Laterally loaded pile in unsaturated soils: a numerical study

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ABSTRACT: The influence of partial saturation on laterally loaded piles response has been studied performing three-dimensional simulation using a finite element code. The analysis simulated a single vertical floating pile embedded in a normally consolidated silty clay, subjected to a static horizontal force applied at pile head. The study aims at exploring the influence of the relative position of water table with respect to the pile length. The hydro-mechanical propriety of soil is kept constant. The constitutive model adopted to simulate the soil stress-strain response is an extension of modified Cam-Clay model that considers the evolution of the yielding surface due to variation of saturation degree. The model is formulated in terms of modified Bishop effective stress, which allows switching continuously from saturated conditions to unsaturated conditions and vice versa. The modified formulation of the hardening parameter allows to correctly reproduce the volumetric behaviour observed in wetting and drying path.

1 INTRODUCTION

Pile foundations are frequently used in geotechnical engineering problem to hold the combination of axial forces, lateral forces and concentrated moment. In some applications, the lateral component of external forces can be crucial in pile design, i.e., tall structures under wind load, bridge abutments, earth-retaining structures, wind turbines, extreme loads such as emergency stop of a high-speed train on a viaduct. Usually the design of this foundation is not focused on ultimate conditions, both for soil and for pile cross-section, but it aims at ensuring the serviceability of elevated structures.

Starting from the 1950s, numerous research studies, both numerically and experimentally, have been performed on laterally loaded piles. In the early theoretical works, the soil is assimilated by a system of discrete springs with a constant sub-grade reaction. In these methods, the inclusion of non-linearity effects led to the so-called *"p-y"* methods developed by Reese et al. (1974, 1975). Centrifuge tests on laterally loaded piles greatly enriched the data benchmarks, allowing validating the theoretical design methods for various soil conditions: Khemakhem et al. (2010) have studied the soil pile interaction in fine graded soils varying the clay over-consolidation ratio.

The elastic continuum approach allowed considering the soil continuity in the load transfer mechanism. Major research contributions in this field can be found in the works of Banerjee and Davies (1978), Randolph (1981), Krishnan et al. (1983). These studies were focused on better understanding the influence of geometrical (slenderness ratio *L/D*) and mechanical (relative pile-soil stiffness *Ep/Es*) parameters in the interaction problem. Randolph pointed out that significant pile deflection and bending moment are usually restrained in the first diameters of depth, and hence the pile-soil interaction is confined to near-surface soil. The so-called flexible piles are elements that do not involve the whole length in holding up the concentrated force or moment applied at the head. In practice, most of the piles have a flexible behaviour: in these conditions, the pile response strongly depends on the relative stiffness *Ep/Es*, evaluated in the significant volume of soil.

The significant soil volume, therefore, can be above the water table and hence in partial saturation condition. Several experimental studies have highlighted the suction influence on stiffness both at small strain levels (Vassallo et al. 2007) and medium deformation levels (Casini et al. 2007, 2008).

The results of a preliminary numerical study about the influence of partial saturation in soil-pile interaction under lateral loading are presented in this paper.

2 FINITE ELEMENT MODEL

2.1 *Geometry and boundary condition*

A numerical model of a single vertical floating pile (L=24m, D=0.8m) embedded in a normal consolidated soil layer is carried out using the finite element code ABAQUS/standard. The problem must be studied with three-dimensional analysis. Due to the symmetry along the vertical plane containing the horizontal load, only half of the problem is modelled, as shown in Figure 1. Both soil and pile are modelled as three-dimensional solid continuum porous elements; beam elements with null stiffness (Young Modulus, E=1 kPa) are tied to the central nodes of the pile, in order to efficiently obtain the bending moment profile along the pile length. The soil follows the simple Cam Clay Model adapted to unsaturated conditions, while the pile is assumed to behave as an elastic material (Ep=36.0 GPa; ν=0.2). Since the pile is modelled as a porous material, the frictional behaviour of the soil-pile interface is still governed by effective stress even above the water table, a value of $\delta=\varphi'$ is adopted, both for lateral interface and base interface.

