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Evaluation of vertical and horizontal bearing capacities of bucket foundations in clay

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ABSTRACT

The present paper presents the results of three-dimensional finite element analyses of bucket foundations in normally consolidated uniform clay under undrained conditions. The stress–strain response of clay was simulated using the Tresca criterion. The bearing capacities were calculated and found to be largely dependent on the aspect ratio of the bucket foundation. Based on the results of the analyses, new equations were proposed for calculating vertical and horizontal bearing capacities. In the proposed equations, the vertical capacity consisted of an end-bearing resistance and a skin friction resistance, whereas the horizontal capacity consisted of a normal resistance, a radial shear resistance, and a base shear resistance. Comparison of the numerical results showed that the proposed equations properly predicted the capacities of the bucket foundations in uniform or non-uniform clays.

1. Introduction

A bucket foundation is a circular surface foundation with thin skirts around the circumference. Bucket foundations have been used extensively in offshore facilities, such as platforms, wind turbines, or jacket structures (Tjelta and Haaland, 1993; Bransby and Randolph, 1998; Houlsby et al., 2005; Luke et al., 2005).

The skirt of a bucket foundation is first penetrated into the seabed by a self-weight. Further penetration is achieved by pumping water out of the bucket foundation, creating a suction pressure inside it. Penetration stops when the top-plate of the bucket comes in contact with the seabed, and the suction pressure confines a plugged soil within the skirt.

Several studies on bucket foundations in clay have been conducted. Previous numerical studies assumed that the foundation was either a skirted strip foundation in two-dimensional (2D) finite element (FE) analyses (Bransby and Randolph, 1998, 1999; Yun and Bransby, 2007a,b; Gourvenec, 2008; Bransby and Yun, 2009) or an equivalent surface circular foundation in three-dimensional (3D) FE analyses without modeling the embedment of the foundation (Tani and Craig, 1995; Bransby and Randolph, 1998). A few numerical studies have performed 3D FE analyses on bucket foundations for wind turbines (Zhan and Liu, 2010), and suction anchor cases (Sukumaran et al., 1999; Monajemi and Razak, 2009). The bearing capacity of the bucket foundation is significantly affected by the skirt embedment depth or 3D shape. Deeper embedment of the bucket foundation induces more vertical and horizontal capacities attributable to the mobilization of the side friction and the lateral resistance along the skirt. A 3D geometry of the foundation should be modeled to consider the shape effect and the soil–bucket interaction.

In addition, previous design equations have been developed based on numerical results, which have the aforementioned limitations. Therefore, the development of design equations based on accurate numerical results, which consider 3D soil-structure interactions and the exact shape of the bucket foundation is necessary.

In the present study, a series of 3D FE analyses were performed to evaluate the effect of the aspect ratios of the bucket foundation, L/D, where L is the skirt length and D is foundation diameter, on the vertical (V_0) and horizontal (H_0) bearing capacities of bucket foundations for wind turbines. The L/D ratio is usually less than 1.0, as shown in Fig. 1. The soil condition was assumed to be normally consolidated uniform clay. The vertical and the horizontal loadings were applied, and the effect of the L/D ratio on the capacity was carefully analyzed. Simple design equations were developed based on the results of the analyses to evaluate vertical and horizontal capacities.

2. Numerical modeling

For a short-term stability problem of saturated clays, the undrained condition can reasonably be assumed to carry out total stress analyses (Tani and Craig, 1995). Therefore, the soil in the present study was modeled as a linear elastic-perfectly plastic

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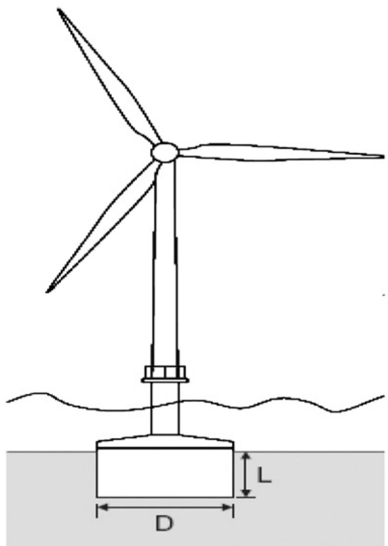

Fig. 1. Bucket foundation for wind turbines (after Houlsby et al., 2005).

