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Model tests on the bearing capacity of wide-shallow composite bucket foundations for offshore wind turbines in clay

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ABSTRACT

This paper presents a new type of wide-shallow composite bucket foundation (WSCBF) for offshore wind turbines, which can be adapted to the characteristics and development needs of offshore wind farms due its special structural form. Several field tests on the horizontal bearing capacity of WSCBF were carried out in saturated clay off the coast of Jiangsu. The deformation mechanism, the soil–structure interaction and the ultimate bearing capacity of the WSCBF are determined depending on the tests. Based on the position of the rotation center, analytical expressions of soil pressure and ultimate bearing capacity for the WSCBF are presented. The accuracy of the test results and analytical expressions is validated and supplemented by numerical simulation with a finite element method. Moreover, by means of numerical simulation, the envelope curve of ultimate bearing capacity of the WSCBF is described in *H–M* load space, clarifying the load-bearing characteristics of the WSCBF under combined loads.

1. Introduction

China is rich in wind energy, especially in offshore areas. Wind energy is a rapidly growing renewable energy industry, but realizing its potential will require resolving a number of challenges in the near future, such as choosing an appropriate foundation type. Suction caissons have been considered as possible foundations for offshore wind turbines (Houlsby et al., 2005a). According to the geological characteristics and hydrometeorological conditions, a new type of wide-shallow composite bucket foundation (WSCBF) has been examined by Tianjin University (Ding et al., 2012; Zhang et al., 2013a), and on October 1st 2010 the only WSCBF for a fully operational wind turbine of 2.5 MW was installed at the offshore test facility in Qidong City in the southeast of Jiangsu Province (Zhang et al., 2013b). This WSCBF has a diameter of 30 m and a relatively small bucket wall height of 7.2 m, as shown in Fig. 1. The WSCBF has reasonable motion characteristics and towing reliability because there are seven rooms inside (Zhang et al., 2013c), arranged in a honeycomb structure as shown in Figs. 1(c) and 7(b). The pressure inside the rooms can control the levelness of the WSCBF during suction installation. An arc transition structure of pre-stressed concrete has been designed on the top of the bucket foundation to ensure that the heavy loading from the upper tower structure is successfully transmitted to the lid of the WSCBF and then into the soil foundation (Lian et al., 2012).

The stability of a bucket foundation is closely related to the offshore topsoil, and the failure mechanism of the bucket foundation under horizontal loads can be obtained through model tests. Byrne conducted a series of tests in a drum centrifuge (Byrne and Cassidy, 2002) to investigate the stress–strain relationship of suction caissons under compound loading on soft, normally consolidated clay. A program of testing caisson foundations in clay at the Bothkennar test site was described by Houlsby et al. (2005b). They present results on the installation of the caissons, cyclic moment loading under both dynamic and quasi-static conditions, cyclic inclined vertical loading, and the pullout of the caisson. Large-scale model tests on suction installation and lateral loading of caisson foundations in saturated silt were carried out by Zhu et al. (2011), who examined the deformation mechanism and soil–structure interaction of a caisson subjected to lateral loads and presented an analytical expression for the ultimate moment capacity.

Numerical analysis is an important way to evaluate the stability of a foundation. Aubeny et al. (2003) present a simplified upper bound solution for estimating the load capacity of suction caisson anchors under inclined loading conditions. Le and Sung (2012) present the results of three-dimensional finite element analyses of bucket foundations in normally consolidated uniform clay under undrained

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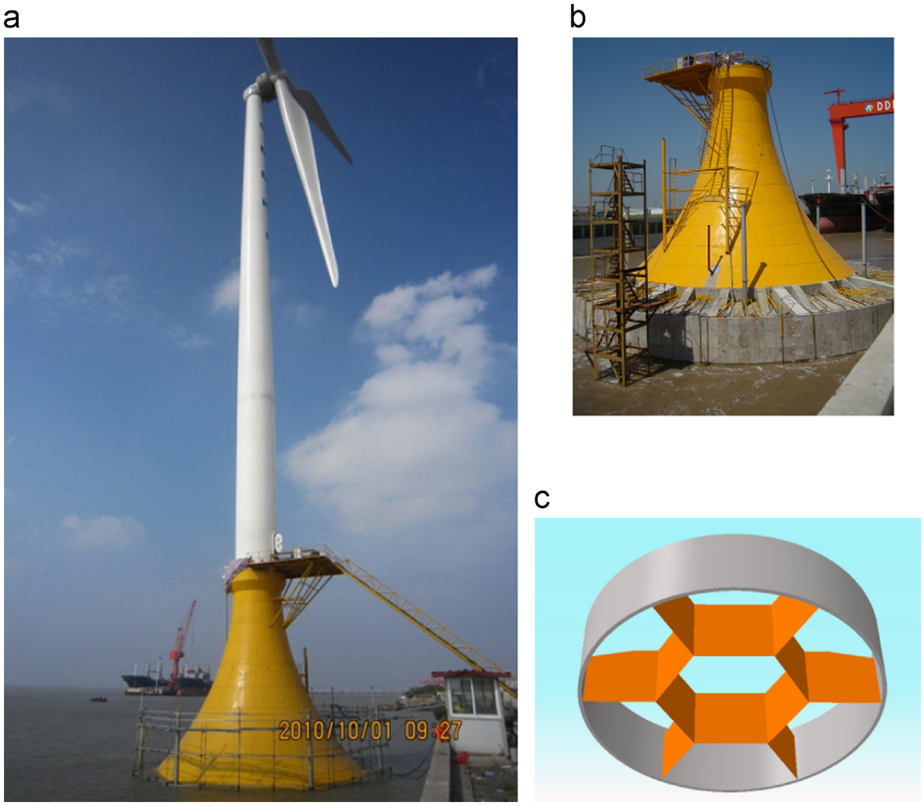

