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Pushover analysis on piles in stratified soil under saturated conditions and dry conditions

.

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RESUMEN

Esta investigación presenta una comparación de las propiedades mecánicas y dinámicas de una arcilla en condiciones saturadas y después de una sequía de 87600 horas utilizando una simulación mediante elementos finitos. Una vez finalizada la simulación se utiliza la curva de degradación del módulo de corte dinámico y el peso unitario para estas dos condiciones del suelo. Estas variables se utilizan para realizar un análisis de pushover sobre tres pilotes rectangulares usando OpenSeesPL. Los pilotes se someten a un incremento de carga lateral hasta que se alcanza el desplazamiento objetivo de la cabeza del pilote en el suelo saturado. Finalmente, se comparan los diagramas de cortante y momento del pilote en condiciones saturadas y secas en el último paso que genero el desplazamiento deseado. Los resultados sugieren que el momento máximo y las fuerzas cortantes sobre los pilotes son mayores en condiciones de suelo saturado.

Palabras clave: Modulo de corte dinámico, simulación por elementos finitos, análisis pushover, suelo saturado, diagramas de corte y momento, pilotes

ABSTRACT

This research presents a comparison of mechanical and dynamic properties of clay in saturated conditions and after a drought simulation of 87600 hours using finite elements. Then the change of dynamic shear modulus and unit weight for these different soil conditions is used to conduct a static pushover analysis over three rectangular piles using OpenSeesPL. The piles are subjected to a lateral load increment until the target displacement in saturated soil is reached. Finally, shear and moment diagrams of the pile on saturated and dry conditions at the last step are compared. The results suggest that the maximum moment and shear forces over the piles are bigger in saturated soil conditions.

Keywords: Dynamic shear modulus, finite elements analysis, pushover analysis, saturated soil, shear and moment diagrams, piles.

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INTRODUCTION

Soil mechanics is a significant topic in civil engineering. It studies the behavior of soils under different stress conditions (Braja & Ramana, 2011). In soil mechanics, the branch of soil Dynamics is of special interest; it helps to describe and study the behavior of soils under dynamic loads (i.e., earthquakes). For several decades an important topic in soil dynamics research has been the analysis of piles-soil interaction under earthquake conditions (Mukhopadhyay et al., 2008). It is known that soil conditions around piles have nonlinear behavior under moderate and strong earthquakes that produce large deformations (Badoni & Makris, 1996). Since all structures are supported by a foundation, the nature of the dynamic load, the nonlinear effect over the foundation and its surroundings is critical on bridges, coastal and offshore structural design (F. Zhang et al., 2000). Due to large deformations nonlinearity effects modify the seismic response of pile foundations (Maheshwari et al., 2004). The dynamic shear modulus degradation curve, soil density, and damping are parameters that describe the seismic response of soils. Therefore, these variables can be used to compute site effects in soils under earthquakes (Villacreses et al., 2020). So, nonlinear behavior for large deformations can be considered. Accordingly, linear elastic methods for pile analysis are not suitable since they don't consider nonlinear behavior. So, they are not useful to compute internal forces and pile lateral displacement under large deformations (Y. Zhang et al., 2020). Several researchers have studied pile's behavior under lateral loads using experimental and numerical analysis methods (Abbas et al., n.d.; Muqtadir & Desai, 1986; Yang & Jeremić, 2005). (Chau et al., 2009) applied a shaking table test to a soil-pile system and then performed a nonlinear finite elements method analysis. (Chandrakala, 2019) made a shake table test simulation over a soft clay-pile structure using the acceleration time history of 1940 El Centro earthquake ground motion. (Abbas et al., 2008) studied the influence of pile shape in the soil-pile interaction system. (Mukhopadhyay et al., 2008) conducted a pushover analysis in stratified sand, determining that maximum deflection happened with a combination of sand clayey layers.

The present study proposes an analysis of how different soil conditions (saturated, dry) affect the dynamic properties of a high plasticity clay and how these changes affect the pile-soil interaction system and the internal forces of the pile. The high plasticity clay was subjected to 87600 hours of drought simulation with a hydrostatic behavior as the initial condition. Using the water retention curve (WRC) the suction was computed, then effective stress and maximum shear dynamic modulus were calculated. From these properties, two simulations of a single square pile of 40x40 cm cross-section embedded in the saturated and dry soil were conducted. Finally, the soil's properties before and after the drought simulation, the pile's head lateral deflection, and the pile's internal forces diagrams are compared. The analysis was done using finite elements method (FEM). Nonlinear behavior on soil was considered using the degradation curve of the dynamic shear modulus, and the pile was subjected to a static pushover analysis. Pushover analysis is used since it applies the load increment of the new step over the structure that has been deformed from the load of the previous step. This method simulates the behavior of a structure that has been deformed from the first stage of an earthquake and it has to resist the second stage of the earthquake with the deformation from the first stage (Mukhopadhyay et al., 2008).

MATERIALS AND METHODOLOGY

The following study used clay as the soil, which according to the Unified Soil Classification System (USCS) it is classified as a high plasticity clay (C.H). This soil has a liquid limit of 87% and a plastic limit of 37%, with a plasticity index of 50%. This Clay has an optimum density of 1.34 g/cm3 with a water content of 31.4% (Villacreses et al., 2021). Relevant data in this study is the soil's Water Retention Curve (WRC) shown in Fig. 1. The WRC curve has been taken from previous research (Villacreses et al., 2021). That research studied the same clay described here.