Nodal displacements are fixed in the X, Y and Z directions at the base of the finite element mesh. The displacements at the lateral boundaries are constrained in the normal directions.

The pile head is at the ground surface level and no-load eccentricity is applied. A mesh refinement is adopted nearby the pile-soil interface both on lateral surface and at pile tip.

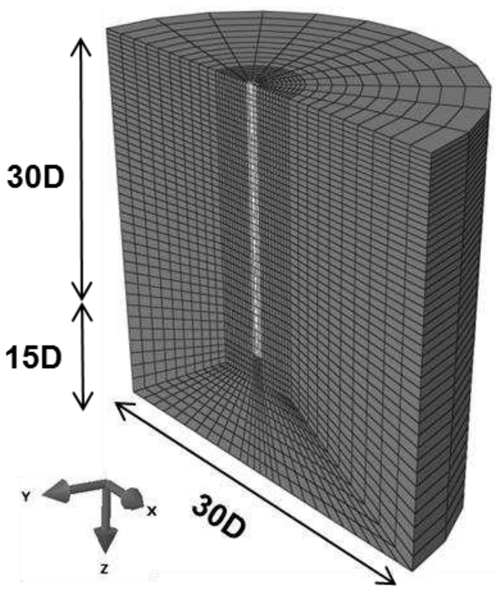

Figure 1. Finite element mesh.

2.2 *Mechanical soil behaviour*

Mechanical soil behaviour is analysed with the Modified Cam Clay Model extended to partial saturation, (Tamagnini 2004). The model is formulated in Bishop effective stresses, where the weighing factor χ it is assumed equal to saturation degree:

$$\sigma'_{ij} = \left(\sigma_{ij} - u_a\delta_{ij}\right) + S_r\left(u_a - u_w\right)\delta_{ij} \tag{1}$$

where σ_{ij} is the total stress; Sr is the saturation degree; (u_a-u_w) is the matric suction and δ_{ij} is the Kronecker delta. The MCCM is an elastic-plastic hardening model widely used to describe the stress-strain response of fine-graded soils (Soranzo et al. 2015; Rotisciani et al. 2017). The flow rule is associated, yielding results both by the development of positive volumetric plastic strain and by the increase of saturation degree:

$$\delta p'_c = \frac{v}{\lambda - \kappa} p'_c \,\delta\varepsilon_v^p - bp'_c\,\delta S_r \tag{2}$$

where, v is the specific volume; λ and κ are respectively the non-dimensional slopes of the normal consolidation line NCL and the unloading-reloading line URL; $\delta\varepsilon_v^p$ is the variation in volumetric strain; b is the mechanical parameter controlling the relative position of the unsaturated NCL at the current saturation degree with respect to the saturated one. The explicit dependence of yielding parameter (p'_c) from saturation degree fairly allows reproducing the increase in apparent pre-consolidation pressure and collapse upon wetting observed in unsaturated soil behaviour. The failure criterion follows a pure frictional law:

$$q_f = Mp' \tag{3}$$

where, M is the slope of failure envelope in the invariant plane.

As the explicit formulation of soil water retention curve is required, the simple Van Genuchten model has been adopted:

$$S_r = S_{r\,res} + \left(S_{r\,sat} - S_{r\,res}\right)\cdot\left(\frac{1}{1+\left(\alpha s\right)^n}\right)^m \tag{4}$$

where, α, n, m are parameters controlling the shape of the function. Classical values of silty clay soils are adopted.

The Hydro-mechanical parameters of the model are summarised in Table 1.

Table 1. Mechanical and hydraulic parameters.

