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Effect of seepage on the penetration resistance of bucket foundations with bulkheads for offshore wind turbines in sand

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ABSTRACT

A bucket foundation with bulkheads (BFB) is a new form of offshore foundation that is divided into seven compartments by an internal skirt and bulkheads. Suction penetration is an important process during the installation of BFBs. However, little attention has been paid to the effect of seepage on the penetration resistance of BFBs in sand. In this paper, a series of experiments and numerical simulations are performed to study the seepage field and the effect of seepage on the penetration resistance of a BFB during suction installation in sand. Moreover, a method of calculating the penetration resistance of BFBs is proposed considering the seepage effect, and the penetration resistance distribution of the BFB test model is analyzed. The analysis results show that seepage obviously reduces the penetration resistance of BFBs, and the ratio of reductions in resistance to the total resistance reaches a maximum value of 0.55 at the final penetration stage. In addition, the soil resistance of the bucket wall is significantly larger than those of the internal skirt and bulkheads for the BFB model.

1. Introduction

As a clean and renewable energy source, wind energy is gradually attracting attention worldwide. As offshore wind farms present the advantages of saving land resources, high wind speed, and minimal influence on the surrounding environment, offshore wind power has become a tendency in the wind power development. China has a rich offshore wind energy resource of over1 billion kW, and its total offshore wind power resources is about 750 million kW. A large number of foundation types for offshore wind turbines have been studied in recent years. The foundation structures mainly include pile foundation, gravity foundation, jacket foundation, and floating foundation (Byrne and Houslby, 2003; Liu et al., 2015b). As a new foundation form, bucket foundations present the advantages of economic feasibility and environment-friendly work principles (Houlsby and Byrne, 2000; Liu et al., 2015a). The Norwegian Geotechnical Institute studied the Europipe 16/11-E large jacket platform in 1994, at which point the suction-type bucket foundation came into being (Bye et al., 1995). Since its first installation in 2002 in Denmark (Houlsby et al., 2005), which featured a diameter of 16 m and a height of 6 m, was successfully, the number of bucket foundations has grown considerably. During installation, large equipment are required to level the bucket foundation, which brings some inconvenience to the construction.

To solve problems related to the installation of bucket foundations, Tianjin University proposed a new type of bucket foundation with bulkheads (BFB). In this structure, seven rooms are divided inside the bucket by bulkheads and a skirt: six peripheral rooms have the same proportions, while the seventh room, which is located in the middle, is slightly larger (see Fig. 1(c)). With this structure, leveling the bucket foundation can be achieved by applying the suction/positive pressure to different compartments (Zhang et al., 2015a,2016a, 2016b). Moreover, the BFB presents reasonable motion characteristics and towing reliability during the wet-tow construction process (Ding et al., 2013; Zhang et al., 2013a, 2013b, 2015b). In 2010, the first composite BFB for offshore wind turbines was successfully installed at the offshore test facility in Qidong City, China, as shown in Fig. 1(a). In 2016, a second BFB was also installed in Xiangshui City, China (see Fig. 1(b)). These developments reveal that the application of BFBs has become an important endeavor in China.

The suction penetration process is a key consideration during the installation of bucket foundations. Keeping the suction within a reasonable range is extremely important. On one hand, excess suction will cause soil plug in the bucket, resulting in the suspension of penetration (Tran et al., 2005). On the other hand, insufficient suction cannot maintain

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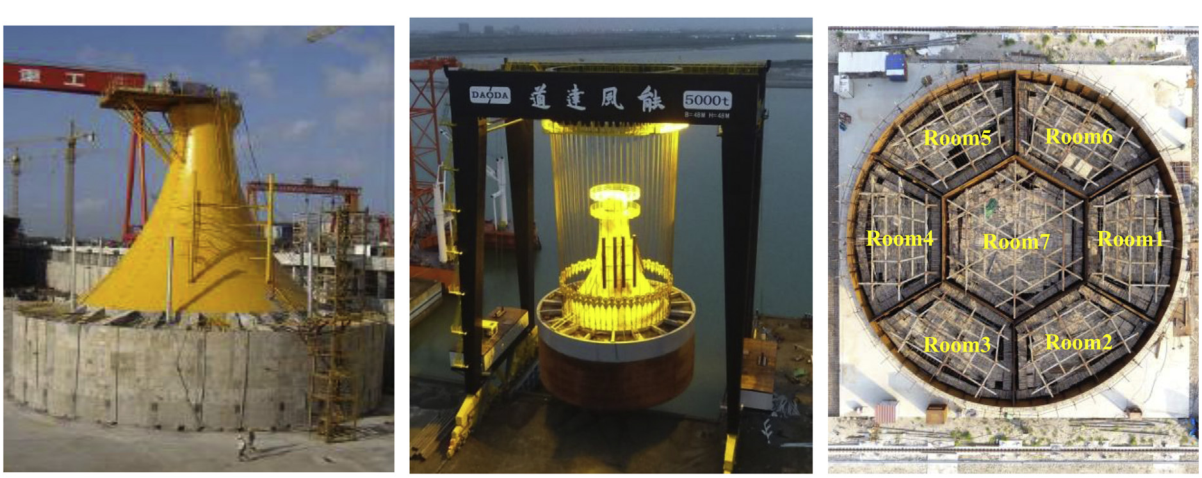
Nomenclature

