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On the behavior of suction buckets in sand under tensile loads

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ABSTRACT

Suction buckets can be used instead of driven piles for the support of jacket or tripod foundations for offshore wind energy converters (OWECs). However, due to the relatively small self weight of offshore wind structures, considerable tensile loads can occur for instance during storms; these loads usually govern the dimensioning of the buckets. Under rapid tensile loading, suction pressures are induced inside the bucket, which can considerably increase the tensile capacity. This paper presents results of numerical simulations based on a coupled pore fluid diffusion and stress analysis which allow for the description of the partly drained load-bearing behavior as well as the quantification of the tensile resistance. It is shown that a high pull-out rate leads to a large increase of the tensile capacity. The maximum capacity is reached when the soil behaves fully undrained or when cavitation of the pore water occurs. In this regard, the main influence parameters are the bucket geometry, the soil permeability, the pull-out rate (loading rate) and, regarding cavitation, also the water depth. It is shown that the mobilization of suction pressures requires a large heave of the bucket, which might be inadmissible with respect to serviceability requirements. Simulations in which variable tension loads are applied with a specific loading rate and then kept constant are also presented. It is found that an accumulation of heave over time occurs when the load exceeds the drained capacity of a bucket. This indicates that cyclic loading of buckets with tensile loads often exceeding the drained capacity might lead to excessive heave.

1. Introduction

Within the next decades, according to the plans of the governments of the European coastal states, an enormous number of offshore wind energy converters (OWECs) shall be erected in the North- and Baltic Seas [1]. Choosing a suitable OWEC foundation type as well as determining the foundation dimensions are great challenges for geotechnical engineers, especially due to very limited experience with the special loading conditions resulting from wind and waves in combination with relatively small self weight of the OWEC structure. In addition to the technical requirements on the foundation further aspects (e.g. logistic and environmental specifications) have to be taken into account. In Germany, restrictions regarding noise emission during the installation of driven piles is an important issue. This restriction will become more important and could severely affect the construction process when several adjacent wind farms are scheduled to be installed at the same time. Therefore, affordable foundation solutions that do not need pile driving are sought.

In this respect, the use of suction buckets instead of driven piles is a promising foundation concept for OWECs, due to its relatively simple installation process and reduced noise emission. Here a steel cylinder with a steel lid on top is penetrated to the ground by pumping water out of the cavity between the bucket lid and the soil thereby generating a suction pressure. Two foundation concepts using suction buckets have to be discerned. Single buckets (monopods) are predominantly loaded by horizontal forces (H) and bending moments (M) [2]. For latticed structures (e.g. tripod, jacket) on several buckets (multipod), the loading of the buckets is predominantly vertical (V). Fig. 1 shows a schematic sketch of an OWEC on a jacket with a multipod suction bucket foundation. The three or four buckets with each skirt length L and diameter D are placed with the greatest feasible distance to each other in order to minimize the change in vertical loading associated with the push–pull mechanism caused by moment loading. For sandy soils, the ratio of L/D is probably in a range between 0.5 and 1.0. Large ratios of L/D are favorable in particular with respect to the drained tensile capacity. However, the skirt length is limited by restrictions from the installation process, as the penetration resistance strongly increases with embedded depth and the mobilizable suction pressure is limited by the restriction due to a potential hydraulic soil failure [3].

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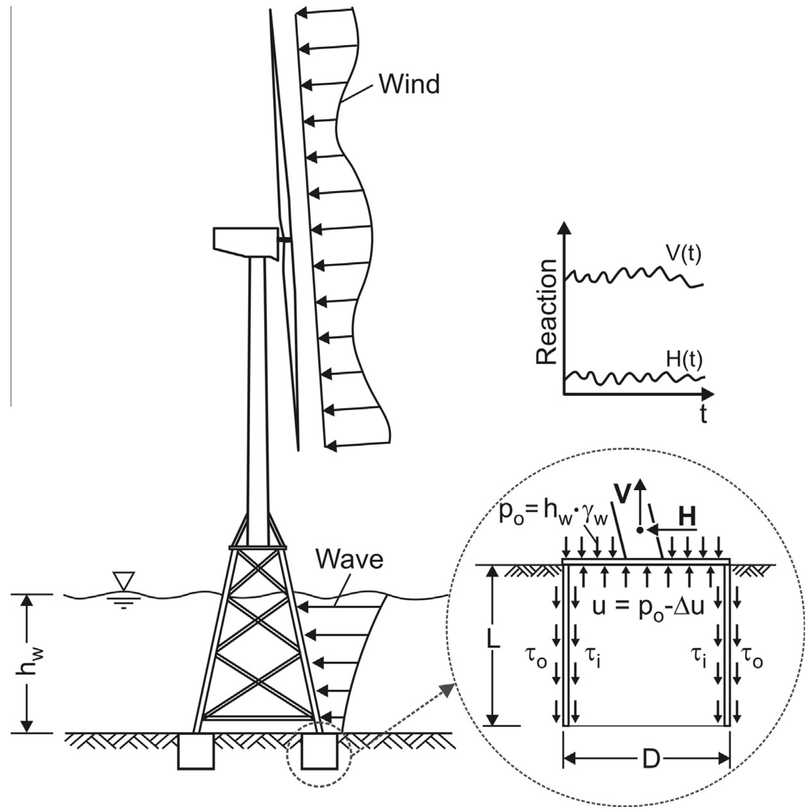