Mechanical Parameters		Hydraulic Parameters	
λ	0.1	Sr_{sat}	1
κ	0.02	Sr_{res}	0
N_0	2.38	α	0.02
ν'	0.2	n	1.7
M	1.07	m	0.41
b	5	K_{sat} (m/s)	1.0E-07

2.3 *Model validation*

A similar model was used with satisfactory results in order to examine the results of an experimental campaign focused on pile response to horizontal loading in unsaturated soils (Lalicata 2017) developed in geotechnical centrifuge at the LCPC of Nantes (Rosquoët et al. 2007). In the centrifuge tests, the influence of suction was studied for a short rigid pile, embedded in a statically compacted silty soil (B-grade kaolin). The test was performed at 100g; the pile (tubular cross section, D=12mm; thickness t=1 mm) with an embedded length of 150 mm, was loaded both in partially saturated condition (water table z_w at 70 mm from ground level) and in fully saturated condition. As for rigid piles, compared to saturated condition, pile head displacement and bending moment strongly reduces in unsaturated soils. For example, the comparison in terms of load deflection curves (at the model scale) for the two different hydraulic conditions is pointed out in Figure 2: black dots refer to experimental data obtained in unsaturated conditions while grey diamonds refer to data obtained in saturated conditions. The solid line represents the model prediction for the two cases. As previously mentioned, the model fairly reproduces the observed behaviour even for significant differences in the soil state conditions. Only for saturated conditions, the differences between model prediction and experimental data can be related to the uncertainties both on consolidation degree and void ratio distribution before the loading step and drainage conditions during loading (Lalicata 2017).

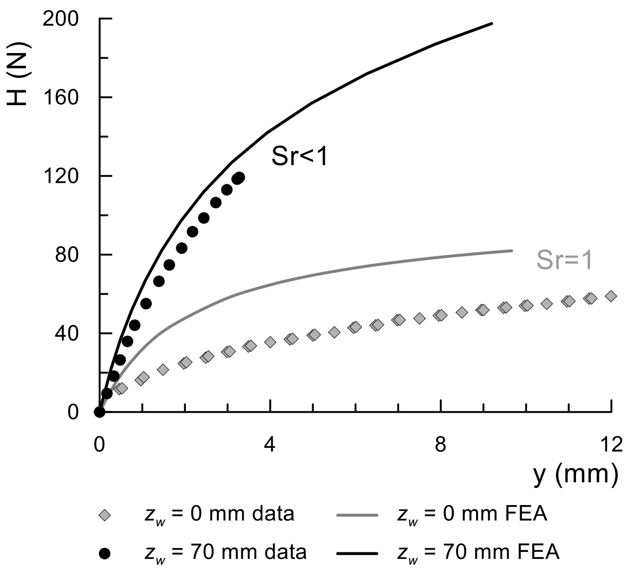

Figure 2. Load-deflection curve at model scale (Lalicata 2017).

3 RESULTS AND DISCUSSION

This paper focuses on the influence of different water table elevations on the response of a free-head flexible pile subjected to lateral loading. A single slender pile (L/D = 30) with an elevated value of relative stiffness evaluated for fully saturated conditions (Ep/Es = 1.9×10^4) has been studied.

In order to shows the results, convenient non-dimensional parameters have been adopted. According to Krishnan et al. (1983), the geometrical variables are normalized by the diameter D, while the mechanical ones are normalized by soil modulus Es in saturated conditions.

When the water table is at a ground level, the soil stiffness increases proportionally with depth. Randolph (1981) found that, for usual pile-soil stiffness ratios the significant volume involved in the interaction problem can be preliminary stated at 10D of the depth. Considering that the most superficial soil layers are the most important, in this study the soil modulus Es used to define the relative soil-pile stiffness has been evaluated at z = 2.5D and therefore, considered representative of the stiffness in the significant volume.

Following the modified Cam Clay Model formulation, soil modulus Es is:

$$Es = E' = 3(1-2\nu')\mathrm{K} = 3(1-2\nu')\frac{vp'}{\kappa} \tag{5}$$

In the simulations, the water table position, z_w, ranges from zero to 24 m and the ratio z_w/D from zero to 30.

Each analysis has been performed in several steps. As the soil has reached the equilibrium with the geostatic gravity load and the imposed hydraulic and boundary conditions, then the so-called "wish-in-place" pile installation has been carried out. As a last step, the horizontal force has been increased monotonically in drained condition for soil. This loading step has been modelled with fully coupled analysis.