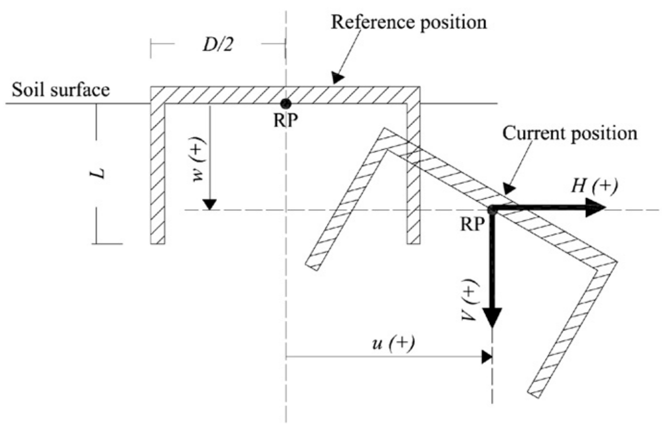

Fig. 2. Bucket foundation geometry and sign convention for loads and displacements (modified after Villalobos et al., 2010).

model based on the Tresca failure criterion ($\phi=0^\circ$ condition). The uniform undrained shear strength of the clay (S_u) was assumed to be 5 kPa with a Young's modulus (E_u) at $400\times S_u$. A Poisson's ratio of $v=0.495$ was applied to simulate the constant volume response of clay under undrained conditions (Yun and Bransby, 2007b; Taiebat and Carter, 2000). The effective unit weight of soil at $\gamma'=6$ kN/m^3, was applied. The bucket foundation had a Young's modulus of $E=E_u\times 10^9$ and was thus considered rigid. The interface between the foundation and the soil was assumed to be rough, and the detachment between the bucket foundation and the soil was prevented (Bransby and Yun, 2009).

All FE analyses were conducted using the ABAQUS software (Simulia, 2010). The first-order, eight-node linear brick, reduced integration continuum with hybrid formulation element C3D8RH was used to model the soil.

Fig. 2 shows the definition of the bucket foundation geometry and the sign convention adopted in the present study. Loading was applied using the displacement-controlled method, which increases vertical (w) and horizontal (u) displacements at a reference point (RP). In addition, this method is more suitable than the stress-controlled method in obtaining failure load (Bransby and Randolph, 1997; Gourvenec and Randolph, 2003).

Fig. 3 exhibits a typical mesh used in the present study. Displacements at the bottom boundary were fully fixed for the x, y, and z

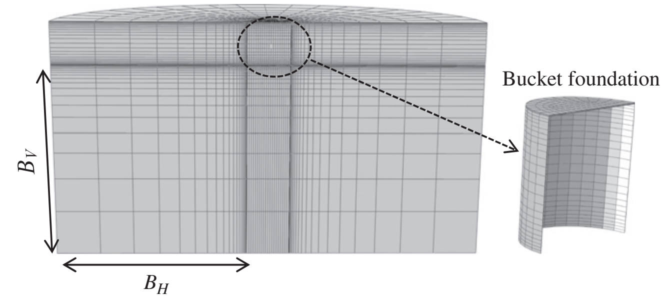

Fig. 3. Definition of boundary extensions and a typical mesh for bucket foundations.

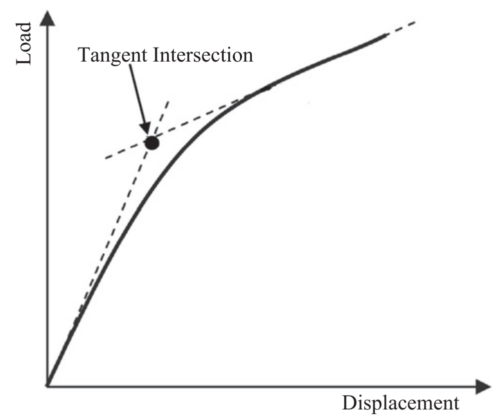

Fig. 4. Tangent intersection method for determining bearing capacity (modified after Mosallanezhad et al., 2008).

directions. Normal displacements at the lateral boundaries were constrained. By applying symmetric conditions, half of the entire system was modeled. The size of the soil elements increased gradually from the bucket foundation to the domain boundary. B_V and B_H are the vertical and horizontal boundary extents from the skirt tip and the side of the bucket foundation, respectively. The bearing capacities gradually decreased as B_H/D or B_V/D increased and became constant at $B_H/D=4.5$ and $B_V/D=4.5$, which were applied for subsequent analyses.

The bearing behavior of the bucket foundation was investigated in terms of normalized bearing capacities $V_0/(A\cdot S_u)$ and $H_0/(A\cdot S_u)$, where V_0 and H_0 are the vertical and horizontal bearing capacities respectively, and A is the cross-sectional area of the bucket. The bearing capacities V_0 and H_0 were determined using the tangent intersection method (Mansur and Kaufman, 1956), as shown in Fig. 4. The method plots two tangential lines along the initial and later portions of the load-displacement curve, and the load corresponding to the intersection point of these two lines is taken as the bearing capacity.

The aspect ratio of the bucket foundation (L/D ratio) varied at 0.1, 0.2, 0.25, 0.3, 0.5, 0.6, 0.75, 0.85, and 1.0. The skirt thickness $t_{skirt}=0.004D$ and top plate thickness $t_{plate}=0.01D$ were applied. Preliminary analyses confirmed that the bucket foundation diameter D had no effect on the normalized bearing capacities. Hence, D was kept at 10 m.

3. Analysis results

3.1. Vertical bearing behavior of the bucket foundations

Fig. 5 presents the normalized vertical load-displacement curves and the vertical capacity of the bucket foundations