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Numerical modelling of suction bucket foundations subjected to axial loading

Modélisation numérique de fondations à godets aspirants soumises à un chargement axial

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ABSTRACT: In multi-caissons foundations, the overturning moments are crucial for the design. The foundation resists to those moments through compression and tension. The tensile capacity of the upwind caisson should be considered in the design. To investigate this tensile behavior, numerical analyses are performed in PLAXIS 2D using a constitutive model which combines a Mohr-Coulomb failure criterion with the concept of state-parameter for sands. Initially, the tensile capacity of the suction bucket in fully drained and undrained conditions is investigated. The suction bucket is pulled out by applying small displacements, until its ultimate capacity is reached. Different values of densities are examined to monitor their effect on the ultimate capacity of the foundation. A parametric coupled consolidation analysis is then performed to study the impact of the permeability of the soil and of the pull-out rate. It is observed that the fully drained and undrained conditions constitute, respectively, the lower and upper boundaries of the ultimate tensile capacity of the foundation. The higher densities lead to higher tensile capacities. With faster loading rates and lower permeabilities, the response of the suction bucket approaches the undrained capacity, as suction is developed beneath the bucket.

RÉSUMÉ: En ce qui concerne les fondations à caissons multiples, les moments de renversement sont cruciaux pour la conception. La fondation résiste à ces moments par la compression et la tension. Cette capacité de traction du caisson en amont doit être prise en compte. Pour étudier ce comportement de traction, des analyses numériques sont effectuées dans PLAXIS 2D, en utilisant un modèle constitutif qui combine un critère de défaillance de Mohr-Coulomb avec le concept d'état-paramètre pour le sable. Premièrement, la capacité de traction du caisson dans des conditions entièrement drainées et non drainées est étudiée. Le caisson est retiré en appliquant de petits déplacements, jusqu'à ce que sa capacité ultime soit atteinte. Différentes valeurs de densités sont examinées pour surveiller leur effet sur la capacité ultime de la fondation. Une analyse paramétrique de consolidation couplée est ensuite réalisée pour étudier l'impact de la perméabilité du sol et du taux d'arrachement. Il est observé que les conditions entièrement drainées et non drainées constituent, respectivement, les limites inférieure et supérieure de la capacité de traction ultime de la fondation. Les densités plus élevées conduisent à des capacités de traction plus élevées. Avec des taux de chargement plus rapides et des perméabilités plus faibles, la réponse du caisson se rapproche de la capacité non drainée, étant donné qu'une aspiration se développe sous le godet.

Keywords: Suction bucket; suction caisson; offshore wind turbine, axial loading; tensile.

1 INTRODUCTION

Climate change constitutes one of the most challenging problems that our world has to deal with. Most of the countries have set the ambitious target of a net zero carbon footprint by 2050, in order to contribute to sustainability and to environmental protection. This target leads more and more to the use of renewable sources of energy as a replacement to fossil fuels. Offshore wind energy has gained in popularity during the last decades. The most common type of offshore foundation is a monopile, particularly for relatively shallow waters. Alternatively, a suction caisson, which is essentially an upturned bucket, can be used as part of the foundation system for offshore wind generators. In effect, in deeper waters, where the loads are higher and the turbines are larger, multiple caisson foundations can be used in tripod or tetrapod structures which include, respectively, three or four caissons. For offshore wind generators, the most important loads are the horizontal forces from waves, currents and wind and the overturning moments that these loads apply to the foundation. The latter are resisted by developing tension and compression forces on the upwind and downwind legs of the structure (Byrne et al., 2002). In this paper the tensile behaviour of the upwind bucket is investigated by conducting parametric numerical analysis in PLAXIS 2D.

2 NUMERICAL MODEL

2.1 Geometry of the problem and ground conditions

The dimensions of the foundation were chosen so as to depict a realistic structure. The diameter (D) of the caisson is 8 m, while the length (L) of the skirt is equal to 4 m (L/D = 0.5). The thickness of the lid (t_{lid}) is 0.2 m and that of the skirt (t_{skirt}) is chosen as 0.05m. The skirt's thickness to diameter t_{skirt}/D ratio is, therefore, 0.625%. Due to the geometry and loading characteristics of the problem, axisymmetric numerical models were used in PLAXIS 2D.