Fig. 1. Schematic sketch of an OWEC on a jacket resting on suction buckets (multipod foundation).

Due to the relatively small self weight of an OWEC structure, at least under storm conditions, considerable tensile loads can act on the single buckets. Therefore, with regards to the bucket dimensions, tensile loading will typically be the most unfavorable load case, and the tensile capacity of a single bucket is thus a crucial design aspect.

For perfectly drained conditions, the tensile resistance of the bucket results from the self weight of the bucket and from skin friction on the inner (τ_i) and outer (τ_o) skirt perimeter. During uplift a gap occurs between the bucket lid and the soil surface. For perfectly undrained conditions, suction pressures prevent the formation of a gap. Consequently this leads to a heave of the whole soil plug inside the bucket. Connected with the occurrence of suction, the soil around the bucket is also affected and shear resistance is mobilized in the surrounding soil. Senders [4] termed this undrained behavior 'reverse end bearing' (cf. Fig. 2). The resistance for undrained conditions is much larger than that for drained conditions which Senders denoted as 'frictional'. For partly drained conditions, the behavior is in between these basic conditions ("intermediate"). Whether drained, partly drained or undrained behavior occurs certainly depends on the combination of bucket geometry, pull-out rate and permeability of the soil.

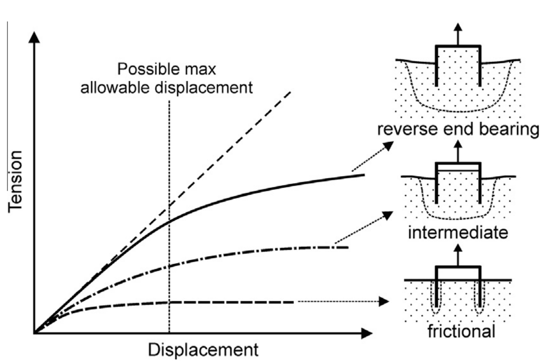

Fig. 2. Failure mechanisms according to Senders [4].

It should also be noted that the pore pressure u beneath the bucket lid (cf. Fig. 1) is limited by the cavitation pressure, which amounts to about $u = u_c = -100\ \text{kN/m}^2$ since the average atmospheric pressure is about $100\ \text{kN/m}^2$. The maximum possible suction $\Delta u = \Delta u_{max}$ is therefore dependent on the hydrostatic water pressure p_o which is the product of water depth h_w and the specific density of water $\gamma_w \approx 10\ \text{kN/m}^3$ (cf. Eq. (1)).

$$\Delta u < -u_c + \gamma_w \cdot h_w = 100\,\frac{\text{kN}}{\text{m}^2} + 10\,\frac{\text{kN}}{\text{m}^3} \cdot h_w \qquad (1)$$

It is still under discussion if an additional tensile resistance resulting from the suction pressure inside the bucket can be taken into account in the design of buckets for OWEC foundations. Although model and field tests presented in several publications (see Section 2) indicate that a significant increase of the bucket capacity is to be expected, it was also found that, depending on the loading rate and duration, a large heave can be necessary in order to mobilize a significant portion of the additional resistance. In consequence, the main challenge in the design of this foundation type will be to avoid exceeding the allowable heave of the buckets for the entire lifetime of the wind turbine. To date, there is no ready-to-use method to predict the admissible tensile reaction with consideration of allowable heave of a bucket.

The paper presents the results of numerical simulations which allow for the description of drained, partly drained and undrained load-bearing behavior and the quantification of the tensile resistance depending on the heave, the pull-out rate (loading rate), the soil permeability and the bucket dimensions. The simulations presented here consider a single loading event with a constant pull-out rate (velocity of heave) V_z. In conjunction with the quite complex loading situation which actually occurs, the description