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Analysis of laterally loaded bucket foundation with external skirt in sand using a Winkler model approach

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ABSTRACT

An investigation is made to present analytical solutions provided by a Winkler model approach for analysis of a bucket foundation with external skirt subjected to lateral loads in sand. The bucket foundation with external skirt consists of an internal compartment and an external short skirted compartment. The lateral stiffness coefficient along the skirt of the bucket foundation in nonhomogeneous soils employing the Mindlin solution for lateral loads is presented. The relationship between horizontal displacement, rotation, moment and shear force of the bucket foundation subjected to lateral loads in nonhomogeneous soils is obtainable in the form of the recurrence equation. The vertical, lateral and rocking stiffness coefficients on the base of the bucket foundation are presented considering the solutions of a hollow rigid cylindrical punch acting on the surface of a soil. An envelope of the combined ultimate horizontal and moment load capacities of the bucket foundation in sand is shown. The relationship between ultimate lateral and moment load capacities and aspect ratios (internal and external skirt-lengths to diameter) is presented. Behavior of the bucket foundation with external skirt in sand up to failure is clarified from the relationship between lateral loads and displacement and that between depth and lateral pressure.

1. Introduction

For designs and analyses of bucket foundations under vertical and lateral loads, an attention has been recently concentrated on not only the ultimate capacity but also the deformation and stiffness of a bucket foundation. A bucket foundation with an external skirt, which will be called “a modified bucket foundation” for brevity, combines an internal compartment with an external short skirted compartment. Recently, the modified bucket foundation has been developed in order to increase the lateral ultimate capacity and decrease the rotation. Particularly, in order to avoid resonances in the structure produced by winds and waves, special attention has been focused on the stiffness of the modified bucket foundation.

Parametric analyses of such short piles as bucket foundations have been performed for a variety of practical cases and most of them are related to homogeneous soils. The integral equation method or the boundary element method (BEM) given by Banerjee and Davies (1977, 1978) and Banerjee (1978) has been used to provide the numerical computer-based solutions for circular piles in nonhomogeneous soils. Poulos (1979), Poulos and Davis (1980), Chow (1987), Zhang and Small (2000), Small and Zhang (2002) and Kitiyodom and Matsumoto (2003) presented the solutions of circular pile foundations in nonhomogeneous soils, using the numerical methods such as the finite element method (FEM) and BEM and the simplified analytical approaches.

The rigorous analytical approach ensures the boundary, continuity and compatibility conditions of the displacement, stress, force, rotation and moment for short piles such as bucket foundations and half-space. Apirathvorakij and Karasudhi (1980) investigated a rigorous analytical approach for the quasi-static bending of a circular pile embedded in a saturated porous half-space. Selvadurai and Rajapakse (1985) studied a rigorous analytical method related to the axial, lateral and rotational loadings of a rigid cylindrical inclusion embedded in an isotropic elastic half-space. Rajapakse and Shah (1987a, 1987b, 1989) presented a rigorous analytical method to solve an elastic circular bar embedded in an elastic half-space subjected to longitudinal, lateral and rotational loads.

It is assumed in a less rigorous analysis for a laterally loaded bucket foundation that the bucket foundation and soil each have one displacement component in the horizontal direction. A less rigorous approach was presented by Spillers and Stoll (1964) to investigate the behavior of laterally loaded piles under static loading. Poulos and Davis (1980) and Poulos (1971a, 1971b, 1972) employed a finite difference method to analyze the behavior of vertically and laterally loaded single circular piles and pile groups. Randolph (1981) presented that the effect of

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variations in Poisson's ratio on the deformation of a laterally loaded pile could be adequately represented by considering a parameter which is a modified shear modulus taking into account Poisson's ratio. Using the variational calculus, Sun (1994) presented a numerical approach and parametric study for the calculation of soil and pile interaction under lateral loading. Guo and Lee (2001) investigated the response of laterally loaded circular piles in homogeneous soil using the modified shear modulus proposed by Randolph (1981) and the simplified stress field. Using the variational approach and the modified shear modulus proposed by Randolph (1981), Basu and Salgado (2008) investigated the effect of Poisson's ratio on the deformation of a laterally loaded rectangular pile in layered soil. Because the method proposed by Guo and Lee (2001) and Basu and Salgado (2008) incorporates the effect of Poisson's ratio into the expression for the modified shear modulus, it may be necessary that the effect of Poisson's ratio and that of the original shear modulus on the horizontal deflection are investigated separately to evaluate each effect on the lateral behavior directly. Douglas and Davis (1964) presented an analytical method for the rectangular rigid plate subjected to horizontal loads in homogeneous soil. To analyze the behavior of circular piles subjected to lateral loads, Elahi et al. (2010) and Liyanapathirana and Poulos (2010) proposed Winkler type methods where the modulus of subgrade-reaction of the Winkler model is evaluated by integration of Mindlin's equation given by Douglas and Davis (1964). Baguelin et al. (1977) investigated the lateral reaction mechanism of piles to provide the modulus of subgrade-reaction in an elastic medium. As a less rigorous approach for a pile with circular cross section in nonhomogeneous soil, Hirai (2012, 2017a) presented an analytical approach based on the elastic continuum analysis using a Winkler model.

