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Evaluation of combined horizontal-moment bearing capacities of tripod bucket foundations in undrained clay

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ABSTRACT

A series of three-dimensional finite element analyses was conducted to evaluate the combined horizontal-moment bearing capacities of tripod bucket foundations for offshore wind turbines in undrained clay. The tripod bucket foundation consists of three single bucket foundations, which enhance the bearing capacities because of the effect of the interaction among individual buckets. A linear-elastic perfectly plastic model, which obeys the Tresca failure criterion, was used to simulate the stress–strain response of clay, in which Young's modulus and undrained shear strength were assumed to increase linearly with depth. The effects of bucket spacing, embedment depth, vertical load, and non-homogeneity of clay on the combined horizontal-moment capacities were analyzed. Finally, the design equation of the combined horizontal-moment capacities was developed as a function of the aspect ratios (skirt length/diameter) of the foundations.

1. Introduction

The tripod bucket foundation, which combines three single bucket foundations in a triangular shape, is a potential alternative to increase the bearing capacities of foundations for offshore wind turbines.

Offshore wind turbines with large power rate need to be installed at deeper water of more than 20 m and are subjected to strong horizontal and moment loadings by the wind, wave and current (Achmus et al., 2009). Therefore, the tripod bucket foundation is well suited for offshore wind turbines at deeper water.

Because of the large horizontal and moment loads of offshore wind turbines, the foundations should be designed by considering the effect of the combined loads (vertical (V), horizontal (H), and moment (M) loads) on the bearing capacity. The foundation will be safe and will not fail if the combined design loads are located within the bearing capacity envelopes. Several investigations have been performed to evaluate the undrained bearing capacity envelopes under V–H–M loading space. These investigations focused on the single skirted or the single bucket foundations (Bransby and Randolph, 1998, 1999; Gourvenec, 2008; Bransby and Yun, 2009; Hung and Kim, 2012, 2014).

Few studies have evaluated the group effect on undrained bearing capacities of rigidly connected multi-footings. Martin and Hazell (2005) applied the plasticity theory to analyze the vertical group effect for the rigidly connected parallel strip footings in clay with different homogeneities. They found that footings with very close spacing induced higher vertical bearing capacity factors in compared with single footings.

Gourvenec and Steinepreis (2007) investigated the undrained bearing behavior of rigidly connected two-surface footing systems under general loading with various footing spacings. The bearing capacities were found to increase with increasing footing spacing. Gourvenec and Jensen (2009) extended the work of Gourvenec and Steinepreis (2007) and analyzed the group effect of two-skirted foundation systems with an aspect ratio of $L/D = 0.5$ (where L is the skirt length of the foundation and D is the diameter or breadth of the foundation) in uniform clay. The combined bearing capacity for H–M loadings was significantly increased with the increase in the footing spacing and embedment depth. These works provided the important concepts for the practical design of rigidly connected multi-footing systems.

However, some limitations, such as the assumption of uniform clay and modeling of 2-dimensional (2D) condition, have to be considered. Such assumptions might not exactly be monitored for some cases that would be encountered in practical applications, such as the case of the tripod bucket foundation in non-uniform soft clay. Gourvenec and Randolph (2003) highlighted that the undrained shear strength of offshore clays usually increases linearly with depth. Previous works systematically indicated that the non-homogeneity of clay significantly affects the bearing capacity factors of the foundations (Houlsby and Martin, 2003; Gourvenec and Randolph, 2003; Hung and Kim, 2014). Therefore, analyses with non-uniform clays have to be addressed. In addition, the geometry effect of foundations serves an important function

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relative to bearing capacities. Previous studies showed that the bearing behavior of foundations is largely affected by embedment depth (Gourvenec, 2008) and foundation geometry (Gourvenec and Randolph, 2003). Thus, modeling the exact 3D shape of a tripod bucket foundation is necessary.

Therefore, this study aims to analyze the effect of bucket spacing and embedment depth on the bearing capacity envelopes of tripod bucket foundations under combined H–M loadings without vertical load. The 3D FE analysis was adapted to model the 3D geometry of tripod bucket foundations and the appropriate soil-foundation interaction. The applicability of the adopted FE modeling was validated by comparing its results with the bearing capacities from the theoretical solutions and model tests. A parametric study was performed by varying L/D ratios, S/D ratios (where S is the spacing between the individual bucket foundation to the center of the tower structure), and the non-homogeneity of clay under different loading conditions.

