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Seismic behavior of pile foundations in unsaturated soils

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Abstract. Earthquakes have caused significant damage to civil engineering structures worldwide due to inadequate lateral load capacity and excessive deformation of pile foundations supporting these structures. The seismic performance of pile foundations interacting with unsaturated soils could be affected by changes in matric suction due to the moisture content variation induced by seasonal weather changes or water table fluctuations. Hence, the main objective of this study is to investigate the effects of unsaturated soil conditions on the seismic response of a pile-soil system in silty clay soils. This study utilized a stand-alone finite element computer code called DYPAC (Dynamic Piles Analysis Code) developed using the Beams on Nonlinear Winkler Foundation (BNWF) approach. Free field soil displacements and p-y curve parameters, inputs needed for DYPAC analyses, were updated based on the soil suction variations. This study found that soil suction can significantly influence the seismic performance of piles interacting with unsaturated silty clay soils, especially as the soil becomes drier in the transition zone. The best seismic performance of the pile, which is the minimum lateral pile displacement, happened in the transition zone between fully saturated and nearly dry conditions.

1. Introduction

Pile foundations are used extensively to safely transfer axial and lateral loads from superstructures to subsurface when superstructure loads are large and/or weak soil layers are present near the ground surface. Lateral loads play a key role in the design and construction of pile foundations, which are used to support high-rise buildings, long-span bridges, transmission lines, and offshore structures.

Earthquakes have caused significant damage to civil engineering structures worldwide due to inadequate lateral load capacity and excessive deformation of pile foundations supporting these structures. The soil layer above the groundwater table is often subjected to moisture variations due to seasonal weather changes or water table fluctuations. These moisture changes will influence the behavior of soils, including their strength and stiffness parameters. Designing a pile foundation in seismic-prone areas without considering the moisture changes of soil interacting with piles may adversely impact the seismic performance of the piles.

Significant studies on the behavior of laterally loaded piles have been reported in the literature. The majority of these studies are primarily concerned with the seismic behavior of piles in saturated soils. Less attention has been paid to the effect of unsaturated soil conditions on the response of laterally loaded piles; however, it is well known that pile behavior is greatly affected by the mechanical properties of soil layers near ground surface [1], which is frequently above the water table. To the best of the authors' knowledge, only a few studies [2–5] have explored the effect of soil suction on the response of laterally loaded piles in unsaturated soils. Mokwa et al. [6], for example, proposed a method for calculating the load versus lateral displacement curves for unsaturated soils based on the results of five full-scale load tests. Stacul et al. [2] used the Modified-Kovacs model to build a hybrid BEM p-y curve technique for single piles that simulates the influence of matric suction by raising the stress state and stiffness of shallow soil layers. Lalicata et al. [3] used centrifuge experiments to study the effect of the degree of saturation on the behavior of laterally loaded piles. In unsaturated soils, they found a considerable increase in soil stiffness and ultimate lateral resistance.

The main aim of this study is to investigate the effects of unsaturated soil conditions on the seismic response of a pile-soil system. This study used a stand-alone finite element computer code called DYPAC (Dynamic Piles Analysis Code) developed using the Beams on Nonlinear Winkler Foundation (BNWF) approach [7]. DYPAC analyzes the seismic response of a single pile in a layer of soil. This computer code models the pile as a beam element and the nonlinear soil behavior as springs and viscous dashpots using a nonlinear p-y element. Predicted suction values corresponding to different moisture contents were used to determine the apparent cohesion used in defining the p-y curve parameters needed in DYPAC modeling.

2. Method of Approach

This section begins with a discussion of the Winkler model used in this study as a soil-pile interaction analysis method and proceeds with the derivation of the governing equations for seismic soil-structure interaction problems using the BNWF approach. The numerical integration, which is based on the Hilber-Hughes-Taylor (HHT)-α method, is then discussed. Finally, site response analysis using DEEPSOIL [8] to obtain free field soil displacements and the effects of unsaturated soil conditions are presented.

2.1. Soil-pile interaction modeling

Winkler (1867) developed a simplified method called Beams on Elastic Foundation (BEF) that is commonly

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used in civil engineering practice today to analyze soil-pile interactions. This approach models the pile as a beam element and the soil as an infinite number of discrete spring elements with the interactions described using a p-y curve. Here, "p" denotes lateral soil resistance per unit length of the pile, and "y" denotes the lateral pile displacement. Later, this concept was extended as the BNWF and used discrete nonlinear springs (Figure 1) to account for the nonlinearity of soils. Full-scale field experiments or reduced-scale centrifuge tests were used to derive the p-y curves. The relationship between p and y is a function of soil depth, soil stress-strain properties, and the pile diameter.

