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Load-bearing behavior of suction bucket foundations in sand

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ABSTRACT

Suction buckets are a promising foundation solution for offshore wind energy systems. The bearing behavior of monopod buckets under drained monotonic loading in very dense and medium dense sand is investigated in this study by means of numerical simulation with the finite element method. Special focus is given to the ultimate capacity and the initial stiffness of the bucket-soil foundation system. The numerical model is validated by comparison with field test results. The bearing behavior of the structure is explained through an evaluation of a reference system. It is shown that the bucket experiences a heave during horizontal loading, which leads to the formation of a gap between the bucket lid and the soil with increasing load. At large loads and rotations close to failure of the system there is no contact between lid and soil, and the whole load is transferred to the soil via the bucket skirt. A parametric study shows how the ultimate capacity and initial stiffness of the system depend on the bucket dimensions and loading conditions, i.e. load eccentricity. Normalized equations for ultimate capacity and initial stiffness are derived from the numerical simulation results, which can be used in the scope of a preliminary design for buckets in sand.

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1. Introduction

The increasing importance of renewable energy in Germany during the last decades stimulated the planning studies of offshore wind energy converters (OWECs) in the North and Baltic Seas. OWECs require specific foundations due to special loading conditions. The technical and economical appropriateness of each type of OWEC foundation is a current topic still being investigated. Selecting the suitable foundation type and dimensioning are essential challenges for offshore wind farms. Byrne and Houlsby [1] stated that a critical component of the design will be the foundation of OWECs.

In this respect, the suction bucket foundation is a relatively novel design concept for OWECs which seems to be favorable due to its potential cost-effectiveness and its advantages regarding environmental issues. A bucket structure consists of a steel cylinder with diameter D, skirt length L and skirt thickness t_S, closed by a generally heavily stiffened upper steel lid. A general view of a typical OWEC with a monopod bucket foundation is illustrated in Fig. 1.

Originally, the suction-installed skirted foundation system was developed for floating offshore platforms in the oil and gas industry. Suction bucket foundations for fixed OWEC structures, however, have very different loading conditions from those of floating offshore platforms which must be considered. OWEC foundations are exposed to heavy moment (M) and lateral (H), but relatively low vertical (V) loads. Byrne [2] and Feld [3] first investigated the application of buckets as wind energy foundations, while Byrne and Houlsby [1] as well as Ibsen et al. [4] presented status reports on that topic. They denoted that there is a considerable uncertainty of the performance of suction bucket foundations for offshore wind farms under the aforementioned combined loading (V, H, M) conditions.

A few laboratory model tests [5,6], field tests [7–11] and numerical analysis based studies [12] were performed to predict the loading response and the loading capacity of suction bucket foundations in sand.

Villalobos et al. [5] carried out small-scale experiments on model buckets with L/D-ratios of 0.5 and 1.0 in loose dry sand. General loading conditions were examined, including also tensile vertical loads. Villalobos et al. defined a yield point from the load–deformation curves and derived moment–horizontal load interaction diagrams for this yield state.

In [6], Villalobos et al. also presented model scale tests with buckets in dense, saturated sand under moment loading. They proposed a yield surface equation similar to that given in [5]. One focus of the investigation was the effect of the installation process on the bucket behavior. It was found that installation by suction leads to considerably smaller capacities than installation by pushing.

Results of field tests with buckets in sand under horizontal loading are presented in [4,7–9]. These tests are used here for the validation of the numerical model and are described in detail in Section 3. Some field tests are also reported in [10,11].

Abdel-Rahman and Achmus [12] presented results of numerical simulations regarding bucket foundations in medium dense sand. Load–deformation curves of bucket foundations under monotonic horizontal loading were calculated for two different bucket geometries and were compared with load–deformation curves of monopile

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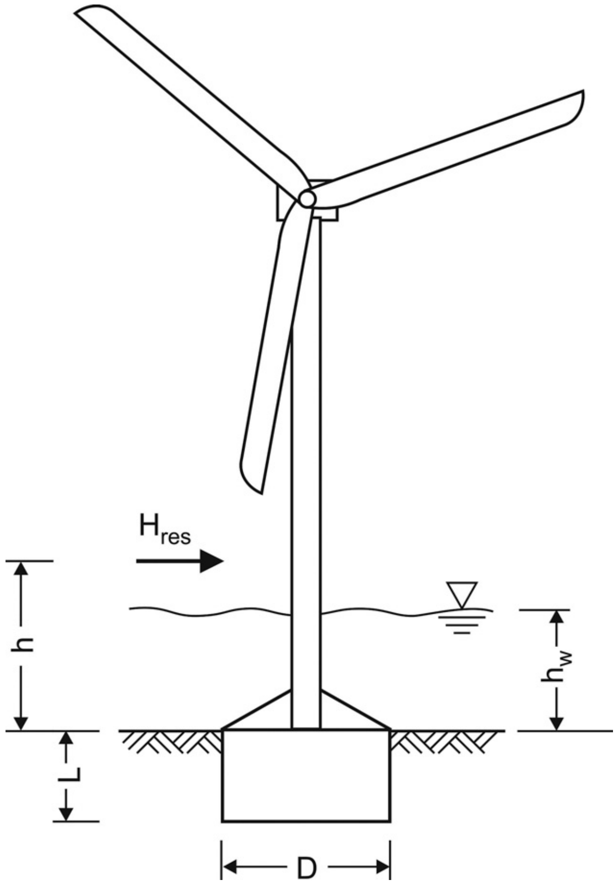

Fig. 1. Schematic sketch of an offshore wind energy converter with a monopod suction bucket foundation.

