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Bearing behavior of wide-shallow bucket foundation for offshore wind turbines in drained silty sand

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ABSTRACT

The failure mode of the wide-shallow bucket foundation is different from that of the traditional suction caisson and the narrow-deep bucket foundation. Results from elasto-plastic analyses of 3D finite element models are presented, aimed at defining the shape of the yield envelope in the *V–H*, *V–M*, *H–M* and *V–H–M* spaces and the failure mode of the bucket foundation. The compressive bearing capacity of the wide-shallow bucket foundation was determined by the displacement. The corresponding load under a vertical displacement of 0.06*D* was the vertical ultimate bearing capacity. The vertical loading had an amplification effect on the horizontal load-bearing and moment capacity, and the horizontal loading which was in the opposite direction to the moment increased the moment capacity by 20–40%. New simplified calculation methods were proposed for the vertical load-bearing capacity and the overturning stability. In the proposed method, the vertical capacity consisted of a top plate resistance of the bucket and a side frictional resistance. The overturning stability was determined by the safety factor method, and depended on the location of the rotation point. A comparison between results from the finite element analysis and the simplified calculation methods showed that the proposed equations properly predicted the capacities of the wide-shallow bucket foundations.

1. Introduction

Recently, foundation structures such as gravity foundation, mono-pile, tripod foundation, suction anchor, jacket foundation and floating foundation were adopted in offshore wind turbines. Mono-pile structures are the most widely used in offshore wind farms and gravity foundation is the second most widely used. However, the strict requirements for construction equipment and technologies restrict the wide application of mono-pile structures in China. Meanwhile, the gravity foundation structure needs more than 5000 t of concrete consumption for the effective transmission of wind turbine loads, and the construction cost of the jacket foundation structure is high (Lian et al., 2012). Nowadays, new foundation structures, such as the wide-shallow bucket foundation, have great advantages in lowering the construction cost and shortening the construction period over conventional ones. Bucket foundation has been used extensively in offshore facilities, such as platforms, wind turbines, and jacket structures. China is a country where multiple typhoons occur, so the wide-shallow bucket foundation is used to resist high moments (Ding et al., 2012). The wide-shallow bucket foundation usually has a large diameter (generally larger than 20 m, especially for wind turbines with more than 3 WM power in China), and the aspect ratio is less than 0.5. Meanwhile, the depth of the skirt is less than 10 m. An all-steel bucket foundation is not economic, so a new type of foundation is proposed which is steel combined with pre-stressed concrete. The bucket foundation is utilized in water of 10–20 m depth. The gas injection and breaking soil method is applied to sink the concrete shell with a thickness of nearly 400 mm to ensure the sinking position of the bucket foundation without liquefaction of the soil inside the bucket. Gas injection pipelines are embedded in the skirt of the bucket foundation along the circumferential direction. The sand under the end of the bucket foundation is scattered under high pressure gas. When the penetration resistance exceeds the force provided by the gas injection and breaks the soil, a negative pressure device is used to ensure sinking of the foundation.

In civil engineering, hydraulic engineering, and coastal and offshore engineering, the foundations are usually subjected to a vertical loading with long-period horizontal loading or cyclic loading components including a horizontal loading and a moment. The vertical loading *V*, the horizontal loading *H* and the moment *M* can be transferred to the foundation through footing beneath the building. Such a loading mode is defined as a combined loading mode as shown in Fig. 1. At present, many researchers use the failure envelope

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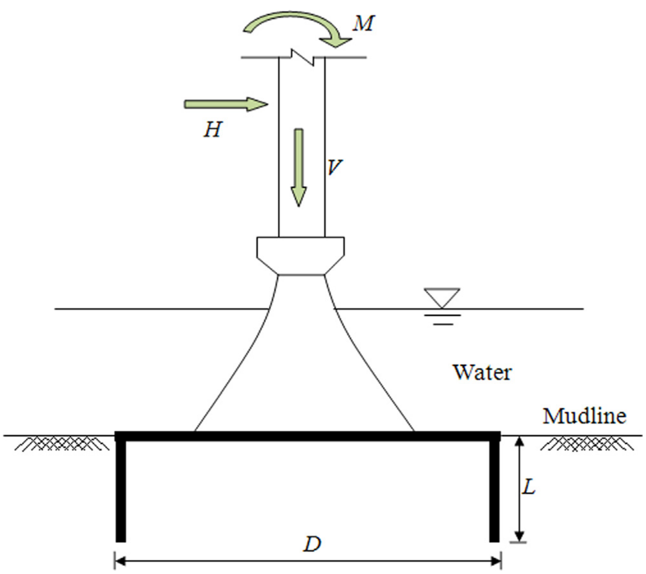

Fig. 1. Suction bucket foundation.

