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Experimental study on installation of hybrid bucket foundations for offshore wind turbines in silty clay

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ABSTRACT

Two large-scale sinking tests of the hybrid bucket foundation were revealed in typical saturated silty clay of China offshore wind farms. The experimental foundation has an outer diameter of 3.5 m and a clear wall height of 0.9 m with seven rooms divided inside the HBF by steel bulkheads, which are arranged in a honeycomb structure. The different pressure inside the seven compartments can control the levelness of the HBF during suction installation. During the sinking process of the bucket foundation, real-time monitoring was conducted of the produced underpressure, the soil pressure and the pore pressure inside and outside the bucket wall, which reflected the sinking state of the bucket foundation. Test results show that suction can be combined with air pumping to reasonably control the sinking speed of the bucket foundation and the levelness at each stage. In the cases where the soil surface at the sinking location for the bucket foundation was relatively horizontal, the levelness could be ensured to meet the standard and design requirements after the sinking of the bucket foundation was completed.

1. Introduction

The soils in the present and potential sites for offshore wind farms in China are mainly soft clay (or silty clay) and fine sand (or sandy silt). In some cases, the high-rising pile cap foundations, mono piles and multi-pile jacket foundation were used in the intertidal zone and shallow sea (10 m or so). As a relatively new form of offshore foundation, bucket foundations are commonly used in recent years in ocean engineering because of the advantages of economic feasibility and environment-friendly work principles (Houlsby and Byrne, 2000, 2005; Liu et al., 2015; Yu et al., 2014a; Zhu et al., 2011). Whilst piled or gravity foundations may often be used, novel designs based on bucket foundation technology may be attractive for many sites.

The hybrid bucket foundation (HBF) is a new type of for offshore wind turbines, which can be adapted to the loading characteristics and development needs of offshore wind farms due its special structural form. The HBF 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 in China in 2010. This HBF has a diameter of 30 m and a relatively small bucket wall height of 7 m. With the seven-room structure, the HBF has reasonable motion characteristics and towing reliability during the wet-tow construction process. Moreover, the pressure inside the compartments can control the levelness of the HBF during suction installation. (Lian et al., 2011, 2012; Liu et al., 2014; Ding et al., 2013, 2015; Zhang et al., 2013b, 2013c, 2014, 2015).

To obtain an approximately equal bearing capacity against overturning moment, monopod bucket foundation has been considered a cost-competitive option for offshore wind turbine substructures (Lian et al., 2014; Zhang et al., 2013a). Many researches (Feld, 2001; Ibsen et al., 2014; Kelly et al., 2006; Senders, 2008; Yu et al., 2014b, 2015) have been given to the cyclic lateral response of skirted foundations, such as field tests, physical models, centrifuge experiments and numerical simulations. During installation, the installation of bucket foundations can be divided into two main phases. According to some relative researches (Cotter, 2010; Houlsby et al., 2005, 2006; Lehane et al., 2014; Li et al., 2015; Madsen et al., 2013; Thieken et al., 2014; Zhu et al., 2013), possible problems during the installation phases could relate to soil limitations, structural limitations or pumping system limitations.

For bucket foundations the installation phases are important parts of the design process. The bearing capacity is determined by the installation accuracy based on several factors, such as penetration depth, applied underpressure, penetration rate, plug heave, tilt, and orientation (Hédi, 2003; Hédi and Colliat, 2002; Senders and Randolph, 2009). In practice, out-of-verticality (tilt) and

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misorientation have been accounted for in the reliability analyses. Typically, the tilt installation tolerance is set to ±5°, provided that the seabed slope angle is less than 5° (DNV, 2005) for suction anchors. By comparison, deflection control of the foundations is vitally important to ensure the normal operation of offshore wind turbines. In China, the design code (FD003-2007) requires the more stringent angular rotation of the foundation to be less than 0.17° (3‰ for levelness) for wind turbines with hub heights more than 100 m.