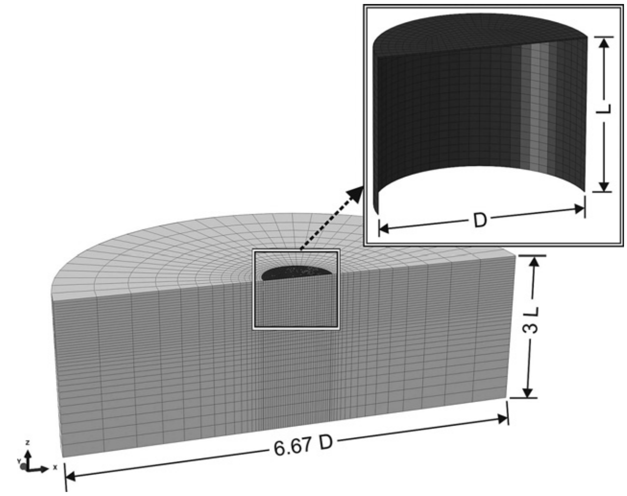

Fig. 2. Finite element model of a suction bucket foundation system.

Table 1
Soil parameters for very dense and medium dense sand.

	Sand, very dense	Sand, medium dense
Buoyant unit weight γ'	11.0 kN/m^3	9.0 kN/m^3
Oedometric stiffness parameter κ	600 [–]	400 [–]
Oedometric stiffness parameter λ	0.55 [–]	0.60 [–]
Poisson's ratio ν	0.25 [–]	0.25 [–]
Internal friction angle φ'	40.0°	35.0°
Dilation angle ψ	10.0°	5.0°
Cohesion c'	0.1 kN/m^2	0.1 kN/m^2

foundations. For the considered systems, it was found that the suction buckets behaved stiffer than the monopiles under small loads but had smaller ultimate capacities.

Zhang et al. [13] investigated the load capacity of bucket foundations and developed an upper bound limit method for prediction. Using centrifuge tests for comparison, they showed that the method is capable of reasonably estimating the load capacity.

Although the behavior and ultimate capacity of suction bucket foundations in cohesionless soil for offshore wind energy systems has been studied as mentioned above, there are only a few design recommendations available, which mainly base on model tests and need further evaluation. It is not yet totally clarified how the bearing behavior and the capacity depend on bucket geometry, loading conditions and soil properties.

The finite element method (FEM) is considered a powerful tool for dealing with these kinds of complex geotechnical problems and is used here to investigate the effect of system and loading parameters on the bearing-behavior of buckets under drained, monotonic loading in sand.

2. Finite element model

In this study, a three-dimensional finite element (FE) model of a monopod bucket foundation system was developed and utilized in the scope of a parametric study. The finite element program Abaqus Version (6.12) [14] was used in the simulations. Considering the symmetry of both geometrical and loading conditions, only one half of the bucket foundation was modeled in order to reduce computational effort. Eight-node volume C3D8-elements were used to mesh both the bucket structure and the soil. Preliminary analyses were carried out for the determination of mesh fineness and model dimensions in order to reach sufficient accuracy of the results and avoid the influence of boundary conditions. Consequently, a soil model diameter of 6.67 times of the bucket diameter (i.e. 80 m for the reference system) and a depth of the soil under the bucket of two times the bucket skirt length was chosen. An exemplary mesh of the finite element model with geometrical properties is presented in Fig. 2.

Displacements were fixed at the model boundaries as follows: in all directions at the bottom, in both horizontal directions on the periphery and in normal direction on the symmetry plane. Since relatively large deflections can occur during lateral loading, geometric non-linearity was considered, i.e. the coordinates of the element nodes were corrected during the loading steps with respect to the current deformations.

An elasto-plastic material law using Mohr–Coulomb failure criterion was utilized for the simulation of soil behavior. The stress-dependent oedometric modulus of elasticity, E_s, was implemented in order to simulate the non-linear soil response accurately (Eq. (1)):

$$E_s = \kappa \cdot \sigma_{at} \cdot \left(\frac{\sigma_m}{\sigma_{at}}\right)^{\lambda} \tag{1}$$

Here $\sigma_{at} = 100$ kN/m^2 is reference stress; κ determines the soil stiffness at the reference stress state; λ rules the stress dependency of the soil stiffness and σ_m is the mean principal stress. Oedometric stiffness parameters κ and λ were selected considering the bandwidths given in the EAU recommendation [15]. Soil parameters for very dense and medium dense sand used in the model are given in Table 1.

This material law was also used for investigations on the behavior of monopiles [16,17], which showed its capability to realistically simulate the system behavior under monotonic loading.

In the modeling of the steel bucket, a skirt thickness of $t_s = 0.03$

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