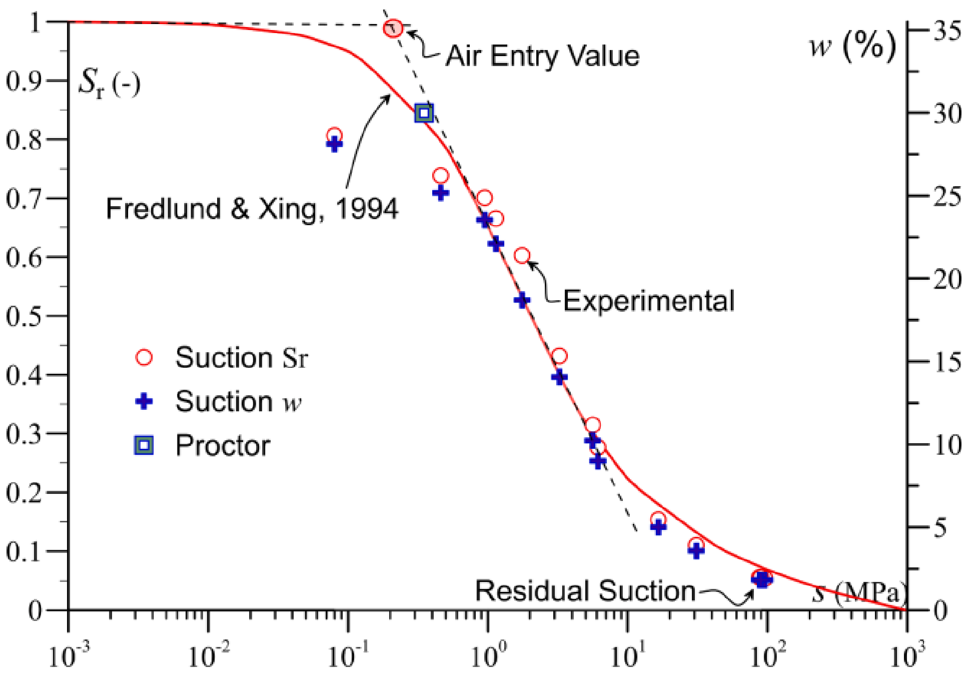

Figure 1 Experimental water retention values and fitting curve of the compacted material conditions (Villacreses et al., 2021).

The WRC curve stablishes a relationship between the saturation (Sr) and suction (ψ) (i.e., volumetric water content, and negative water pressure) (Villacreses et al., 2021). From this figure, the air entry value and the residual suction are identified. Air entry value is defined as the pore pressure required to allow the air to start entering between the soil’s large pores space, and residual suction describes the saturation degree that requires higher pressures to remove residual soil water.

Fig. 2 was obtained from data from previous research (Villacreses et al., 2021). The data describes the evolution of shear modulus at different soil deformations for different suction values. When the suction (s) increases due to lower water content in the clay (Fig. 1), the shear modulus (G) also increases. For a 98.5 MPa suction in the soil, the maximum shear modulus reaches 700 MPa.

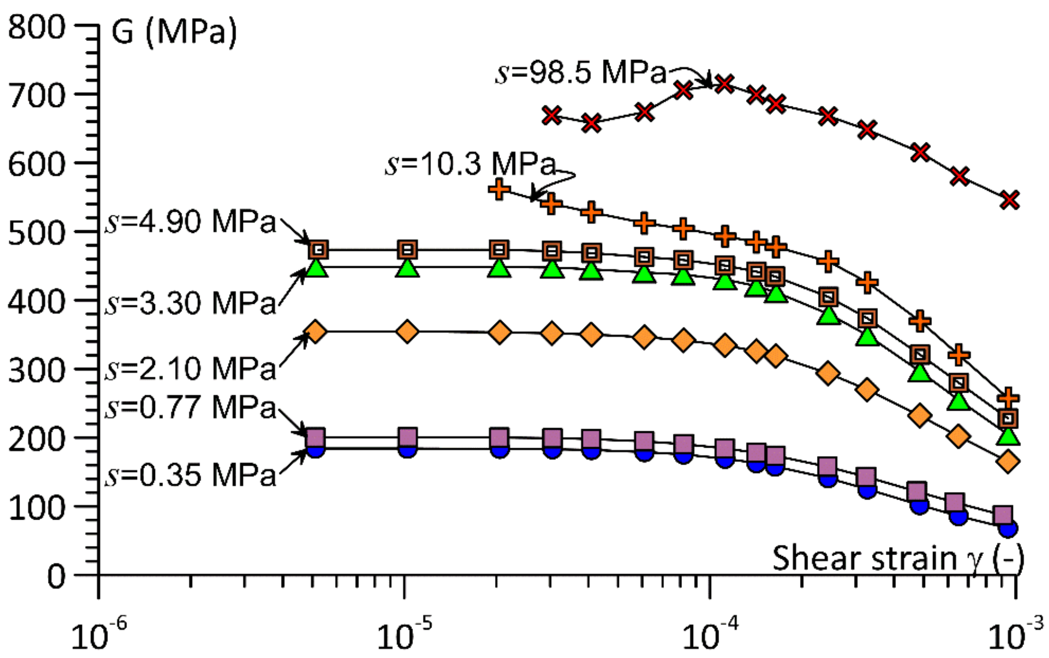

Figure 2 Shear modulus degradation curves for different suction conditions (Villacreses et al., 2021).