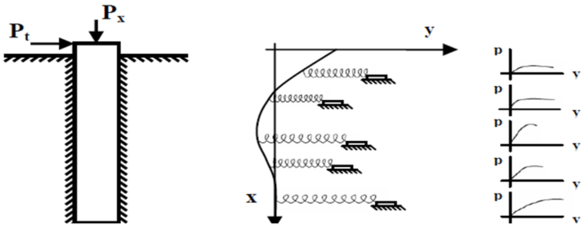

Fig. 1. Discrete nonlinear springs along the pile to simulate soil-pile interactions [9].

It is important to carefully account for soil-pile yielding, gapping, radiation damping, and soil cave-in and recompression when applying the BNWF models to problems involving cyclic and dynamic loading [10]. Incorporating these factors into the nonlinear *p-y* elements is a very complex and challenging task, even when the soil system is homogeneous.

The p-y model that used in this study is Boulanger et al. [11] model. They developed a nonlinear *p-y* element that includes elastic, plastic, and gap components (Figure 2) that are connected in series. The elastic component simulates the far-field motion of the soil using a linear spring and a dashpot in parallel to model radiation damping. The plastic component simulates the near field motion of the soil adjacent to the pile using a nonlinear spring that considers the degradation of stiffness and strength. The gap component simulates the drag force on the pile when it moves within the gap by using a nonlinear drag spring. The transition from the gap to contact was made smooth by a parallel nonlinear closure spring. For this study, the input parameters p_{ult} and y_{50} were based upon Matlock's [12] equations:

$$p_{ult} = c_u b N_p \tag{1}$$

$$N_p = \left(3 + \frac{\gamma' x}{c_u} + \frac{Jx}{b}\right) \le 9 \tag{2}$$

$$y_{50} = 2.5 b \varepsilon_{50} \tag{3}$$

where b = pile diameter; N_p = lateral bearing capacity factor; γ' = average buoyant unit weight; x = depth; c_u = undrained shear strength; and ε_{50} = strain corresponding to a stress of 50% of the ultimate stress in a laboratory stress-strain curve. ε_{50} was taken as 0.02 for $c_u \le 48\ kPa$, and 0.01 for $48 < c_u < 96\ kPa$ based on the typical values proposed in the literature for soft and medium stiff clay, respectively. Also, J was taken as 0.5 according to Matlock's recommendations for soft clay and 0.25 for medium stiff clay.

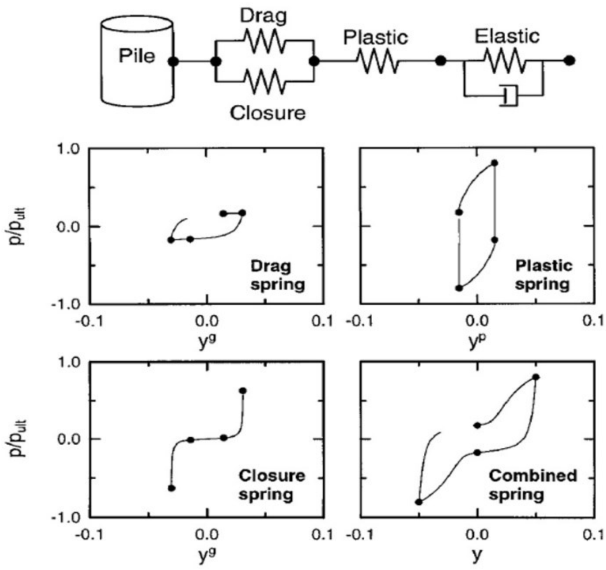

Fig. 2. Nonlinear p-y element that includes elastic, plastic, and gap components [11].

2.2. Derivation of the Governing Equation

This study considers a beam on a nonlinear Winkler foundation (Figure 3) under dynamic loading. It is desirable to incorporate the axial loading to consider P-Δ effects. In the following derivations, the total pile displacement (y_{tot}) is a sum of the base (e.g., bedrock) displacement (u_g) and the pile displacement relative to the base (y_{rp}). The soil displacement relative to the base is denoted by y_{rs}. The time histories of y_{rs} is an input to this analysis and are typically obtained by performing a site response analysis of the free-field far from the pile.

