Ocean Engineering 79 (2014) 1–9

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Group effect on bearing capacities of tripod bucket foundations in undrained clay

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ARTICLE INFO

Article history:
Received 18 March 2013
Accepted 29 December 2013
Available online 27 January 2014

Keywords:
Bucket foundation
Group effect
Bearing capacity
Finite element analysis
Non-uniform clay
Undrained shear strength

ABSTRACT

Tripod bucket foundations are being used as alternative foundations to resist large horizontal and moment loadings from offshore wind turbines. The bearing capacity of the tripod bucket foundation differs particularly from that of the single bucket foundation due to the interaction among individual buckets of the tripod. This paper investigated the group effect of tripod bucket foundations in clay by three-dimensional finite element analysis. Parametric studies were performed varying the spacing between each bucket foundation, embedded depth of the bucket foundation, and loading directions. Normally consolidated clay under an undrained condition was modeled using a linear elastic-perfectly plastic model obeying the Tresca failure criterion. The undrained shear strength and Young's modulus of clay were assumed to linearly increase with depth. The group efficiency factor, which is the ratio of the bearing capacity of the tripod bucket foundation to that of the single bucket foundation, was evaluated based on finite element analysis for vertical, horizontal and moment loadings. Results showed that the efficiency factors were functions of the bucket spacing and embedment depth of the foundations.

1. Introduction

Designs of foundations for offshore wind turbines must provide resistance against large horizontal and moment loadings, which significantly increase with water depth. The tripod bucket foundation, which combines three single bucket foundations into a triangular shape, is a potential alternative to increase the bearing capacities of the foundation for offshore wind turbines. This type of foundation is well suited for offshore sites with water depth ranging from 20 to 50 m (Veritas, 2007).

The procedure for installation of the tripod bucket foundation into the seabed is similar to that of the single bucket foundation. The skirt of the bucket is first penetrated into the seabed by self-weight. Water is then pumped out of the bucket, producing suction pressure inside the bucket, to allow for further penetration. The penetration stops when the top-plate of the bucket touches with the seabed, and the suction pressure confines the soil plugged within the skirt.

Fig. 1 presents the geometry of the tripod bucket foundation. S is the spacing between each bucket and the wind turbine tower at the center. L is the skirt length and D is the diameter of the bucket. The spacing ratio and the embedment ratio of the tripod bucket are denoted by S/D and L/D, respectively.

The bearing capacity of the tripod bucket foundation would be influenced by bucket spacing, embedment depth of the bucket and non-uniformity of clay. The bearing capacity of the tripod bucket foundation differs particularly from that of the single bucket foundation through the interaction among individual buckets of the tripod. Numerous studies have focused on the group effect of deep pile foundations; however, studies on the group effect of the tripod bucket foundation remain scarce.

Martin and Hazell (2005) applied the plasticity theory to analyze the group effect between two-dimensional parallel strip footings under vertical load. The group effects were mainly influenced by the spacing between footings. The effect of the non-homogeneity of clay was considered negligible except the footings at close spacing. Hung and Kim (2012) demonstrated the change in the bearing behavior of the single bucket foundations under horizontal loading from pure horizontal sliding to a rotational movement with the increase in L/D ratio. This result suggests that L/D can influence the group effect of the tripod bucket foundation.

Gourvenec and Steinepreis (2007) performed two-dimensional (2D) finite element (FE) analysis to investigate the undrained bearing behavior of two-surface footing systems in uniform clay. Vertical, horizontal, and moment capacities were analyzed according to the spacing between footings.

Gourvenec and Jensen (2009) extended the work of Gourvenec and Steinepreis (2007) and analyzed the group effect of the two-skirted foundation systems with $L/D=0.5$ in uniform clay by 2D FE

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0029-8018/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.oceaneng.2013.12.017

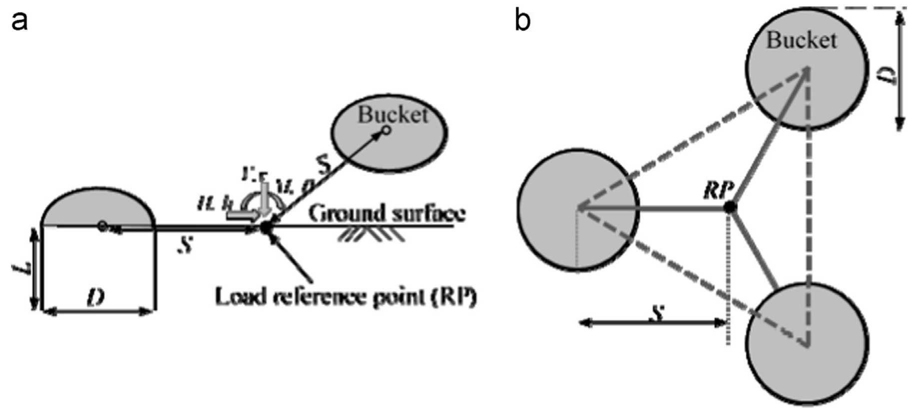

Fig. 1. Geometry of tripod bucket foundation and conventions of load and displacements: (a) side view and (b) top view.

analysis. They showed that the group effect in the vertical bearing capacity was negligible. With the increase in spacing between footings, the horizontal bearing capacity increased significantly and converged into a constant value, whereas the moment bearing capacities increased continuously.