From fig. 2, the maximum shear modulus for different suction values was calculated using interpolation. Finally, the curve of effective stress (σ_{ef}) vs maximum shear modulus (G_{max}) in the soil was calculated. It is shown in Fig. 3.

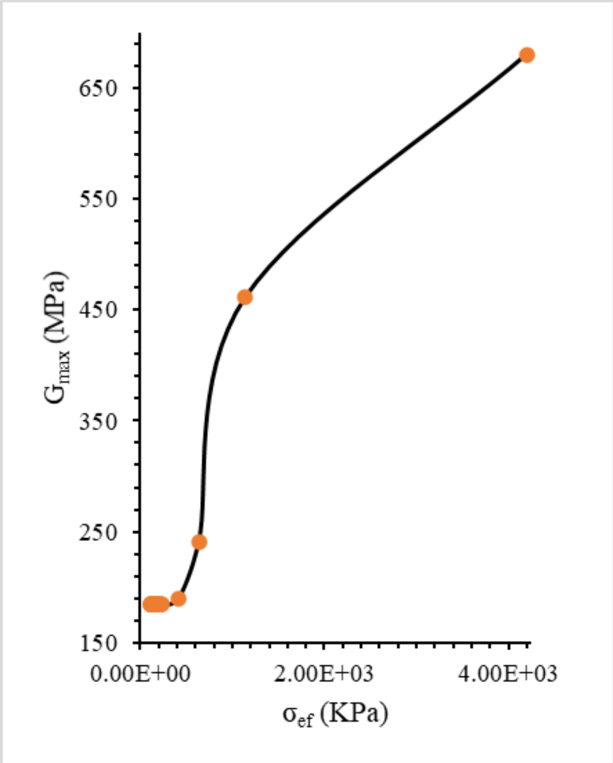

Figure 3 Effective stress vs maximum shear modulus

The effective stress was calculated from a relation between the soil matric suction and an effective stress parameter(Bolzon et al., 1996; Fleureau et al., 1995; Oberg & Sallfors, 1995). This relation is represented in equation 1.

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \qquad (1)$$

Where, σ' is the effective stress, χ is the effective stress parameter, u_a is the pore air pressure, u_w is the water pressure and σ is the total stress. The difference (u_a-u_w) is known as matric suction. Equation 1 allows to include the contribution of water suction in the effective stress of soils. The effective stress parameter helps to estimate the fraction of suction that contributes to the effective stress; this variable was estimated using equation 2 (Khalili & Khabbaz, 1998).

$$\chi = \left[\frac{(u_a - u_w)}{(u_a - u_w)_b}\right]^{-0.55} \qquad (2)$$

Where, $(u_a$-$u_w)_b$ is the air entry value (420 kPa) obtained from fig. 1. With equations 1 and 2, it is possible to calculate the effective stress for different suction or saturation values. An assumption in this approach was made when the soil is in saturated conditions. The assumption was that the effective stress produced by suction (u_a-u_w) is zero since there is almost no suction when the soil is saturated (Fig 1). Then, the effective stress is calculated as the difference between the total stress minus the pore pressure. Since pore pressure increases in saturated conditions the effective stress is reduced, fig 3 shows that for low values of effective stress (σ’) (i.e., between 0-300 MPa), the shear modulus is almost constant 184 MPa.

This research studies how the influence of weather in the soil affects the pile response profiles and resistance due to lateral loads. The methodology is divided into two stages. First, a finite-difference simulation of the soil in a saturate condition over a drought process of 87600 hours. The second stage is a static push-over analysis of three square piles of 10, 15, and 20 meters depth in the saturated soil and the soil with 87600 hours of drought.

Stage I. Simulation of the soil in saturated conditions over a drought process of 87600 hours

The soil's initial state is assumed as saturated with water pressure in hydrostatic conditions. Data used from previous research (Villacreses et al., 2021) measured the change of the soil mass due to evaporation in the drying process. This was measured in a climatic chamber design by Lozada et al. (2019). The change of soil mass measure can be transformed into water flux; this parameter was used to solve the continuity equation of water flow in unsaturated soils using Richard’s formulation for finite differences (Villacreses et al., 2021). Using the hydrostatic water pressure, the retention curve, and the humidity profile as initial conditions, the high plasticity clay was subject to a drought simulation of 87600 hours.

Stage II. Static Push over analysis in high plasticity clay

Pushover analysis is a useful method to estimate the ultimate load capacity of a structure under severe conditions such as earthquakes. A load is applied over the structure, and then it is analyzed. After the analysis, the load is monolithically increased and analyzed again; this iterative process continues until the target displacement in the node control of the structure is reached or surpassed (Mukhopadhyay et al., 2008). When the analysis has concluded, the results of all iterations are plotted, and it gives the pushover curve. This curve usually compares step analysis versus displacement in the node control. It is also possible to visualize the displacement, shear, and moment diagrams on the structure for each analysis step.