In Figure 3, the horizontal load H is plotted in relation to the head displacement y/D, for different elevations of water table, z_w/D. As expected, initial stiffness increases for deeper water table level. Nevertheless, the increment of partial saturation positive effects becomes gradually less important, as z_w/D increases.

The stiffness gain observed for increasing values of z_w/D, can be explained by the increment of mean effective stress p', induced by partial saturation as in Equation (1) that is controlled, at the same time, both by suction (increasing with z_w/D) and saturation degree (decreasing with the position of water table).

The load-deflection curves obtained in unsaturated condition show higher load compared to the saturated one for any displacement value. The curves exhibit a non-linear trend due to progressive soil yielding induced by load increases. Due to the aforementioned p' increment, the operative soil stiffness in unsaturated conditions decays slowly compared to the saturated one in a given displacement range.

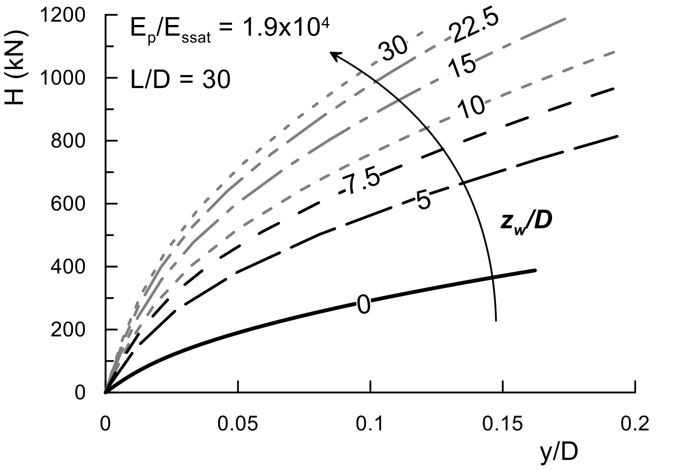

Figure 3. Influence of water table on the load deflection curves.

Although the system response is strongly dependent on operative stiffness, the significant influence of partial saturation can be observed also in the elastic soil modulus (*Es*) distribution with depth (Fig. 4).

With regard to the fully saturated distribution, black solid line in Figure 4, the distributions of soil modulus exhibit a non-zero values at *z/D*=0. Above the water table, the slope of *Es* depends on *Sr*: great variation of the parameter gives a steep slope to stiffness, when the saturation degree is close to 1, the slope is the same as observed in saturated conditions.

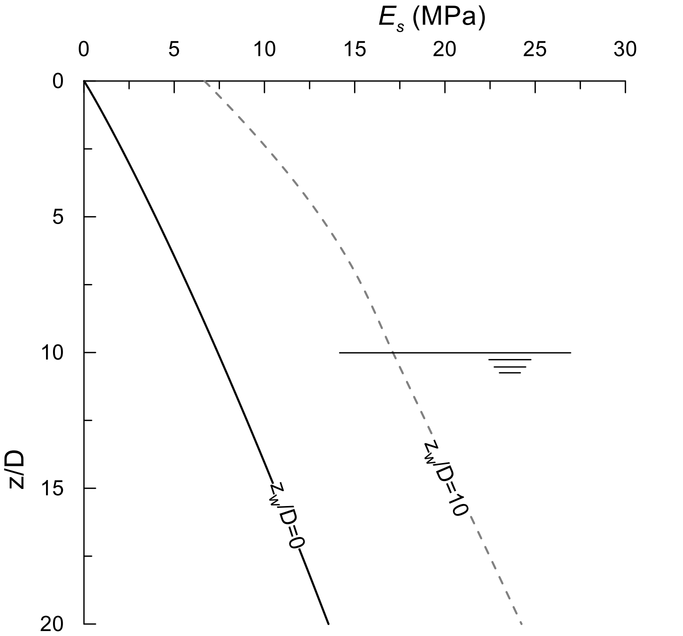

Figure 4. Soil modulus, *Es* distribution.