The region modelled extends 44m (5.5D) from the axis of symmetry, while the bottom boundary of the domain is located at a distance of 40 m (10L) below the tip of the skirt. Such dimensions were observed to eliminate any boundary effects. The soil domain was discretised using 15-noded triangular elements, whereas the bucket was simulated using plate elements. The soil-structure interaction was modelled using interface elements, where the normal and shear stiffness values were adopted as $K_N = K_S = 10^6\ kN/m^3$. A Mohr-Coulomb failure criterion was employed to describe the strength of the interface, with an angle of shearing resistance matching that of the soil at Critical State, i.e. $\phi_{interface} = \phi_{CS} = 32°$ (see section 2.2).

A single layer of Dunkirk sand (see Zdravkovic et al. (2020) for additional information on this material) with the groundwater table at the surface (to correctly modelled the effective stress) was considered. The coefficient of earth pressure at rest, K_0, was assumed to be 0.47 ($= 1 - \sin\ \phi_{CS}$).

2.2 Materials and constitutive modelling

The soil was simulated using the IC MAGE M02 model (Taborda et al., 2021), implemented as a PLAXIS User-Defined Soil Model. This model combines a non-associated Mohr-Coulomb failure criterion with the state-parameter framework proposed by Been and Jefferies (1985). Thus, the strength and dilatancy of the material are direct functions of the state parameter, defined as $\psi = e - e_{CS}$ where e_{CS} denotes the void ratio at Critical State for the current mean effective stress level. According to this model, for denser-than-critical samples, i.e. $\psi < 0$, the peak strength of the material is larger than that at Critical State, with the material exhibiting plastic dilatancy. As the sample approaches Critical State, $\psi \rightarrow 0$, the available strength reduces to that at Critical State (quantified simply by ϕ_{CS}) and the dilation decreases to 0. Full details on the formulation of this model are given in Taborda et al. (2022). Within the elastic region, soil behaviour is defined by a hypoelastic model, according to which the shear modulus depends on void ratio, mean effective stress and deviatoric strain (Equation 1).

The selected constitutive model was calibrated for Dunkirk sand and validated by successfully reproducing the field tests on large diameter monopiles performed as part of the PISA project. The full set of parameters is listed in Table 1. The suction bucket's material is steel, with a unit weight of γ_{steel} = 78.5 kN/m^3, Young's modulus of E_{steel} = 200 GPa and a Poisson's ratio of ν = 0.3. It is assumed that it behaves elastically.

$$G_{max} = G_0 \frac{1.0}{0.3+0.7\cdot e^2} \left(\frac{p'}{p'_{ref}}\right)^{0.5} \qquad (1)$$

Table 1. IC MAGE M02 parameters for Dunkirk sand.

Parameter	Value	Parameter	Value
Plastic behaviour		*Elastic behaviour*	
$e_{CS,ref}$	0.91	G_{ref}	88.6 MPa
λ	1.05	m_G	0.5
ξ	0.19	ν	0.17
ϕ_{CS}	32°	a	4E-04
k_1	1.5	b	1.40
k_2	-0.2	R_G	0.10
l_1	4.3	p'_{ref}	101.3 kPa
l_2	0.2		

2.3 Loading and type of analysis

The suction bucket is pulled upwards by applying a prescribed displacement at the centre of the lid until the maximum capacity is reached.

At first, fully drained and undrained elastoplastic analyses were performed to characterise the response of the suction bucket under these two limiting conditions. Different values of relative density (D_R = 60%, 75% and 90%) were also examined to assess the effect of the density on the tensile capacity of the foundation. Following that, a set of coupled consolidation analyses were performed. These analyses were performed for D_R = 75% and different values of permeability (k = 10^{-3}, 10^{-4}, 10^{-5} and 10^{-6} m/s), which were combined with various pull–out rates, in order to assess how close each combination of parameters was to drained and undrained conditions.