The results of the three piles (10, 15, 20 meters depth) with a cross rectangular section of 40x40 cm embedded have been obtained using OpenSeesPL. A 25 m soil profile was used in the analysis, it was assumed that the piles were pinned at the top, and there is no vertical load applied on the piles due to superstructure. The soil parameters were defined using a Pressure Independent MultiYield U-CLAY1 material. The mass density, maximum shear modulus, maximum compressibility modulus, and the shear modulus degradation curve were defined at each soil layer of 1 m. The cohesion (95 kPa), and the friction angle (0°) were obtained from the Mohr-Coulomb failure envelope under matric suction.

The soil parameters were obtained from stage one simulation data. The water content profiles gave values at each meter throughout the 25 meters depth of soil before and after the 87600 hours of drought simulation. These profiles were used to calculate the saturation degree. Then, fig. 1 was used to approach the suction for each saturation degree. Finally, from fig. 2, the shear modulus degradation curves were computed by interpolation, and the maximum shear modulus was taken from fig. 3, where the effective stress was calculated for every meter using equations 1, 2.

With the domain for saturated soil and the domain for 87600 hours of drought soil defined in the program, three simulations were analyzed. The three simulations were of a single elastic concrete pile with 10 m, 15 m, and 20 m depth respectively. A horizontal load was applied on the piles' heads (node control). This load was increased until the piles' heads reach a lateral deflection equal to 2% of their length (Chopra, 2001; Mukhopadhyay et al., 2008). The piles have a cross rectangular section of 40x40 cm. Both piles and soil domain were discretized with 0.5 m depth elements.

RESULTS AND DISCUSSION

The results obtained in this research from simulations are shown and discussed by stages as the previous section.

Stage I. Simulation of the soil in saturated conditions over a drying process of 87600 hours

Fig. 4 shows the pore pressure in the 25 m soil stratum before and after the 87600 hours of drought simulation. As it was explained in the previous section Fig. 4a describes the hydrostatic pore pressure in the soil before the simulation; notice that in the first 5 meters the pore pressure is negative. Fig. 4b shows how the suction (negative pore pressure) grows radically in the first 3 meters of soil. This result was expected since in non-saturated conditions the water retained in pores forms a meniscus between the soil particles, which generates a suction due to water surface tension between soil particles.

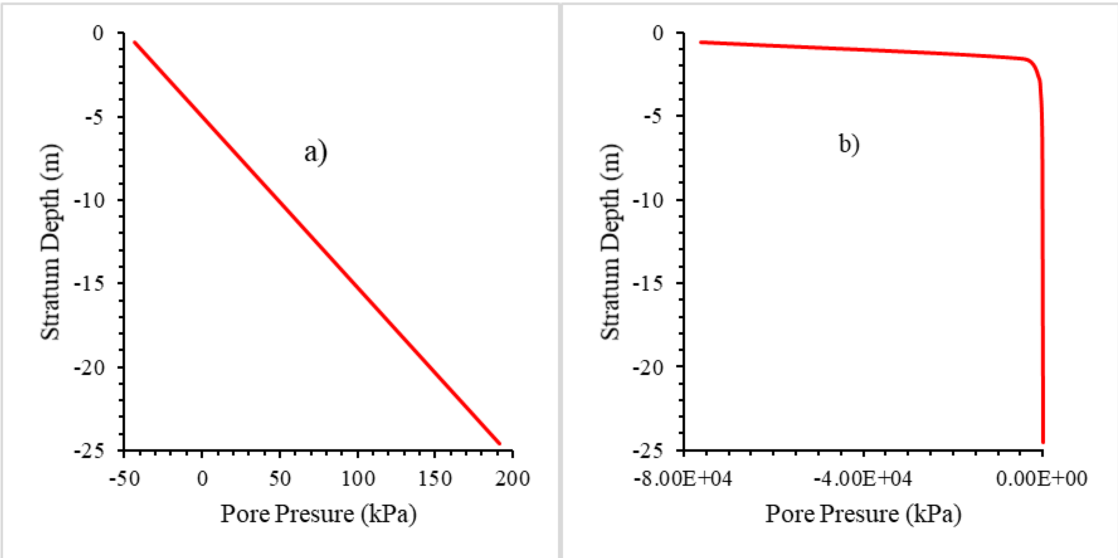

Figure 4 Pore pressure in soil stratum (a) saturated; (b) 87600 hours of drought simulation

Using equations 1, 2 and the data from fig. 4 the effective stress in the soil stratum has been calculated. In Fig. 5a notice that in the first 5 meters, the slope of the line is steeper because the pore pressure is negative at those points. Consequently, the suction parameter in equation 1 contributes to increasing the effective stress due to negative pressure. Fig. 5b shows how the effective stress is much bigger in the first 3 meters due to suction. This result shows that compressibility and resistance of the soil increase when the soil is subjected to periods of drought. Therefore, a large lateral load will be required to deform the piles' heads up to the same deformation as saturated soil. It can be seen that after 5 meters depth the effective stress in fig. 5b starts to behave like the effective stress from fig. 5a because the soil layers under this depth are saturated.