In Figure 5, the normalized bending moment distribution *M/HD* is pointed out along normalized depth *z/D*, for different water table position (*zw/D)*. The curves shown in Figure 5 refer to a very low load (H = 30 KN), therefore, it may be assumed as a low plasticization level in the soil, even for fully saturated conditions. As soil stiffness grows, the system flexibility increases, leading to a significant reduction of maximum bending moment and that also moves towards the ground surface: for z_w/D = 0, the maximum moment is located at 5.*5D* while for z_w/D = 30, it is reduced to 3.8*D*. As outlined by Randolph (1981) and Krishnan et al. (1983), the critical length is a function of relative stiffness: here, due to the increase in soil stiffness induced by partial saturation the critical length decreases from 18*D* (z_w/D = 0) to 14D (z_w/D = 10-20-30). The same considerations made for higher loads emphasize the differences between saturated and unsaturated conditions related to the different yielding distribution in the soil. With respect to saturated soil, the plasticization level is always smaller in unsaturated conditions for any load; hence the differences pointed out in Figure 5 increase as load increases.

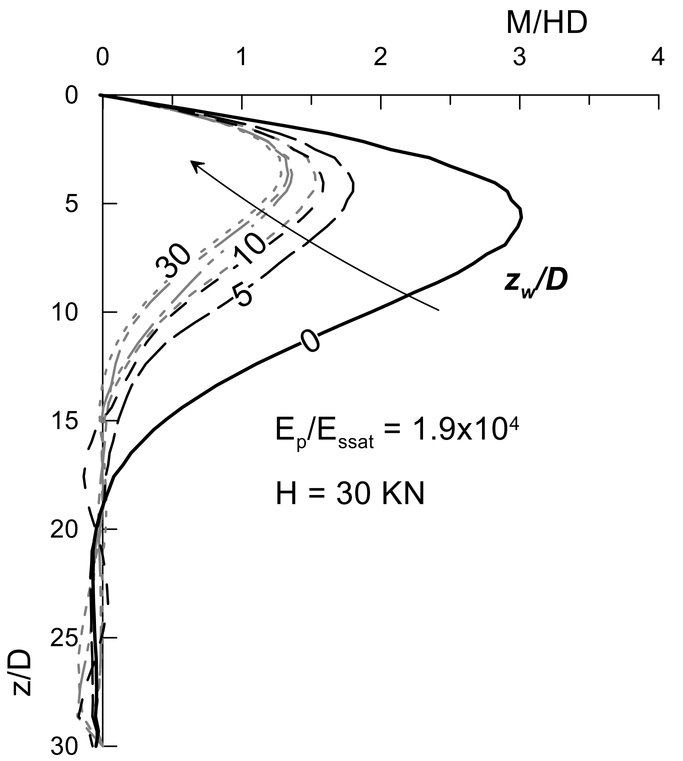

Figure 5. Normalized Bending moment for different water table positions.

For low deformation levels, it is still possible to refer to an elastic interpretation. The effects of partial saturation can be observed by looking at the trend of head displacement and maximum bending moment in function of *zw/D*, as shown in Figure 6 (a) and (b). The results are presented in terms of non-dimensional parameters $\frac{y}{D}\cdot\frac{E_s D^2}{H}$ for displacement and $\frac{M}{HD}$ for bending moment (Krishnan et al. 1983). The parameters have been evaluated for *y/D*

= 0.01, and for soil modulus, the saturated values at z = 2.5D has been used.

Switching from saturated condition to z_w/D = 5, it can be observed that a steep reduction of 56% of head displacement after witch the displacement smoothly decreases up to a reduction of 80% for z_w/D = 30. The variation of maximum bending moment with z_w/D, Figure 6 (b) shows the same trend qualitatively. The bending moment appears to be less affected by partial saturation than lateral displacement. With respect to saturated condition, z_w/D = 0, the reduction ranges from 40% (z_w/D = 5) to 50% (z_w/D = 30).