D_o	Outside diameter of the bucket foundation with bulkheads
D_i	Inner diameter of the bucket foundation with bulkheads
D	Average value of the inner and outer diameters
H	Height of the bucket foundation with bulkheads
D_{mo}	Outside diameter of the middle compartment
D_{so}	Outside diameter of the side compartment
t	Thickness of the bucket wall, internal skirt, or bulkheads
A_{tip}	Sum of tip areas of the penetrated bucket wall, internal skirt, and bulkheads
A_{side}	Sum of side areas of the penetrated bucket wall, internal skirt, and bulkheads
A_{cross}	Horizontal cross-sectional area of the bucket foundation with bulkheads
δ	Friction angle between the sand and skirt wall
q	Effective overburden pressure
q^*	Effective overburden pressure considering seepage effect
γ, σ'	Unit weight of soil, effective unit weight of soil
ω	Water content
φ	Friction angle
e	Void ratio
D_r	Relative compactness
k	Hydraulic conductivity
p	Excess pore water pressure
p'	Normalized excess pore pressure
L	Suction loss
σ'	Effective vertical stress of soil under no pore water flow
σ'^*	Effective vertical stress of soil under seepage conditions
W	Weight of BFB
W'	Submerged weight of BFB
s	Applied suction pressure
h	Penetration depth
h'	Scaled penetration depth
K	Ratio of horizontal to initial vertical effective stresses at the skirt wall
Q_{side}	Side friction under no pore water flow
Q^*_{side}	Side friction considering seepage effect
Q_{tip}	Tip resistance under no pore water flow
Q^*_{tip}	Tip resistance considering seepage effect
F_{test}	Penetration force measured in tests
R_{total}	Penetration resistance under no pore water flow
$R^*_{wall}, R^*_{skirt}, R^*_{bhs}$	Penetration resistances of the bucket wall, skirt, and bulkheads considering the seepage effect, respectively
$\Delta R_{wall}, \Delta R_{skirt}, \Delta R_{bhs}$	Reductions in the penetration resistance of the bucket wall, skirt and bulkheads caused by seepage, respectively
R^*_{total}	Sum of the resistance of the bucket wall, skirt, and bulkheads considering the seepage effect
ΔR_{total}	Sum of the reduced resistance of the bucket wall, skirt, and bulkheads caused by seepage

Subscripts

wall	Bucket wall
skirt	Internal skirt
bhs	Bulkheads

continuous bucket penetration. Thus, evaluating the penetration resistance of the bucket foundation before installation is necessary. Because the penetration mechanism of bucket foundations in clay is simple, the predicted value of the construction suction is relatively accurate (Houlsby and Byrne, 2005). However, calculating the penetration resistance in sand is difficult because of the seepage effect caused by suction. Seepage flow could reduce or enhance the effective stress in the surrounding soil and change both the wall friction and tip resistance (Bye et al., 1995; Erbrich and Tjelta, 1999; Tjelta, 1994, 1995). Several related works employing experiments and numerical simulations have been performed (Lian et al., 2014; Mehravar et al., 2015; Tran and Randolph, 2008). Researches showed that seepage can significantly reduce the inner friction of the bucket wall and the tip resistance. The methods to calculate the penetration resistance of bucket foundations have also been proposed considering the seepage effect (Guo et al., 2016; Harireche et al., 2014; Houlsby and Byrbe, 2005; Senders and Randolph, 2009). The approach proposed by Houlsby and Byrbe (2005) is based on the bearing capacity theory with friction angle. Senders and Randolph (2009) proposed a CPT-based approach for penetration resistance in which resistance reduction factors used the ratio of current to critical suction as input value. In addition, during the process of bucket installation in sand, suction should be controlled to avoid the formation of piping channels which would prevent further penetration and may cause the failure of the penetration installation (Achmus and Schröder, 2014; Feld, 2001; Ibsen



(a) (b) (c)

Fig. 1. Bucket foundation with bulkheads: (a) BFB installed in 2010 (b) BFB installed in 2016 (c) Inside view of the BFB.