The vertical load from an offshore wind turbine is relatively low compared with that of offshore oil and gas platforms (Achmus and Abdel-Rahman, 2012; Kuo et al., 2012). Thus, the combined H–M loads from the wind, wave and current will mainly affect the safety of offshore wind turbines (Houlsby et al., 2005, Yun and Bransby, 2007a). The connection between individual bucket foundations and the tower structure of tripod bucket foundations system was simply considered to be fully rigid, following the suggestion of previous works (e.g. Murff, 1994; Gourvenec and Steinepreis, 2007; Gourvenec and Jensen, 2009).

2. Numerical simulation

2.1. Material properties and FE meshing

Fig. 1 shows the geometry of the tripod bucket foundation and the sign conventions adopted in this study. The L/D ratio was varied as 0.25, 0.5, 0.75, and 1, and the S/D ratio was varied as 1, 1.5, 2, 2.5, and 3. Preliminary analyses confirmed that D has 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 not likely 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 that obeys the Tresca failure criterion. The undrained shear strength s_u was assumed to increase linearly with depth by using Eq. (1) (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 undrained shear strength with depth.

Bransby and Yun (2009) confirmed that the bearing capacity factors are not dependent on the individual parameters of s_{um} or k but rather on the normalized parameters of kD/s_{um}. Thus, the non-homogeneity of clay was defined by the normalized parameter kD/s_{um}. The normally consolidated clay was applied with $s_{um}=1.25$ kPa and $k=1.25$ kPa/m, inducing a non-homogeneity ratio of $kD/s_{um}=10$. The effective unit weight γ' and Young's modulus E_u of the clay were set at 6 kN/m^3 and $400\times s_u$, respectively. The Poisson's ratio ν of the clay was fixed as 0.495 to simulate the constant volume response of the clay under undrained conditions (Taiebat and Carter, 2000; Yun and Bransby, 2007a).

All FE analyses were performed using the ABAQUS software (Simulia, 2010) with small strain analysis. The first-order, eight-node linear brick, reduced integration continuum with hybrid formulation element C3D8RH was used to model the soil. The hybrid element is appropriate for simulating the incompressible clay, whose volume does not change under undrained condition.

Fig. 2 shows the FE meshes and boundary extensions of the soil domain at $S/D=2.5$ and $L/D=1$. Only half of the entire system was modeled owning to symmetry. The vertical and horizontal

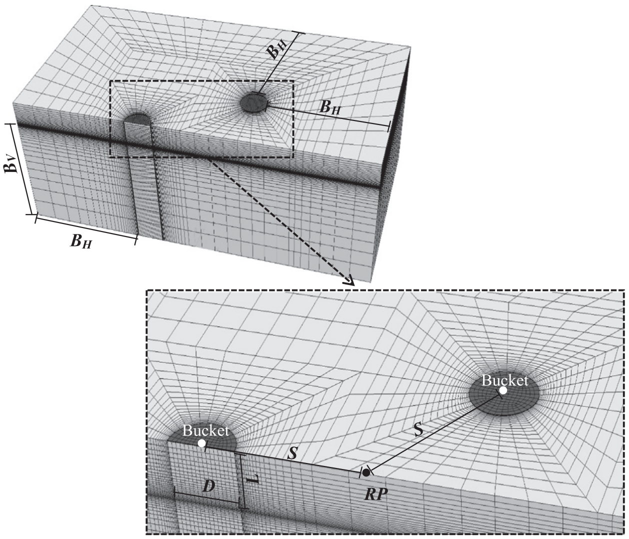

Fig. 2. FE mesh and boundary extensions of the tripod bucket foundation domain ($S/D=2.5$, $L/D=1$).

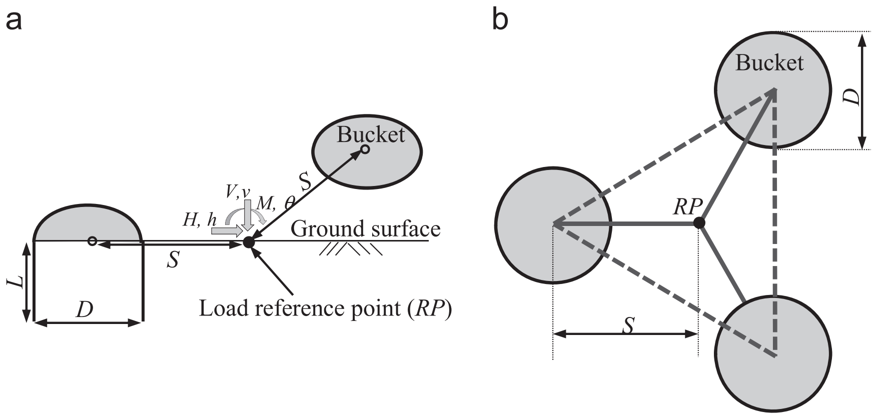

Fig. 1. Geometry of the tripod bucket foundation and the load and displacement conventions. (a) Side view. (b) Top view.