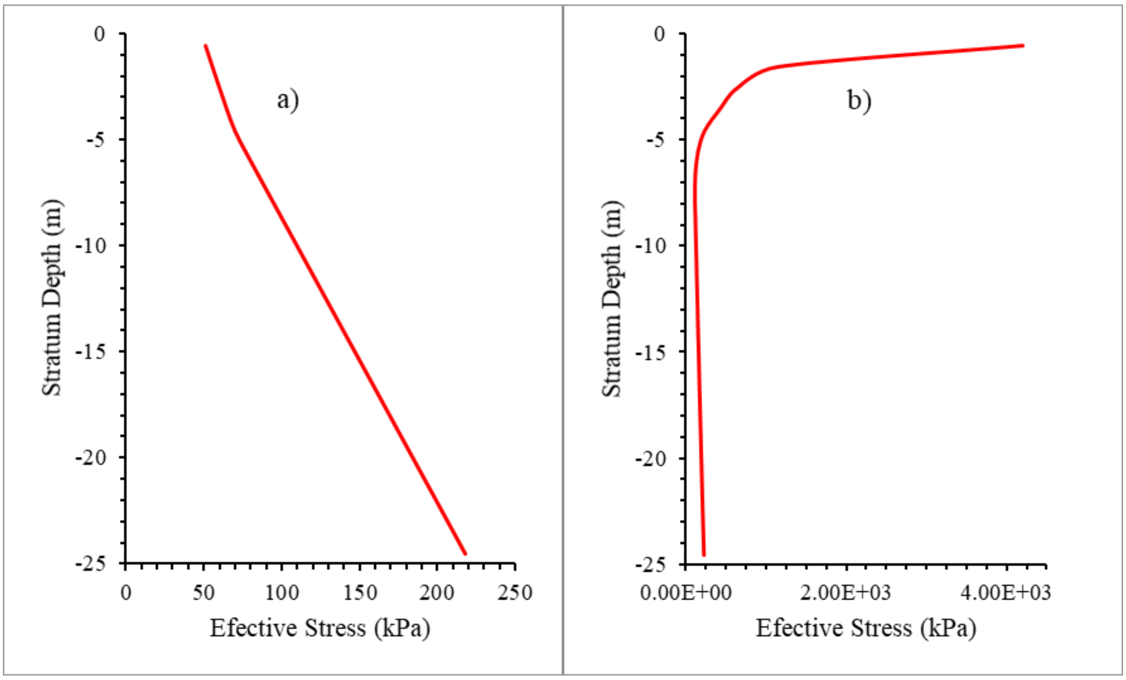

Figure 5 Effective stress in the soil stratum (a) saturated (b) 87600 hours of drought simulation

From fig. 5 and fig 3, it is possible to plot the maximum shear modulus at each point in the soil stratum. Results are present in fig. 6. In fig. 6a, the maximum shear modulus is almost constant in all the stratum. This effect happens because effective stress values in the soil stratum are small (between 0 to 400 MPa). The effective stress is small because in saturated conditions the contribution of the suction in the effective stress is nearly zero, and the pore water pressure is high, as explained in previous sections. So, the maximum shear modulus is almost constant over the soil stratum.

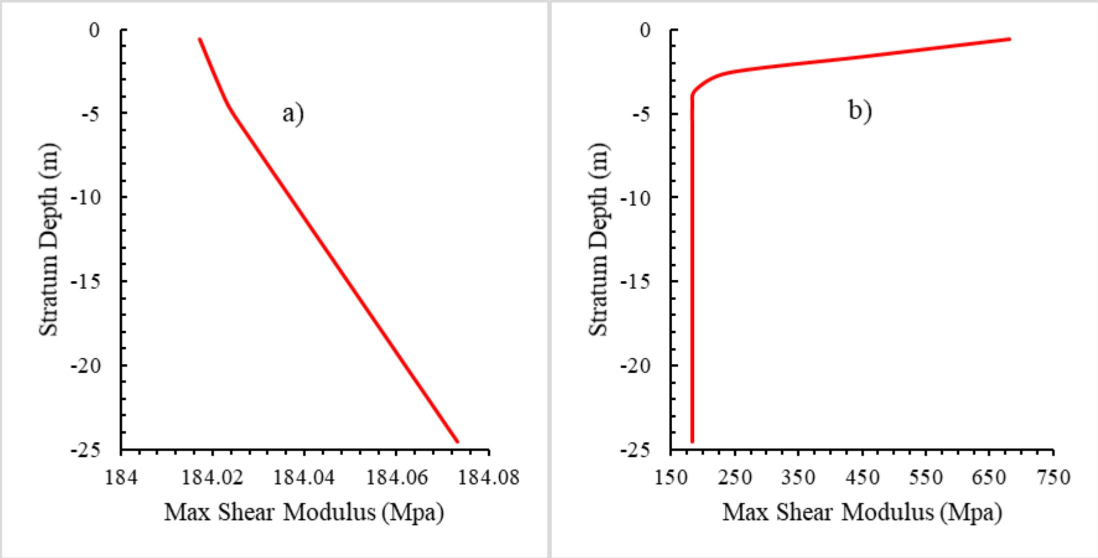

Figure 6 Maximum shear modulus in soil stratum (a) saturated (b) 87600 hours of drought simulation