3 RESULTS

3.1 Drained and undrained conditions

The capacity curves for both drained and undrained conditions are depicted in Figure 1. As expected, the capacity in the undrained cases (dashed lines) is higher than that in the drained cases (solid lines) because in the latter the basic resistance of the suction bucket to the upward moving derives solely from the side friction developed inside and outside the skirt (Houlsby, Kelly & Byrne, 2005). As a result, the full capacity mobilises at very small displacements, with the lid of the suction bucket quickly losing contact with the foundation soil. Conversely, in undrained conditions, the resistance of the suction bucket to the upward movement is controlled by the suction within the soil that develops due to the tensile loading, which in this case was limited to a maximum negative pressure of 100 kPa. Therefore, the full separation between the bucket and the soil requires considerably larger displacements than those observed for the drained analysis, with a much higher capacity being mobilised. Clearly, the effect of the relative density of the soil is almost unnoticeable when the strength of the interface is assumed to be independent of the characteristics of the surrounding soil. This is in agreement with the fact the tensile axial capacity is controlled predominantly by the strength of the interface. Additional analysis, where the value of $\phi_{interface}$ was adjusted to reflect the changes in peak strength resulting from increases in relative density, showed a considerable spread in tensile capacity (Figure 2). These are described in Eleftheriou (2021) but are not reported herein for brevity.

3.2 Coupled consolidation analysis

3.2.1 Effect of pull-out rates

Fully coupled consolidation analyses were also conducted as part of this study, which required the definition of hydraulic boundary conditions. These consisted of considering the axis of symmetry as ‘closed’, thus preventing flow through it, whereas the top of the soil mass was assumed to remain at constant head, implying that water could flow across it as needed. Assuming a relative density of 75% and a relatively low value of soil permeability ($k = 10^{-6}\ m/s$), 6 different coupled consolidation analyses were performed. In each analysis, the maximum vertical displacement applied was 20 mm, with the duration per loading phase controlling the pull-out rate in mm/s, which varied between 0.000012 mm/s (or 1 day/mm) and 0.14 mm/s (or 0.00008 days/mm).

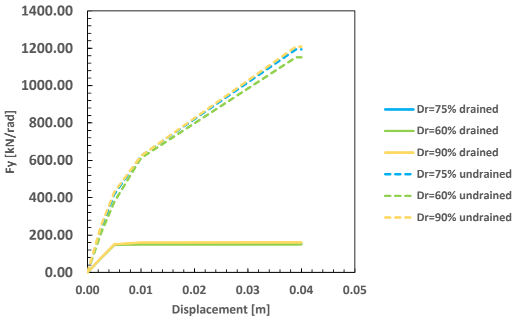

Figure 1. Comparison of capacity of drained and undrained conditions for different values of density.

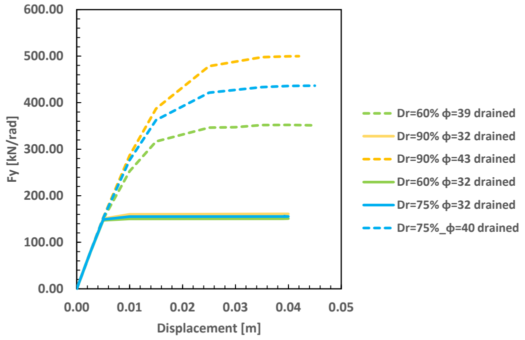

Figure 2. Capacity curves of the buckets for different values of density and different values of angle of shearing resistance at the interface – drained conditions.