Fig. 1. The WSCBF: (a) 3 MW WSCBF prototype project, (b) releasing water into the dockyard after prefabrication, (c) bulkheads inside the WSCBF.

conditions and propose new equations for calculating the vertical and horizontal bearing capacity. Predicting the failure envelope of a bucket foundation under combined loading is key to evaluating the limiting bearing capacity of the foundation. Bransby and Randolph (1998) studied the *V*–*M*, *V*–*H* and *M*–*H* yield locus of bucket foundations using a finite-element analysis and upper-bound plasticity analysis, assuming the soil to be undrained and suggested a simplifying transformation for the yield locus in *H*–*M* space. Wu et al. (2008) generated the failure envelopes of suction bucket foundations in different loading spaces and provided the corresponding empirical calculation formulas. Gourvenec and Barnett (2011) consider a fully encompassing failure envelope in (V, H, M/B) load space to be a useful tool to define the ultimate limit states for design, and proposed a closed-form expression that allows the prediction of the undrained bearing capacity of a skirted foundation.

The technology of WSCBF is sufficiently mature, and the critical steps are onshore prefabrication, self-floating towing and one step installation in the appointed sea area (Zhang et al., 2013d; Ding et al., 2013). Because it is a new form, evaluating the limit-bearing capacity of WSCBF is more difficult than using the classical formula for the bearing capacity of a foundation. The collaborative bearing mechanism of foundation and soil is equalized by the subdivision plates inside the WSCBF and represents a departure from previous research. Presenting an appropriate method of calculating the ultimate bearing capacity will help this type of foundation gain wider acceptance and lead to its wider application in practical engineering.

2. Experimental equipment and design

2.1. Soil

The WSCBF evaluation was carried out in a large artificially excavated test pool located along the coast of Jiangsu. The pool is 10 m × 10 m, as shown in Fig. 2. The soil in the tests is saturated clay from a planned wind farm site off the coast of Xiangshui in Jiangsu province. The soil was placed in the tank by an excavator layer by layer, to a total depth of 3 m. The top soil requires elaborate preparation to make it flat. The soil around the pool is mainly fine sand. The pool was filled with water for at least six months, followed by soil laboratory tests to characterize the saturated clay. The saturated density of the soil is 1806 kg/m^3 and the water content is 33.5%. Its liquidity index and plasticity index are 1.19 and 11.75. The compressive modulus E_s of the soil is taken as 3.69 MPa for a proper ultimate state, and its cohesion strength c and internal friction angle φ are 3.84 kPa and 7.14°, respectively. The compressive modulus of the soil is obtained from consolidation test, as shown in Table 1.

2.2. Wide-shallow composite bucket foundation

The bucket foundation in the tests has an outer diameter (D) of 3.5 m and a clear wall height (L) of 0.9 m. The seven rooms are divided inside the bucket by bulkheads as shown in Fig. 7(b). The six peripheral rooms have the same proportions, and the middle one is a little larger. A steel tube is connected to the lid and reinforced by six ribbed plates as part of this WSCBF, and the tube is also used for horizontal loading as part of a wind turbine tower. The tube is 0.66 m in outside diameter, 5 m in height and 0.008 m in thickness. The lid, the wall, the bulkheads, tube and ribbed plates have the same thickness. Lifting lugs are required and attached to the tube for applying horizontal load at the height of 2 m, 3 m, 4 m, and 5 m. This WSCBF is made of steel with a net weight of approximately 2.8 t.

The suction installation (Zhu et al., 2011; Erbrich and Tjelta, 1999) of the WSCBF requires a vacuum system, which mainly consists of a vacuum pump, a water–air converter, vacuum control values and seven wired hoses connected the rooms to the vacuum