During installation, to most efficiently prevent lateral movement and keep the bucket foundation from tilting, the adjustment process should be performed during the earliest stages of weight penetration (Tran et al., 2007; Zhang et al., 2013a). In practice, the tilt problem is usually caused by buried geohazards, such as stones or boulders along the skirt circumference in unforeseen ground conditions. Besides, the difference among the applied suction and the penetration resistances of the seven sections would lead to a tilt angle to a certain extent. It is a convenient method to improve compartment inclination by controlling the inside differential pressure. In the paper, the installation model tests on a hybrid bucket foundation with seven compartments were performed in order to investigate the feasibility of a foundation tilt adjusting technique by applying suction/positive pressure and intermittent pumping among the rooms. The tests represent the tilt adjusting techniques with adjusting the tilt of a mono bucket foundation with seven compartments during the entire installation process based on three tests.

2. Experimental equipment and soils

2.1. Experimental equipment

The typical hybrid bucket foundation consists of a mono-caisson foundation and an arc transmission structure made of prestressed concretes, as shown in Fig. 1. The HBF has the reasonable towing reliability with seven rooms inside arranged in a honeycomb structure. In the present research, the prototype design is a 3 MW HBF of 2100 t with the rest structure of 710 t. The model scale of the HBF is nearly 1:10 since the experimental model of HBF is made of steel instead of reinforced concrete and steel structure in prototype. The hybrid bucket foundation in the tests has an outer diameter (D) of 3.5 m and a clear wall height (L) of 0.9 m, as shown in Fig. 2. The seven rooms are divided inside the bucket by bulkheads. 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 HBF, and the tube is also used for horizontal loading as part of a wind turbine tower. The lid, the wall, the bulkheads, tube and ribbed plates have the same thickness. The dimensions of the model are listed in Table 1.

Fig. 1. The 2.5 MW offshore wind turbine supported by CBF.

To obtain the pressure inside the compartment, soil pressure, and water pore pressure, pressure transmitters, soil pressure cells and pore water piezometers were fixed on the HBF (see Fig. 3). There are twenty six soil pressure sensors with a diameter of 0.02 m embedded in the steel plate, with eight in the top cover (see Fig. 3(a)), two at the skirt tip, along the skirt eight toward inside and the remaining eight toward outside (see Fig. 3(b)–(d)). Meanwhile, there are eight water pore pressure sensors embedded in the skirt wall of the caisson, with four toward inside and the remaining four toward outside (see Fig. 3(b)–(d)), while there are another two sensors fixed on the top cover of the HBF (see Fig. 3(a)). In addition, there are seven pressure transmitters on the top lid of the bucket for every compartment. The main equipment used in model tests includes the gas/water pump system and tube system and data collection system. The layout scheme and picture of the experimental equipment on test site is illustrated in Fig. 4.

2.2. Soils

The HBF tests were carried out in a large artificially excavated test pool located along the coast of Jiangsu. The soil in the tests is

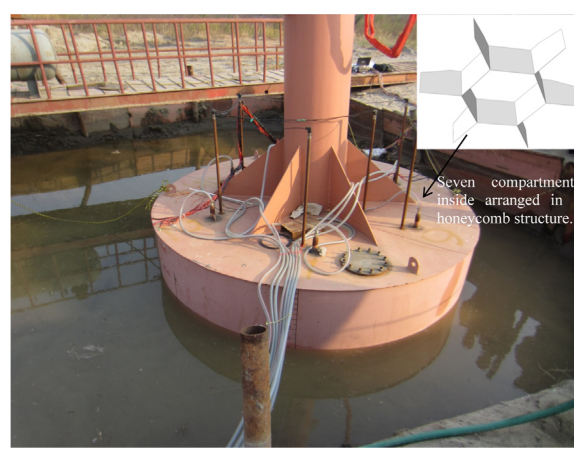

Fig. 2. The test model of composite bucket foundation.

Table 1
Details of the model dimensions.

	Prototype	Model
Diameter D (m)	35	3.5
Skirt length L (m)	9	0.9
L/D	3.89	3.89
Skirt and bulkhead thickness t (m)	0.03	0.008
D/t	1166.7	437.5
Tip area (m^2)	6.447	0.1718
Net area (m^2)	955.178	9.4445
Total weight (kg)	2,810,000	2810.7