to derive the ultimate bearing capacity; the failure envelope is defined as a convex curved surface in the vertical loading, horizontal loading and moment space when the general shear failure mode occurs. Several studies have been conducted on bucket foundations, including studies on the behavior of the suction bucket foundation under vertical loading, horizontal loading and moment. Murff (1994) presented a failure locus which was symmetric and the maximum moment coincided with zero horizontal loading, whereas the numerical analysis showed that the maximum moment was sustained with a negative horizontal loading. The failure locus obtained from Murff's equation became non-conservative when $MH \geq 0$. Bransby and Randolph (1998) identified two different upper-bound plasticity mechanisms for strip footings under the moment and horizontal loading: a scoop mechanism and a scoop-wedge mechanism. The latter mechanism resulted in a greater ultimate moment capacity for bucket foundations. The non-symmetric failure locus predicted by the current numerical technique was very similar to the failure locus obtained by Bransby and Randolph (1998) for strip footings using finite-element analysis. Ei-Gharbawy (1998) conducted a series of laboratory tests to study the behavior and pull-out capacity of suction bucket foundations under the vertical and inclined loading conditions. Sukumaran and McCarron (1999) documented an application of the finite element method to estimate the capacity of suction bucket foundations installed in soft clays and subjected to axial and lateral loads under undrained conditions. Shen Zhujiang (2000) studied the effect of vertical loading V, horizontal loading H and moment M on the ultimate bearing capacity of the foundation, and presented the forward failure mode, backward failure mode and pressed failure mode by varying the loading point on the footing. Aubeny and Murff (2005) presented upper-bound lateral solutions to estimate the lateral load capacity of suction bucket anchors as a function of the load attachment point and load inclination angle. The effects of overturning moment on the bearing capacity of the suction bucket have been studied using the finite element method by Wang and Jin (2008), and Bransby and Yun (2009), and the failure mode of the suction bucket foundation under the horizontal loading was investigated. The results have shown that the overturning moment induced by the eccentric horizontal force reduced the axial capacity. Taiebat and Carter (2005) employed the finite element method to investigate the behavior of suction bucket foundation under a combination of axial, lateral and torsional forces, assuming that the bucket was fully bound to the subsoil, where it was shown that the torsional force obviously reduced the axial and lateral capacities. In their study, a typical bucket with an aspect ratio (L/D) of 2 was used. Through the finite element method, Zhan and Liu (2010) studied the response of a monopod suction bucket installed in uniform clay soil to support wind turbine structures, considering the combination of vertical, lateral, overturning and torsional forces (V–H–M–T), and the interaction of these forces was presented in the form of failure locus. Wang et al. (2010) used the Engel Assumption, in accordance with three-dimensional space problems, and established the formula of the eccentric horizontal load-bearing capacity. Lian et al. (2011) presented a calculation method for the horizontal ultimate bearing capacity and the overturning resistance. Le and Sung (2012) proposed equations for the vertical and horizontal load-bearing capacities based on finite element analysis results. A soil plug was considered in the numerical simulation, which was impossible to be formed for the wide-shallow bucket foundation.

Past research results did not propose any explicit method to calculate the bearing capacity under the combined action of V–H–M. A variety of failure modes is assumed in order to calculate the bearing capacity, and the most dangerous condition is chosen to design the bucket foundation, which is cumbersome and inaccurate. Furthermore, previous theoretical formulas and numerical simulations did not consider the detachment between the soil inside the bucket and the bucket itself, and analytical results were conservative. For wide-shallow bucket foundations, the soil plug is hard to form unless the subsoil is reinforced. At the same time, the foundation was assumed to be either a skirted strip foundation in two-dimensional (2D) finite element (FE) analysis (Bransby and Randolph, 1998, 1999; Yun and Bransby, 2007a, b; Gourvenec, 2008; Bransby and Yun, 2009) or an equivalent surface circular foundation in three dimensional (3D) FE analysis (FEA) without modeling the embedment of the foundation (Tani and Craig, 1995; Bransby and Randolph, 1998) in previous numerical studies. The bearing capacity of the bucket foundation is closely related to the aspect ratio. For the wide-shallow bucket foundation, the diameter of the bucket has a significant influence on the bearing capacity, and so does the skirt embedment depth to some extent. In addition, design equations have been developed based on the previous numerical results, which have the aforementioned limitations. Therefore, the development of design equations based on more accurate numerical results, which consider 3D soil–structure interaction and the exact shape of the bucket foundation, would be necessary.

In the present study, a series of 3D FEA were performed to evaluate the effect of the aspect ratio (L/D, where L is the skirt length and D is the foundation diameter. The L/D ratio is less than 0.5) on the vertical (V) load-bearing capacity, the horizontal (H) load-bearing capacity, and the moment (M) bearing capacity of the bucket foundations for wind turbines. The soil was assumed to be homogenous silty sand. A simple formula for the bearing capacity was developed based on the analytical results.

2. Numerical modeling

The bucket foundation was assumed to be 'wished in place', i.e. neglecting the footing installation process. Therefore, small strain finite element (SSFE) analyses were performed for this study (Zhang et al., 2011). The SSFE approach essentially calculates the capacity of an installed foundation, where only small displacement excursions are required to mobilize the ultimate footing bearing capacity. The analyses were carried out with the commercial software Abaqus version 6.10.

2.1. Foundation model and soil properties

The aspect ratio of the bucket foundation (L/D) varied at 0.2, 0.25, 0.33, 0.4 and 0.5. The bucket foundation material was reinforced