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Experimental and numerical studies on lateral bearing capacity of bucket foundation in saturated sand

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ABSTRACT

The lateral bearing capacity of bucket foundation was studied by tests and FEM. The characteristics of bearing capacity under horizontal loading were obtained experimentally. In this paper the results of the numerical and tests study on the bearing capacity and failure mode of bucket foundations that support wind turbine structures in homogeneous medium sand were presented, considering the frictional contact behavior of interface between skirt and subsoil. The height to diameter ratios (L/D) were taken from 0.3 to 1.0. The results of test and FEM showed that the rotation is the main failure mode of bucket foundation, and the center of rotation changes with the height to diameter ratios. The inclination angle for the ultimate lateral bearing capacity of the wide-shallow bucket foundation is about 3.0°, which is different from small diameter foundations, such as suction anchors and piles. The comparison of results from FEM, tests and simplified calculation method proves the accuracy of the research results.

1. Introduction

A wide-shallow bucket foundation is an upturned close-end steel or reinforced concrete cylinder with height to diameter ratio less than 0.5 and the length of skirt less than 10 m. It is lowered to the seafloor, allowed to penetrate the bottom sediments under its own weight first, and then pushed to full depth with suction force produced by pumping water out of the interior. In recent years, suction caisson as the predecessor of the bucket foundation have been used increasingly often for gravity platform jackets, jack-ups (Clukey et al., 1995; Allersma et al.,1997; Allersma et al., 2000), they also have the potential of being used for several other purposes, such as offshore wind turbines, subsea systems and seabed protection structures (Housby and Byrne, 2000; Byrne et al., 2002; Byrne and Houlsby, 2004; Andersen and Jostad, 1999). The first advantage of bucket foundations are attractive because of the convenient method of installation and repeatedly use. The second advantage is that it may mobilize a significant amount of passive suction during uplift. Despite some studies about the bearing capacity and failure mode of the bucket foundation have been studied (Aas and Andersen, 1992), but there are less studies on the earth pressure distribution along the skirt and top of bucket and the change of the gradient. The horizontal loading condition is significant when bucket foundations are used as the foundation of offshore wind turbines. Wave loading, ice loading or wind loading causes the foundation to be subjected to horizontal loadings. The lack of experience with these loading conditions lead to a proposal for a test program intended to gain a deeper understanding. The considerable expense and time consuming nature of prototype tests mean that the investigation of the bearing capacity of real scale devices under different circumstances is of limited practicality. It is much easier to change parameters in small scale tests. The soil type may be varied. The dimensions of the bucket foundation and other process parameters may be varied conveniently also.

Some field tests have been reported in the open literature, but the height to diameter ratios are large, Ibsen et al. (2014) carried out an extensive test program on small-scale foundations in the laboratory, and the height to diameter ratios of bucket foundations were more similar to our research, but those tests did not consider the pressure of the top of the bucket. Jin et al. (2014) studied the horizontal ultimate bearing capacity of suction bucket foundation in saturated sand ground by the numerical simulation method, but the ratio of length to diameter L/D was large, and the model did not take into account the separation of the bucket wall and soil. A number of investigators have tested scale models of bucket foundations in geotechnical centrifuges. Early experience with this technology often involved relatively stiff soils and axial compressive loadings applied at the top center of the bucket. Speed dependent loading tests on clay at 1 g were performed by Jones et al. (1994) and Steensen-Bach (1992).

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Table 1
Dimensions of bucket models.

Number	Material	Diameter D (cm)	Height L (cm)	Skirt thickness t (cm)	Height to diameter ratio L/D	Weight W (kg)
1#	Steel	50	15	0.8	0.3	52
2#	Steel	50	25	0.8	0.5	65.5
3#	Steel	40	30	0.8	0.75	56.5
4#	Steel	30	30	0.8	1.0	41

Later designs for floating structures in deeper water, where horizontal or inclined mooring lines are attached to buckets, led to the need for increased lateral capacity. Although the offshore industry is deploying bucket foundations in those configurations, a number of design issues remain unresolved.

In the view point above, the lateral bearing capacity of single bucket in saturated sand are carried out by using the finite element method and model tests. The criterion of overturning instability is obtained.

2. Introduction of experiment

The bucket models were steel cylinder bucket with different height to diameter ratios that was 0.3, 0.5, 0.75 and 1.0. The main dimensions of bucket models were shown in Table 1. The diagrammatic sketch and physical map of the buckets were shown in Fig. 1.

