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Investigation of the load-bearing capacity of suction caissons used for offshore wind turbines

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ABSTRACT

This paper presents the results of three-dimensional finite element analyses of the suction bucket foundation used for offshore wind turbines. The behavior of the bucket and the response of soil supporting the bucket in dense and medium dense sandy soils subjected to static horizontal load are investigated. Field tests results and a centrifuge model test are used to validate the numerical model. Dimensionless horizontal load-displacement and overturning moment-rotation relationships are derived utilizing the Power law and Buckingham's theorem. The results show good agreement between the numerical analysis results and the straight lines obtained from the Power law until a specific value of horizontal load and overturning moment. Regarding stress behavior of soil supporting the bucket, due to soil densification and bucket movement, maximum stresses are seen near the bucket tip at the right inside of the bucket. The major part of the applied load is transferred by the bucket skirt. Numerical analysis modeling results show that the bucket rotation and displacement are highly dependent on the bucket geometry and soil properties in addition to loading conditions. Normalized equations and figures for the ultimate horizontal load and overturning-moment capacities are presented and can be used for the preliminary design of the bucket foundations in sandy soils.

1. Introduction

Due to the high demand for energy, the use of environmentally-friendly sources of energy, such as wind energy, has been increasing. As the installation of wind turbines has risen, the use of land-based turbines has steadily shifted towards the use of offshore ones. This tendency has substantially increased from a decade ago, as seen in Europe, where almost 90% of all new wind farms in 2012 were installed in offshore areas [1]. The size of wind turbines is also increasing with the increase in the demand for wind energy. The larger wind turbine size, the more stress there will be on the whole structure, particularly on the foundation. Because of the cost effectiveness and easy installation, suction buckets are considered a promising alternative for the foundation of offshore wind turbines. A wide-range of investigations and research have verified that the bucket foundation is practical for various soil conditions at water depths from near-shore to approximately 40 m [2]. Hence, suction bucket foundations may be applied to offshore wind turbines. Employment of the bucket foundation may reduce the steel weight by half; the installation of the bucket foundation is much easier and does not need heavy installation equipment in comparison with a traditional monopile solution. A suction caisson is a capped top cylindrical steel plate with a severely stiffened steel lid that is moved down into marine sediment and permitted to embed in seafloor layers under its own weight first before being pressed to the full depth with negative pressure created by suction. A general schematic sketch of a typical offshore wind turbine with suction bucket foundation is presented in Fig. 1.

Use of the suction bucket as an alternative to conventional gravity platform foundations and monopiles has been studied for the last ten years [3–8]. Traditionally bucket foundations have been widely used in the oil industry for platforms and jacket structures [9,10]. The loading conditions are quite different in the wind turbine structure. Unlike oil and gas platforms, suction buckets for wind turbine foundations are subjected to a substantial lateral load and overturning moment, with moderately low vertical loads.

During the last decade, a number of laboratory experimental studies and field tests were carried out for both monotonic and cyclic response of bucket foundations in clay [11–13] and sand [14–22].

Bryne and Houlsby [23] studied the response of bucket foundations under the combination of horizontal, vertical and moment loads for both cyclic and monotonic loading conditions by carrying out a series of small-scale laboratory model tests. They found

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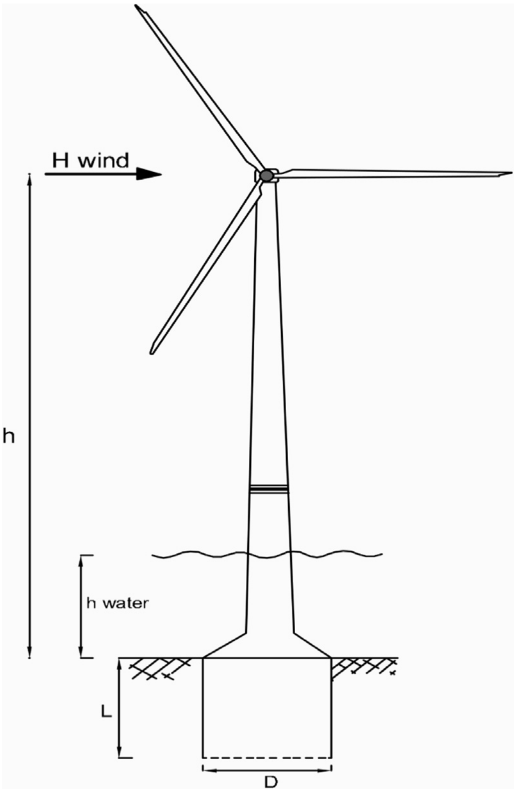

Fig. 1. A general schematic sketch of a typical offshore wind turbine with suction bucket foundation.