From fig. 5b since the effective stress values are greater than fig. 5a values in the first soil layers, the shear modulus from fig. 6b is also greater than the shear modulus from fig. 6a in the first soil layers. The suction due to drought had an impact on soil resistance since the maximum shear modulus is large. It can be seen that the shear modulus degradation curve has large values for large suction values (Fig. 2), so the shear modulus does not decay so fast with the deformation. This result implies that even with a soil deformation of 0.1% (Fig. 2) or greater, the shear modulus is large enough to prevent plasticization, and higher values of lateral load are needed to deform the soil. Making it stiffer than the same soil under saturated conditions.

Stage II. Static Push-over analysis in high plasticity clay

The numerical model was conducted in OpenSeesPL using the soil properties describe in previous sections. This part of the section makes a comparison between the results of three piles (10, 15, and 20 m) surrounded by a soil domain saturated and after 87600 hours of drought. Fig. 7 shows the loading protocol used to reach the target displacement of 2% of the pile's length deformation on the head.

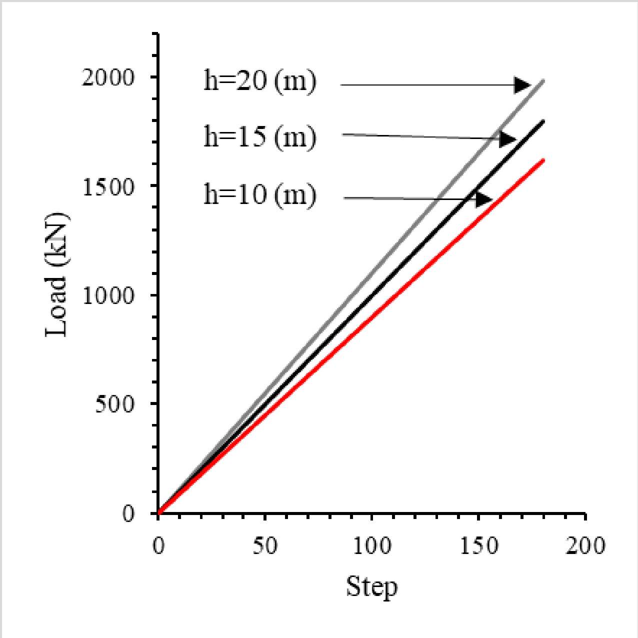

Figure 7 Load protocol used on static pushover analysis

The load protocol change depending on the analyzed pile, for a 10 meters depth pile the loading protocol was 180 steps with increments of 9 kN, for a 15 meters depth pile, it was 180 steps with 10 kN increments and for a 20 meters depth pile, it was 180 steps with increments of 11 kN. The control node was the center of the piles' heads. After loading protocol was applied, the displacements of the control nodes were obtained for every step. Fig. 8 shows these results for saturated soil and dry soil.

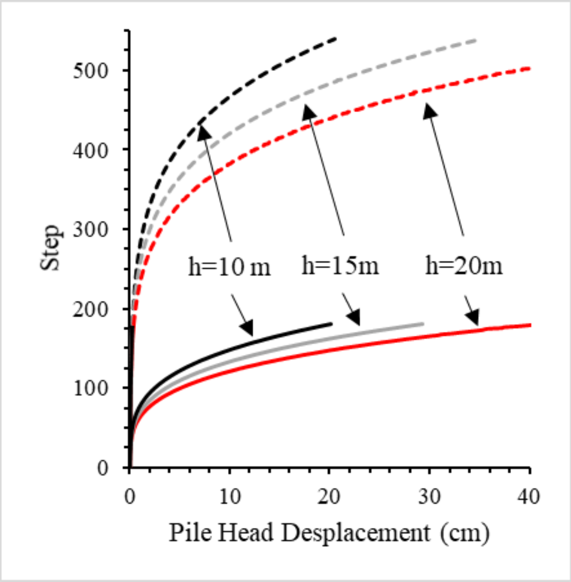

Figure 8 Displacement on piles' heads for each load step.

It is observed that all piles on saturated soil reach the target displacement at step 180, while piles on 87600 hours of drought soil are on the elastic range at the same step. This phenomenon happened because dry soil is much stiffer than saturated soil, so higher loads are required to reach the target displacement (i,e., for a 10 meters pile on dry soil 540 steps of 9 kN increments were required, for a 15 meters pile, it was 540 steps of 10 kN increments, and for a 20 meters pile were required 500 steps of 11 kN increments). The final lateral loads required to reach the target displacement in dry soil were 4860 kN, 5400 kN, and 5500 kN for 10, 15, and 50 m piles respectively. Notice that fewer steps were required to reach target displacement on the 20 m pile in dry soil. This happens because the lateral deformation in the 20 m pile is larger than the other piles, so the deformation in the soil is also large and from fig. 2, it is known that dynamic shear modulus is small for large values of soil deformation, therefore the clay becomes less stiff allowing greatest lateral deflections with fewer load values.