The soil specimen was medium sand with a dry density of 1660 kg/m^3. The sand was laid in a concrete pit with a size of 4×4×3 m. The thickness of sand was 1.5 m. The water level was 6 cm over the sand layer surface. The soil parameter was measured by soil tests after the maintenance of soil completing (See Table 2). A tension rod displacement sensor with a range of measurement of 0–60 cm was used to measure the displacement of the bucket foundation. A force transducer with a range of measurement of 0–200 kN was used to measure loads. The 4 cm thick filter was laid on the bottom of the pit for uniform drainage and preventing piping. It was 4 days until the sand finished draining.

The dowel par at the bucket top was connected with one end of the force transducer, and the loading head was connected with the other end of the transducer. When the bucket was applied on compressive or uplift vertical loading, the hole on the bucket's top is not sealed. The bucket was first penetrated into the sand layer by the gravity, and then was connected with the loading head. The bucket continued to sink under vertical pressure until the top of bucket contacted the sand. The tension rod displacement sensor was located at the bucket's top to measure the displacement of the bucket. Figs. 2 and 3 show the testing equipment.

The horizontal loading was applied on the bucket foundation by a hydraulic jack. A pressure transducer was fixed on the dowel par. The center of pressure transducer and the hydraulic jack was installed on the same horizontal plan. The loading was applied continuously meanwhile the displacement had a corresponding increase. When the displacement increased and the force decreased or did not change, the experiment was finished. Fig. 4 shows the test result of horizontal loading.

3. Introduction of finite element method

ABAQUS FE package (ABAQUS, 2013) was used to investigate the behavior of bucket foundations with different height to diameter ratios L/D=0.3, 0.5, 0.75 and 1.0, which were corresponded to the models. The ratio of prototype to model was 60. Due to three-dimensional loading conditions, a full-cylinder representing the soil and the bucket was considered. The discretized model area had a radius of five times the bucket diameter. The bottom boundary of the model was extended five times the bucket diameter below the toe of the bucket. With these model dimensions, the calculated results of the bucket are not significantly influenced by the boundaries. An example of the three-dimensional finite element model for bucket foundation is shown in Fig. 5. The constitutive model of the sand is Mohr–Coulomb. The bucket and the soil used linear brick elements with reduced integration and hourglass control (C3D8R). Relatively fine meshed were employed at the edge of the bucket and below the bucket toe in order to capture localized failure, while coarser meshes were used away from the bucket in order to reduce computational effort. No vertical and horizontal displacements were adopted as bottom constraint, and no horizontal displacement was adopted as lateral constraint.

Unlike FE analyses carried out by Monajemin and Abdul Razak (2009), in the paper bucket was fully bonded to surrounding soil, here the contact behavior of the interface between skirt and soil was simulated by contact pair algorithm. Normal “hard” contact model was used to describe the detachment and contact between shirt and soil. When skirt was in contact with soil, normal pressure and tangential frictional resistance was transferred between interfaces, accompanied by Coulomb's friction activated. The coefficient of friction is 2/3tanϕ, and the parameter ϕ is the internal friction angle of soil. Otherwise, no forces were transferred between skirt and soil.

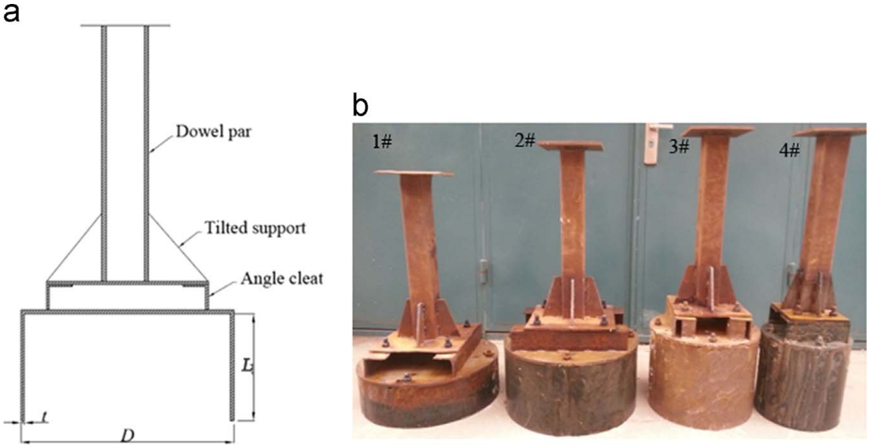

Fig. 1. (a) Diagrammatic sketch. (b) Physical map of bucket models.