Other studies observed the significance of geometry on the bearing behavior of the foundation (Gourvenec and Randolph, 2003). Thus, modeling of the tripod bucket foundation in three-dimensional (3D) geometry is essential.

The present study involved a series of 3D FE analyses to investigate the group effect of the tripod bucket foundation in non-uniform clay on the undrained bearing behavior. A parametric study on the group effect was conducted varying the S/D, L/D, and non-uniformity of clay. The bearing capacities of single and tripod bucket foundations were then compared, and the group efficiency factors were evaluated. The group efficiency factor is the ratio of the bearing capacity of the tripod bucket foundation to that of the single bucket foundation. The bearing capacity of the tripod bucket is conveniently evaluated by multiplying the group efficiency factor and the bearing capacity of the single bucket foundation, which can be determined using the suggested equations in the previous studies (Zhan and Liu, 2010; Hung and Kim, 2012, 2014).

2. Numerical simulation

2.1. Material properties and FE modeling

Fig. 1 presents the geometry of the tripod bucket foundation and the sign conventions adopted in this study. L/D was varied as 0.25, 0.5, 0.75, and 1, and S/D was varied as 1, 1.5, 2, 2.5, and 3. Preliminary analysis confirmed that D had no effect on the normalized bearing capacities (Hung and Kim, 2012). Thus, D was maintained at 10 m for all analyses. The skirt thickness was fixed at $t = 25$ mm, which is the common thickness of steel bucket foundations. Deformation of the bucket in soft clay is difficult to occur; thus, the bucket foundation was modeled as a rigid body.

The normally consolidated clay under undrained conditions was modeled as a linear elastic-perfectly plastic model obeying the Tresca failure criterion. The undrained shear strength s_u was assumed to vary linearly with depth by the following equation (Houlsby and Martin, 2003):

$$s_u = s_{um} + kz \tag{1}$$

where s_{um} is the undrained shear strength at the ground surface, z is the depth below the ground surface, and k is the increasing rate of strength with depth.

Preliminary analyses were performed to confirm that bearing capacity factors are dependent not on the individual parameters of s_{um} or k, but on the normalized non-homogeneity ratio of kD/s_{um}. This observation was also indicated by other previous works (e.g., Houlsby and Wroth, 1983; Houlsby and Martin, 2003; Martin and Hazell, 2005; Bransby and Yun, 2009; Gourvenec and Mana, 2011; Hung and Kim, 2014). Thus, the non-homogeneity of clay was defined by the normalized parameter kD/s_{um}. The kD/s_{um} value would vary in the range of 0–30 (Houlsby and Wroth, 1983; Martin and Hazell, 2005; Gourvenec and Mana, 2011). The increasing rate k of undrained shear strength would vary from $k = 1$ kPa/m to 2 kPa/m for normally or slightly over-consolidated clays (Randolph and Gourvenec, 2011). For marine clays, the undrained shear strength has a relationship with the vertical effective stress as $s_u = 0.2\sigma'_{v0}$ to $s_u = 0.4\sigma'_{v0}$ (Lambe and Whitman, 1969), or typically $s_u = 0.22\sigma'_{v0}$ (Mesri, 1989). Therefore, $k = 1.25$ kPa/m was selected by applying the effective unit weight of $\gamma' = 6$ kN/m^3. The normally consolidated clay would have a negligible undrained shear strength s_{um} at the ground surface (i.e., $s_{um} \approx 0$). A small value of $s_{um} = 1.25$ kPa was chosen to overcome the difficulty of convergence in FE simulation as well as to consider the non-homogeneity of clay with $kD/s_{um} = 10$. The Young's modulus E_u of soil was set at $400s_u$. The Poisson's ratio ν of soil was fixed at 0.495 to simulate the constant volume response of clay in undrained conditions (Taiebat and Carter, 2000; Yun and Bransby, 2007a).

All FE analyses were performed using the Abaqus software (Simulia, 2010) with small strain FE analyses. The first-order, eight-node linear brick, reduced integration continuum with hybrid formulation element C3D8RH was used to model the soil, whereas the foundation was simulated using the C3D8R element. The hybrid element is appropriate for simulating the incompressible or nearly incompressible clay, which has no volume change under undrained condition.

Fig. 2 shows a typical mesh and boundary extensions of the soil domain for the tripod bucket foundation. Half of the entire system was modeled by applying symmetric conditions. The vertical and horizontal displacements at the bottom boundary, as well as the horizontal displacements at the lateral boundaries, were constrained. The size of the soil elements gradually increased from the bucket foundation to the domain boundary. Optimum mesh sizes were used to minimize the effect of the mesh size on the results. The total number of elements were dependent on L/D and S/D ratios, and varied between 20,000 and 27,000 for single bucket foundations, and between 40,000 and 75,000 for tripod bucket foundations. The typical calculation time was varied about 5 h for the single bucket, and 15 h for the tripod bucket using the Intel(R) Core (TM) i5 CPU.

B_V and B_H in the Fig. 2 present the vertical and horizontal boundary extents from the skirt tip and the side of the bucket foundation, respectively. The boundary with $B_H/D \geq 4.5$ and $B_V/D \geq 4.5$ is known to have minimal effect on the bearing capacities for a single bucket (Hung and Kim, 2012). In addition, the analyses for the tripod bucket