclic loading.

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REFERENCES

Andersen, K.H., Dyvik, R., Schroder, K., Hansteen, O.E. & Bysveen, S. 1993. Field tests of anchors in clay. II: Predictions and interpretation. *Journal of Geotechnical Engineering* 119(10): 1532–1549.

Andersen, K.H., Murff, J.D., Randolph, M.F., Clukey, E.C., Erbrich, C.T., Jostad, H.P., Hansen, B., Aubeny, C., Sharma, P. & Supachawarote, C. 2005. Suction anchors for deepwater applications. In Susan Gourvenec & Mark Cassidy (ed.), *Frontiers in Offshore Geotechnics, ISFOG2005; Proc. the 1st Intern. Symp., Perth, Australia, 19–21 September 2005*. London: Taylor & Francis Group: 3–30.

Byrne, B.W. & Houlsby, G.T. 2003. Foundations for offshore wind turbines. Philosophical Transactions of the Royal Society of London, Series A: Mathematical and Physical Sciences 361(1813): 2909–2930.

Choo, Y.W., Kim, D.J., Kim, S., Kim, J.H., Kim, D.S., Jee, S.H. & Choi, J.H. 2012. Centrifuge tests of monopod and tripod bucket foundations for offshore wind turbine tower. In Viswanadham & Gaudin (ed.), *Physical Modeling in Geotechnics; Proc. of 1st Asian Workshop, Asiafuge 2012, Mumbai, India, 14–16 November, 2012*. India: Bloomsbury.

Dyvik, R., Andersen, K.H., Hansen, S.B. & Christophersen, H.P. 1993. Field tests of anchors in clay. I. Description. *Journal of Geotechnical Engineering* 119(10): 1515–1531.

Gourvenec, S. 2007. Failure envelopes for offshore shallow foundations under general loading. *Géotechnique* 57(9): 715–728.

Houlsby, G.T. & Byrne, B.W. 2000. Suction caisson foundations for offshore wind turbines and anemometer masts. *Wind Engineering* 24(4): 249–255.

Houlsby, G.T., Ibsen, L.B. & Byrne, B.W. 2005. Suction caissons for wind turbines. In Susan Gourvenec & Mark Cassidy (ed.), *Frontiers in Offshore Geotechnics, ISFOG2005; Proc. the 1st Intern. Symp., Perth, Australia, 19–21 September 2005*. London: Taylor & Francis Group: 75–93.

Houlsby, G.T., Kelly, R.B., Huxtable, J. & Byrne, B.W. 2006. Field trials of suction caissons in sand for offshore wind turbine foundations. *Géotechnique* 56(1): 3–10.

Hung, L.C. & Kim, S.R. 2012. Evaluation of vertical and horizontal bearing capacities of bucket foundations in clay. *Ocean Engineering* 52: 75–82.

Kim, D.J., Choo, Y.W., Lee, J.S., Kim, D.S., Jee, S.H., Choi, J., Lee, M.S. & Park, Y.H. 2013a. Numerical Analysis of cluster and monopod suction bucket foundation. *Ocean, Offshore and Arctic Eng.; Proc. of the OMAE 2013 32nd intern. conf., Nantes, France, 9–14 June, 2013*.

Kim, D.S., Kim, N.R., Choo, Y.W. & Cho, G.C. 2013b. A newly developed state-of-the-art geotechnical centrifuge in South Korea. *KSCE Journal of Civil Engineering* 17(1): 77–84.

LeBlanc, C., Ahle, K., Nielsen, S.A. & Ibsen, L.B. 2009. The monopod bucket foundation, recent experience and challenges ahead. *European offshore wind 2009 conference & exhibition, Stockholm, Sweden, 14–16 September 2009*.

Sparrevik, P. 2002. Suction Pile Technology and Installation in Deep Waters. OTC 14241.

Zhu, B., Kong, D.Q., Chen, R.P., Kong L.G. & Chen, Y.M. 2011. Installation and lateral loading tests of suction caissons in silt. *Canadian Geotechnical Journal* 48(7): 1070–1084.