a small effect on the load-displacement response using various rates of loading. High correlation between the bucket response and vertical loading conditions was reported. For clay and sandy soil, Houlsby et al. [11] and Houlsby et al. [14] performed field tests on a model foundation to predict the cyclic response of the bucket foundation under horizontal and vertical loads. Kelly et al. [22] evaluated the bucket foundation behavior under a cyclic moment and vertical loads by executing a laboratory model and field model tests; a comparison of the results was also accomplished. By using small-scale experiments, Villalobos et al. [23] investigated combined load tests on the model of suction caissons in dry sand with low relative density. They presented moment–horizontal load interaction diagrams using hardening plasticity theory obtained from the load–displacement curves. Villalobos et al. [19] studied the effect of installation on the moment capacities for suction buckets by performing small-scale experiments in dense sand. They discovered that the installation method does not have any impact on the horizontal and rotational plastic ratio, while more vertical uplift displacement was seen in the case of the pushed installed method than suction installed. Zhu et al. [24] conducted large-scale model tests to estimate bucket horizontal load capacity with suction installation with regard to different load eccentricities in silty soil. They found that the rotation center of the bucket at failure is at a depth of around four-fifths of the skirt length, almost directly below the lid center.

A few numerical analysis based studies were carried out to determine the bearing capacity of suction caissons as the offshore wind turbine foundation. Zhang et al. [25] used an upper bound limit method to predict the bucket load capacity. Using centrifuge tests, they presented the capability of this method for estimating load capacity. For embedment ratios of 0.5 to 2.5, Deng et al. [26] performed numerical analysis on the horizontal load capacity of suction caissons in cohesive and non-dilating soils. Using finite element methods, Achmus et al. [27] investigated the horizontal and moment load capacity of the bucket foundation in sandy soil.

Despite all the above studies regarding the load and bearing capacity behavior of suction caissons used for offshore wind turbines, there is sparse design guidance for such types of foundations, which principally are based on small-scale experiments. It is not yet entirely known how suction caissons behave under various loading conditions considering soil properties and bucket dimensions. This highlights the need to examine thoroughly the bearing behavior of bucket foundations by utilizing the finite element method (FEM).

The finite element method can present general results by simulating physical modeling with various conditions. Additionally, the instantaneous computation and graphical illustration of a wide range of physical parameters, such as model dimensions and stress behavior, enables the designer to quickly analyze performance and possible modifications. The finite element method can be used as an influential implement to handle various complicated geotechnical issues and is utilized in this study to evaluate the bearing behavior of suction bucket foundations for dense and medium dense sand under monotonic loading. Although in the current practice of foundation design, dynamic and cyclic loads are dealt with either by equivalent static loads, i.e., a pseudo-static approach, or rigorously with time history, i.e., a dynamic approach, the focus of this study was on the evaluation of the static loading conditions. However, by assessing the ultimate horizontal loading and overturning moment, other loading conditions, such as cyclic loading, were also covered. Considering loading circumstances, bucket dimension and soil physical properties, a parametric study was conducted. Further investigation using the Power law was carried out to study the bucket response consisting of bucket displacement and rotation subjected to a static load in addition to the behavior of the soil supporting the bucket. The dimensionless form of equations was also developed for preliminary design equations and curves by considering various aspects that might influence the bucket behavior.

2. Numerical modeling

A 3D finite element model of a suction caisson was simulated to assess the bucket behavior in addition to soil supporting the bucket considering different loading conditions and bucket dimensions. The finite element program Plaxis 3D [28] software was used for simulation modeling. Taking advantage of the symmetrical nature of the problem, only one-half of the suction caisson was considered for modeling. Ten-node tetrahedral elements were utilized for modeling of soil volume. In this type of element, a second-order interpolation of displacements is provided. Additionally, six-node triangular plate elements with five degrees of freedom per node in the rotated coordinate system were employed to simulate the bucket foundation. Interface elements were utilized at caisson-soil interfaces. For modeling of the constitutive behavior of the soil and interface, the elastic perfectly plastic stress-strain relationship and Mohr-Coulomb failure criterion was used. To achieve adequate precision of the outcomes and abstain from the boundary condition effect, mesh convergence and boundary domain analysis were carried out. Regarding convergence study and physical boundary domain, the size of the soil elements was gradually decreased to obtain the optimum mesh fineness and boundary domain.

Fig. 2 shows a three-dimensional view of the numerical model with geometrical properties. As shown, 6 and 3 times the bucket diameter were chosen, respectively, as the length and width of the model. In addition, a depth of 2 times the bucket skirt was considered as the depth of soil under the bucket tip. To achieve more accurate results, soil volume of 3 times the bucket diameter and 2 times the bucket skirt length was also considered with smaller local mesh.