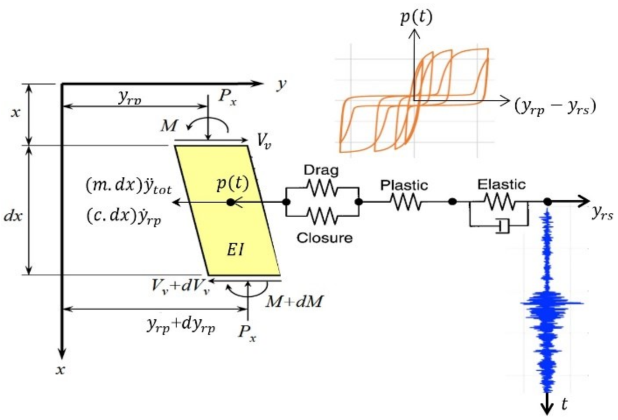

Fig. 3. An infinitely small element from a dynamic beam

As shown in Figure 3, the equilibrium of moments (ignoring second-order terms) leads to the following equation

$$(M + dM) - M + P_x dy_{rp} - V_v dx = 0 \tag{4}$$

Rearranging Equation. 4 leads to the following equation,

$$\frac{dM}{dx} + P_x \frac{dy_{rp}}{dx} - V_v = 0 \tag{5}$$

By differentiating Equation. 5 with respect to x, the following equation is obtained

$$\frac{d^2M}{dx^2} + P_x \frac{d^2y_{rp}}{dx^2} - \frac{dV_v}{dx} = 0 \quad (6)$$

where the following relationship is noted (assuming EI is a constant),

$$\frac{d^2M}{dx^2} = EI\frac{d^4y_{rp}}{dx^4} \quad (7)$$

The horizontal equilibrium of forces leads to the following equation:

$$(V_v + dV_v) - V_v + (m.dx)\frac{d^2y_{tot}}{dt^2} + (c.dx)\frac{dy_{rp}}{dt} + p(t)dx = 0 \quad (8)$$

Rearranging Equation. 8 leads to the following equation,

$$\frac{dV_v}{dx} + m\frac{d^2y_{tot}}{dt^2} + c\frac{dy_{rp}}{dt} + p(t) = 0 \quad (9)$$

and substituting Equations 6 and 7 into Equation. 9 will result in,

$$m\frac{d^2y_{tot}}{dt^2} + c\frac{dy_{rp}}{dt} + \{P_x\frac{d^2y_{rp}}{dx^2} + EI\frac{d^4y_{rp}}{dx^4}\} + p(t) = 0 \quad (10)$$

where:

$$\frac{d^2y_{tot}}{dt^2} = \frac{d^2u_g}{dt^2} + \frac{d^2y_{rp}}{dt^2} \quad (11)$$

Based on Winkler foundation approach, the lateral soil resistance per unit length $(p(t))$ can be related to pile diameter (b), soil subgrade modulus (K_T), and relative pile displacement $(y_{rp} - y_{rs})$ via the following relation

$$p(t) = bK_T(y_{rp} - y_{rs}) \quad (12)$$

and substituting the Equations 11 and 12 into Equation 10 will result in

$$m\frac{d^2y_{rp}}{dt^2} + c\frac{dy_{rp}}{dt} + \{P_x\frac{d^2y_{rp}}{dx^2} + EI\frac{d^4y_{rp}}{dx^4}\} + bK_T(y_{rp} - y_{rs}) = -m\frac{d^2u_g}{dt^2} \quad (13)$$

where:
m = mass per unit length,
c = damping coefficient per unit length,
P_x = axial load in the pile, and
EI = flexural rigidity.