The change in soil properties at dry conditions increments the load required to displace the pile's head, but it also changes the shear and moment diagrams. Fig. 9 and fig. 10 show the shear and moment diagrams of all piles in saturated and dry soil at step 180.

Fig. 9 shows that the shear force is greater under saturated conditions than dry conditions, and the same effect happens in all piles. At 1 meter depth, the shear force in the 10 m pile is 1200 kN under saturated conditions and 200 kN under dry conditions. In this figure, it is possible to identify that the maximum shear force that is not in the top has different positions depending on the soil's condition.

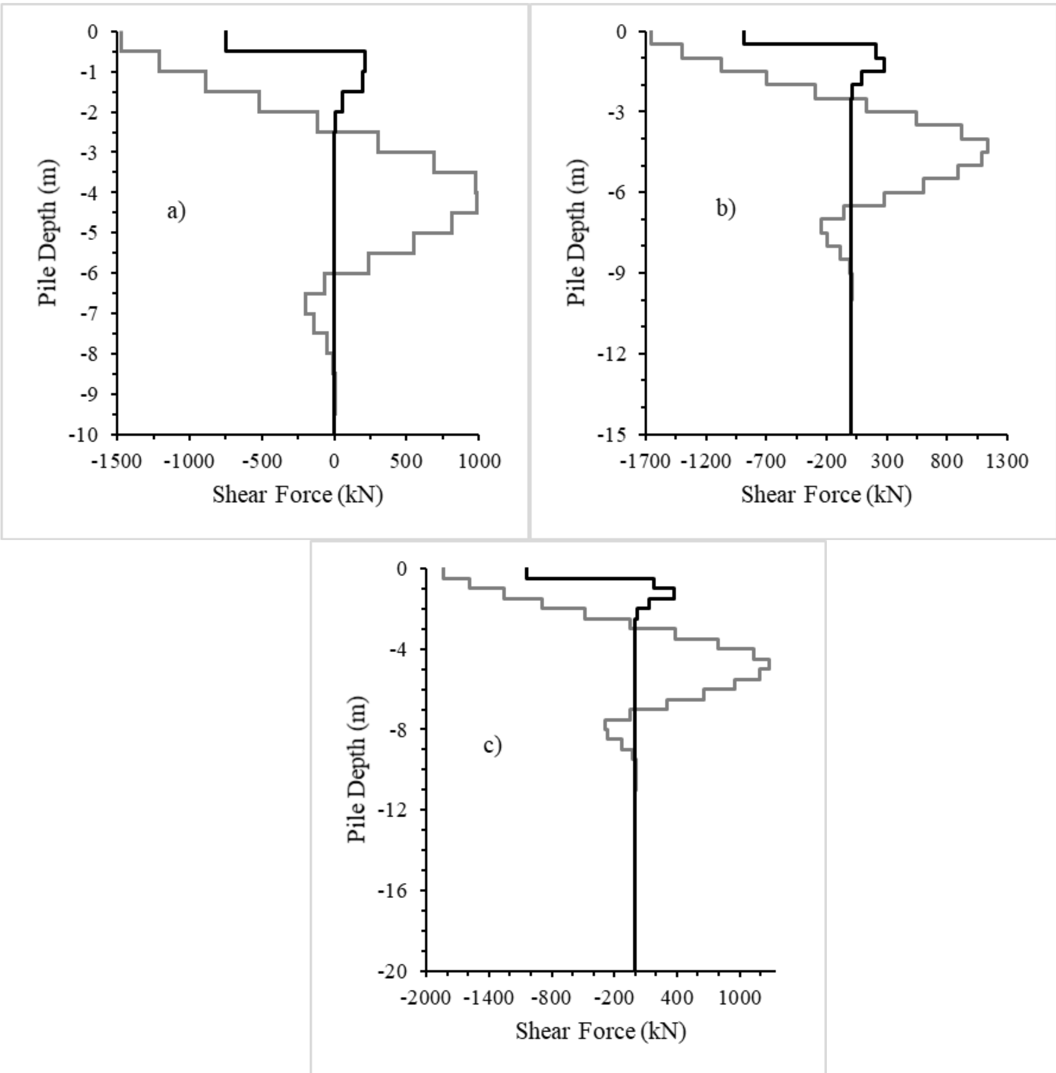

Figure 9 Shear diagrams at step 180 on saturated soil (gray line) and dry soil (black line); (a) 10 m depth pile; (b) 15 m depth pile; (c) 20 m depth pile.

Fig. 10 describes the same effects, moment diagrams over the piles in saturated condition are way greater than the diagram in dry condition and the moments need more depth to dissipate. The position of the max moment also changes and also, the max moment in saturated soil is six times greater than the max moment in dry conditions (e.i., in the 10 m depth pile the max moment is 1870 kN m in saturated conditions, and 285 kN m in dry conditions). In general, under saturated conditions, the pile's depth require to dissipate the internal forces is 2.5 times greater than the depth required in dry conditions. The internal forces are larger in saturated conditions because the deformation in the pile is greater than dry conditions at the same pushover step, so the rate of change in the relative transversal rotation in the pile is large, this effect increases the internal forces.