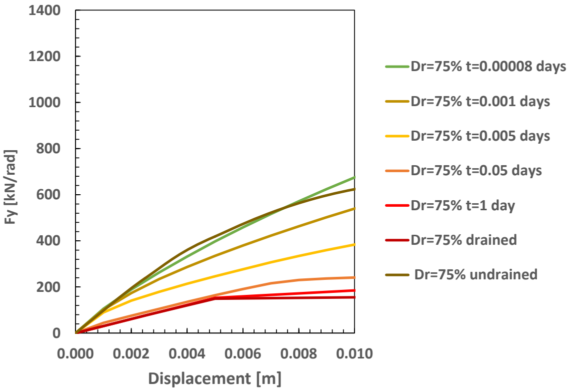

Figure 3. Tensile capacity of the suction bucket for different pull-out rates and a permeability of 10^{-6} m/s.

As shown in Figure 3, when the bucket was pulled out at the fastest rate (green line), the modelled response was similar to that of the fully undrained analysis. As the rate of loading decreases, the behaviour of the foundation approaches that observed for drained conditions (dark red line). Clearly, the tensile capacity increases as loading rate increases, while a higher displacement is needed in order for the tensile capacity to be fully mobilised.

3.2.2 Effect of permeability

Clearly, the transition from drained to undrained is not solely a function of the loading rate, with the permeability having a crucial role. For two distinct pull-out rates (0.002 mm/s or 0.005 days/mm, and 0.14 mm/s or 0.00008 days/mm) different values of permeability were examined, covering the range typically observed for sand deposits: 10^{-6} m/s, 10^{-5} m/s and 10^{-4} m/s.

The obtained results are shown in Figure 4 (slow pull-out rate) and Figure 5 (fast pull-out rate). It is interesting to note the combined effects of the permeability and loading rate: for the larger pull-out rate, a permeability of 10^{-6} m/s was sufficiently low to guarantee undrained conditions. However, for the lower pull-out rate, this value of permeability leads to a response between those observed in the drained and undrained analyses. Similar patterns can be observed for the other values of permeability.

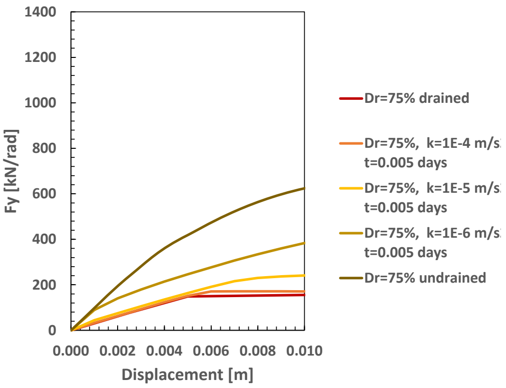

Figure 4. Tensile capacity of the suction bucket for different values of permeability (loading rate = 0.002 mm/s).

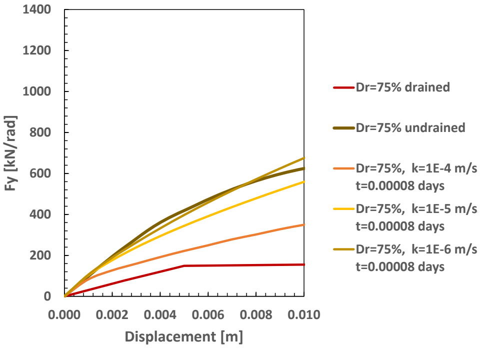

Figure 5. Tensile capacity of the suction bucket for different values of permeability (loading rate = 0.14 mm/s).

4 CONCLUSIONS

The objective of this paper was to determine the role of density, loading rate and permeability in the tensile capacity of a suction bucket, founded on a dense sand (Dunkirk sand). The obtained results show that the tensile axial behaviour of the suction bucket is primarily controlled by the characteristics of the interface. As a result, the density of the soil has negligible effect on the modelled response unless the changes in soil strength are reflected on that of the interface. As expected, the simulated behaviour is highly affected by the drainage conditions, with the undrained response being characterised by considerably higher capacity. Therefore, the balance between pull-out rate and permeability needs to be considered carefully as the two control the ability to prevent the build-up of negative pore water pressures below the lid. Both low pull-out rates and high permeability provide opportunity for water to flow around into the area beneath the lid, leading to conditions closer to those in drained analyses.

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