The spatially discrete nonlinear governing equation for a dynamic soil-structure element can be given in matrix form as in the following equation:

$$[m_e]\ddot{y}_{rp} + [c_e]\dot{y}_{rp} + [k_e]y_{rp} + b[K_T](y_{rp} - y_{rs}) = -[m_e]\ddot{u}_g \quad (14)$$

where $[m_e]$, $[c_e]$, and $[k_e]$ are element mass, damping, and pile stiffness matrices, respectively; and $[K_T]$ denotes the tangent stiffness matrix of the *p-y* curve. The effect of axial load is neglected in this equation, assuming lateral displacements are small and P-Δ effect can be neglected. The global equations for a dynamic soil-structure system can be given as

$$\mathbf{M}a + \mathbf{C}v + \mathbf{K}_\mathrm{p}d + \mathrm{P} = -\mathbf{M}\ddot{u}_\mathrm{g} \quad (15)$$

$$\mathrm{P} = b\mathbf{K}_\mathbf{T}(d - u) \quad (16)$$

where M, C, and K_p are global mass, damping, and pile stiffness matrices, respectively. P is a soil resistance vector. a, v and d denote relative pile acceleration, velocity and displacement vectors, respectively, u and $\ddot{u}_g$ denote relative soil displacement and base motion vectors, respectively.

2.3. Numerical Solution

In nonlinear dynamic problems, a robust time-stepping scheme can dampen the spurious effects of high-frequency modes and converge quickly to improve computational efficiency. The Hilber-Hughes-Taylor (HHT)-α method [13], also called the α-method, is a widely used numerical integration scheme in structural dynamics. A precursor of the HHT-α method is the Newmark time integration method. The HHT-α method has better accuracy and desirable numerical damping characteristics than the Newmark method. Muraleetharan et al. [14] implemented HHT-α method-based time integration scheme to solve the governing nonlinear equations for dynamic behavior of saturated soils. The current study combines the HHT-α method with the Newton-Raphson method to solve the nonlinear equations.

2.4. Site Response Analysis

Nonlinear analyses are performed for a level ground using the computer code DEEPSOIL [8]. The G/G_{max} and the damping ratio (%) curves are defined as functions of shear strain (%). These curves for silty clay were modeled using *Darendeli* [15] nonlinear model. Dickenson [16] proposed the empirical relationship for the shear wave velocity (v_s) for cohesive soils. The relationship is given by $v_s = 18(c_u)^{0.475}$ (v_s is in m/s and c_u in kPa) and this equation is used to calculate the shear wave velocity of silty clay. Also, it is important to note that the influence of suction is considered in free-field displacement analyses by changing the shear strength and hence the shear wave velocity for each suction scenario according to the equation given above. For simplicity, G/G_{max} and the damping ration curves were, however, kept the same for all suction values. Free field soil displacements were obtained for each suction value and then used as an input for DYPAC analyses.

2.5. Unsaturated Condition Effects

The influence of soil suction is incorporated into the p-y curves and site response analyses using the concept of apparent cohesion, which is a nonlinear relationship and was proposed by Vanapalli et al. [17] as follows:

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)(\tan\phi')\left(\frac{S - S_r}{100 - S_r}\right) \quad (17)$$

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$$C = c' + (u_a - u_w)(\tan \phi')\left(\frac{S - S_r}{100 - S_r}\right) \quad (18)$$

where τ is the shear strength of an unsaturated soil; c' is the effective cohesion for a saturated soil; ϕ' is the effective internal friction for a saturated soil; $(\sigma_n - u_a)$ is the net normal stress on the plane of failure; $(u_a - u_w)$ is the matric suction of the soil on the plane of failure; S is the degree of saturation; S_r is the residual degree of saturation; and C is the apparent cohesion and these values were used for c_u in Eq. 1 and 2 to calculate the p_{ult} values. The values of C were also used for c_u values in the Dickenson equation to evaluate the shear wave velocities for DEEPSOIL analyses. Hence, the free field soil displacements evaluated by DEEPSOIL analyses and p-y curves obtained by Boulanger model were recalculated for each suction scenario with the apparent cohesion value coming from Eq. 18. It means that by changing the matric suction, the cohesion will be changed, and then the shear strength and shear wave velocity will be changed; consequently, the free field soil displacement will be updated. Also, by changing the suction and apparent cohesion the p_{ult} and y_{50} will be updated in the p-y model. Both changes will affect the seismic response of a pile foundation as the moisture conditions in unsaturated soil changes.

3. Illustrative Case Study

An illustrative case study is presented to show how a pile foundation's seismic response can be affected in unsaturated soils by changes in moisture conditions. As shown in Figure 4, the pile has a length of 17 m, 2m of the pile was assumed to be above the ground surface. The pile diameter was assumed to be 0.28 m. The soil deposit includes eight silty clay layers in which the effective cohesion changes linearly from 20 kPa on the ground surface to 50 kPa at the bottom. The silty clay has a 10° internal friction angle and PI = 15. Also, the analysis provides an option to include a seismic mass on top of the pile that was assumed to be 660 kg in the current study.