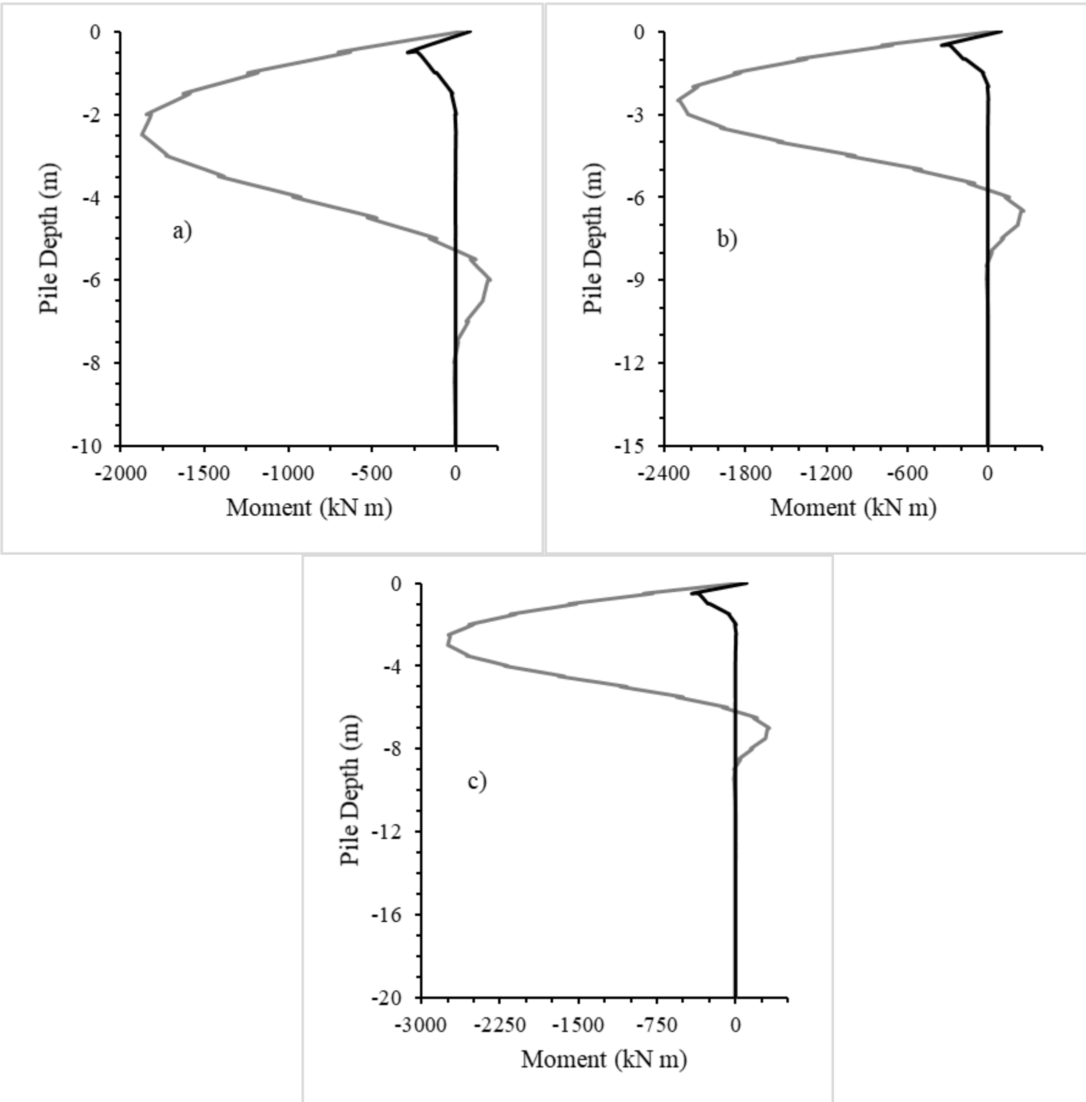

Figure 10 Moment diagrams at step 180 on saturated soil (gray line) and dry soil (black line); (a) 10 m depth pile; (b) 15 m depth pile; (c) 20 m depth pile.

Both moment and shear diagrams on piles have higher values on saturated soil than diagrams on dry soil, it happens since dry soil is stiffer than saturated soil, so in the first dry soil strata that have higher effective stress values don't let the pile have large deformations and relative rotations. This effect generates a reduction in the internal forces of the pile and dissipates these forces to a lesser depth.

CONCLUSIONS

This research explores how the difference between saturated and dry clay affects its properties and how these changes in mechanical and dynamic properties affect increasing or decreasing the pile's demand resistance. The main findings are summarized as follows:

1. Long periods of drought over clays increase the effective stress and maximum shear modulus since suction generated from negative pore pressure in dry soil strata contributes to effective stress.
2. Less load is required to deform a pile until the plastic range for saturated soil conditions.
3. An increment on the saturation condition of the soil generates an increment of the maximum shear and moment forces, and the position of these maximum forces over the pile change.
4. Both saturated and dry conditions of soil need to be considered on pile structural design since forces over the pile chance in magnitude and position.

Further investigation needs to be done to study the behavior of different piles' shapes under different types of soils such as silts and sands for different saturated and dry conditions and the axial load due to superstructure needs to be include.

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