For the prediction of the behavior of laterally loaded piles with the complicated geometry such as wings, fins or rectangular cross sections as well as a bucket foundation, analytical and numerical approaches have been developed. Dührkop and Grabe (2009) presented the method to calculate the laterally loaded piles with bulge which improves the lateral bearing capacity of foundations. Peng et al. (2010) showed a nonlinear 3-D analysis of laterally loaded fin piles using the finite element analysis (FEA). Peng et al. (2011) investigated the effect of the length of fins upon the lateral behavior of cyclically loaded piles through small-scale experiments. Bienen et al. (2012a,b) presented the response of piles with wings to reduce pile head deflection under monotonic and cyclic lateral loadings. Lehane et al. (2014) investigated the benefits of combining a footing with a monopile to improve the resistance of pile foundation. For laterally loaded finned piles, Nasr (2014) performed the model experiments and 3-D FEA to improve the lateral bearing capacity of piles. Hirai (2015) investigated a Winkler model based on the two lateral soil displacement components in a three dimensional soil to provide analytical solutions of horizontal response of a rectangular pile subjected to lateral loads in nonhomogeneous soil.

Bucket foundations in offshore wind turbine structures have been investigated because of its potential cost-effectiveness and its advantages for environmental issues. Bucket foundations used in offshore wind turbine structures are exposed to heavy moment (M) and lateral (H) loads, but relatively low vertical (V) loads. Much research has been carried out to provide mainly the various forms of yield and failure envelopes in a three-dimensional space of V, H and M (Watson and Randolph, 1998; Bransby and Randolph, 1998, 1999; Taiebat and Carter, 2000; Gourvenec and Randolph, 2003; Houlsby et al., 2005; Yun and Bransby, 2007; Gourvenec, 2008; Bransby and Yun, 2009; Gourvenec and Barnett, 2011). These approaches have been focused on predicting the capacity of foundations subjected to combined loads, and a few approaches have been used to predict behaviour before failure. Villalobos et al. (2009) carried out the experiments on dry sand and investigated the pre-failure behaviour using a work hardening plasticity theory. Hung and Kim (2012) presented the vertical and lateral behavior before failure by use of the 3-D FEM for bucket foundations in normally consolidated uniform clay under undrained conditions and showed the effect of the aspect ratio on ultimate capacities V and H of the bucket foundation. Achmus et al. (2013) investigated the relationships between load and deformation of a bucket foundation in sand by means of the three-dimensional FEM and showed the ultimate capacities interaction diagrams of V, H and M of the bucket foundation. Ibsen et al. (2014a,b) carried out an extensive test program of dense saturated sand subjected to combined loads and investigated the behaviour of a bucket foundation using a plasticity hardening model that is capable of describing the entire behavior of sand. Bienen et al. (2012a,b) presented the combined vertical, horizontal and moment capacities envelopes for a modified bucket foundation in clay by using the FEA. Li et al. (2015) conducted experiments and the FEA of a modified bucket foundation in sand and presented the effect of internal and external skirt lengths on ultimate load capacities.

An evaluation of pullout load capacity of a bucket foundation in sand has been made by Hirai (2017b) using a three-dimensional displacement approach (3DDA) for results of a small-scale model test regarding sand. For results of a prototype scale regarding clay, an assessment of pullout load capacity of a bucket foundation in clay has been carried out through 3DDA (Hirai, 2017c). Therefore, the present approach using 3DDA is capable of predicting the response of a bucket foundation for a prototype scale as well as a small-scale model test.

In the following presentation, for a modified bucket foundation in a nonhomogeneous soil, an investigation is made to propose analytical solutions for lateral loads. First, the lateral stiffness coefficient along the skirt of the modified bucket foundation in a nonhomogeneous soil employing the Mindlin (1936) solution for a lateral load is presented. Second, the relationship between horizontal displacement, rotation, moment and shear force of the modified bucket foundation subjected to lateral loads in a nonhomogeneous soil is obtainable in the form of the recurrence equation. Third, the vertical, lateral and rocking stiffness coefficients on the base of the modified bucket foundation are presented considering the solutions of a hollow rigid cylindrical punch acting on the surface of a soil and the equivalent elastic modulus in the equivalent elastic method (Hirai, 2008). Fourth, the vertical stress of a soil underneath the base of the modified bucket foundation subjected to vertical and moment loads is presented considering only compression and permitting no tension on the base. Fifth, an envelope of the combined ultimate horizontal and moment load capacities of the modified bucket foundation in sand is investigated. For the relationships between ultimate lateral and moment load capacities and aspect ratios (internal and external skirt-lengths to diameter), comparison of the results calculated by the present method for the modified bucket foundations in sand is made between those obtained from experiments. Behavior of sand up to failure is investigated through the relationship between lateral loads, strain and displacement and that between depth and lateral pressure.

2. Formulation of lateral responses of modified bucket foundation

In order to obtain a solution for the values of vertical and horizontal pressures along a modified bucket foundation and vertical and horizontal displacements of the modified bucket foundation, it is necessary to give expressions for vertical and lateral displacements of the modified bucket foundation and the soil at each element in terms of the unknown vertical and lateral pressures on the modified bucket foundation.

Fig. 1(a) shows a modified bucket foundation subjected to a vertical load V, lateral load H and moment load M on a lid of the modified bucket foundation in a nonhomogeneous soil. The present procedure uses the elastic moduli of Young's modulus E_{Sm} and Poisson's ratio ν_{Sm} and the length H_{Sm} of the mth layer in the n layers comprising the lid and nonhomogeneous soil, where $m = 1$-n and mb denotes the mb-th soil layer beneath the base of the modified bucket foundation; L and d_B are the length from a soil surface and the diameter of the internal compartment respectively; L_S and d_L are the length from the soil surface and the diameter of the external compartment; and t_L and t_S are the thickness of the lid and that of both the internal and external skirts for the modified bucket foundation respectively.