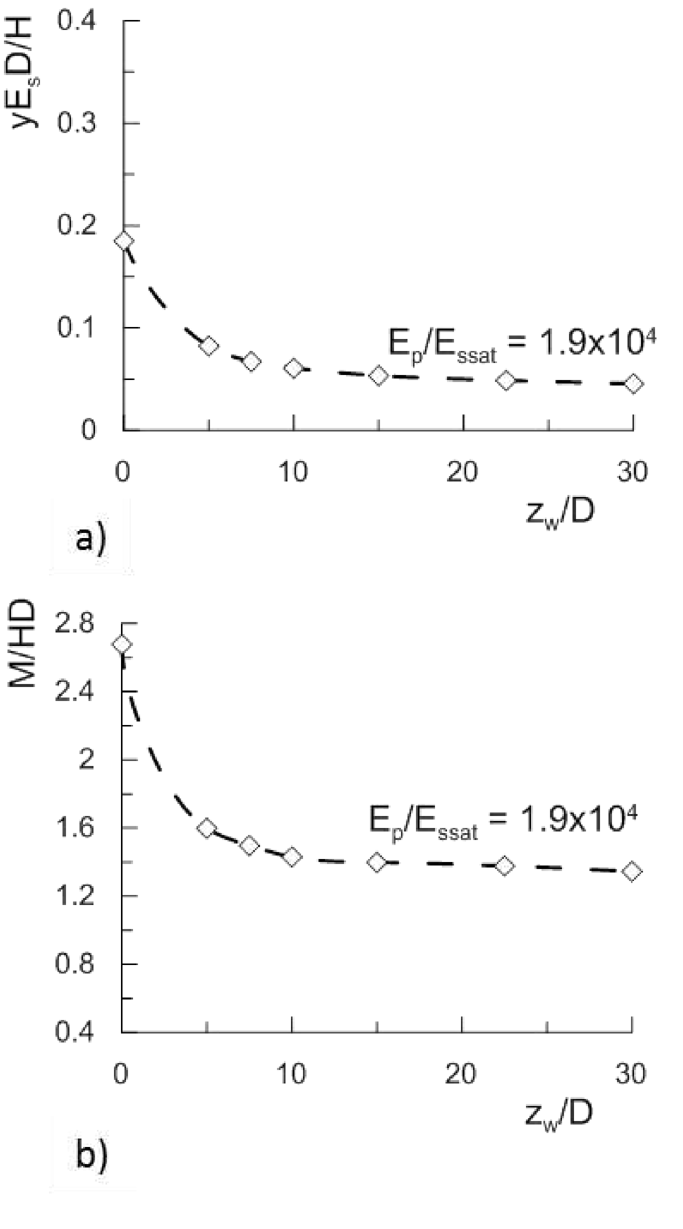

Figure 6. a) Head displacement with respect to the water table position; b) Maximum normalized bending moment in function of water table position.

4 CONCLUSIONS

This study analyses the pile behaviour under lateral loading in saturated and unsaturated porous media using a hydro-mechanical model formulated in terms of Bishop's effective stress and implemented in the commercial code Abaqus/Standard. The study has been carried out by means of a three-dimensional finite element model that considers the main features of laterally loaded pile and partially saturated soils. The soil stress-strain response has been modelled with the Modified Cam Clay Model extended to unsaturated conditions; the SWRC is described by the Van Genuchten equation with the typical parameter of a silty clay.

The study highlights the importance of an increase of stiffness and strength induced by suction above the water table in the pile response. For free-head flexible piles in working condition, a marked reduction of pile head displacement and bending moment have been observed even for low depths of the water table. Due to increasing stiffness, the critical length reduces, and the soil-pile system becomes more flexible. The results can be extended to any pile with greater slenderness ratio but same initial relative stiffness. As load increases, the observed differences grow, both for head displacement and maximum bending moment. At the same load, the maximum bending moment is smaller in unsaturated soil conditions and it is closer to the pile head.

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