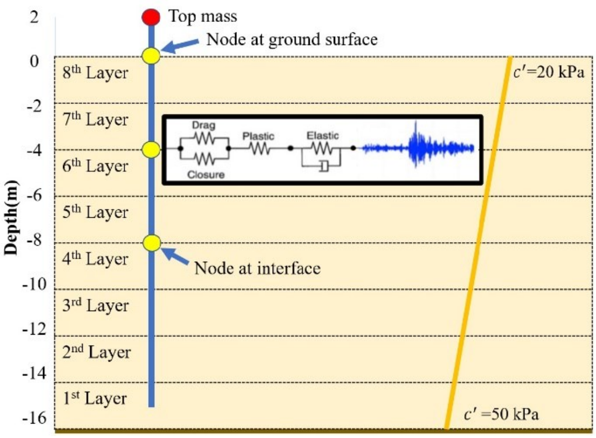

Fig. 4. Schematic illustration of DYPAC finite element model.

The soil water characteristic curve (SWCC) used in this study is presented in Figure 5. As can be seen, the residual degree of saturation is almost 40%. Based on the SWCC, the suction values of 0, 40, 100, 300, and 400 kPa were considered for various moisture scenarios in this study ranging from fully saturated soil to nearly dry conditions.

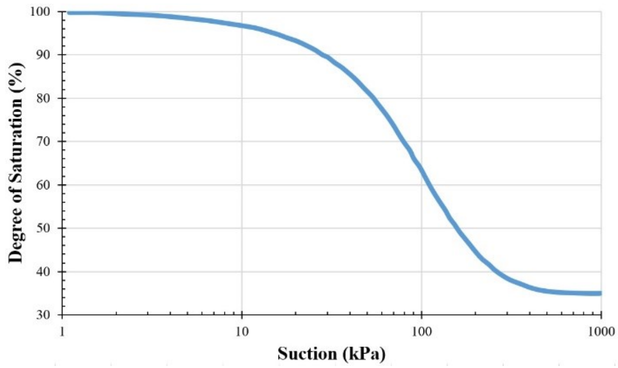

Fig. 5. Soil water characteristic curve of the silty clay used in this study.

The base motion event used in this study is a scaled version of a motion recorded during the 1989 Loma Prieta earthquake in California. Figure 6 shows the base motion acceleration-time history used in DEEPSOIL analyses and DYPAC modeling.

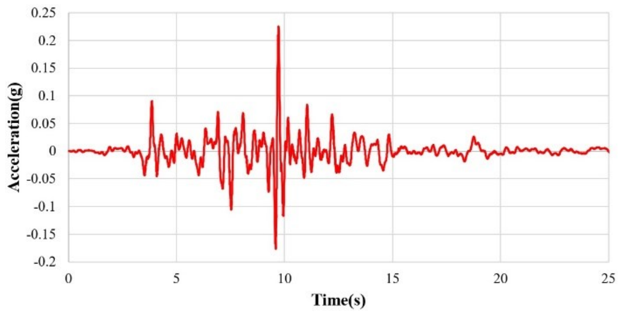

Fig. 6. Base motion acceleration-time history used in the illustrative case study.

4. Results and Discussion

Site response analyses were performed to obtain the free-field soil displacement data as an input for DYPAC analyses. As shown in Figure 7, the free-field soil displacement at the node on the ground surface is compared for different suction scenarios. As presented, the overall trends of the graphs are identical. However, the maximum values of the soil displacement time histories are significantly different. The free-field soil displacement decreased with the soil suction and then increased after the suction reached 100 kPa.

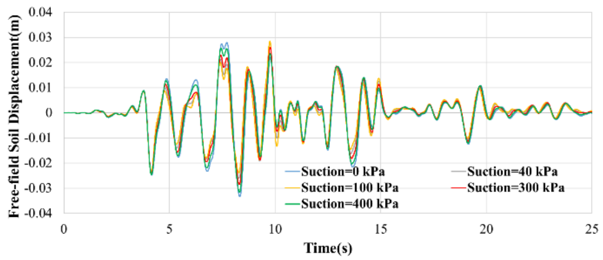

Fig. 7. Free-field soil displacement at the ground surface for the Loma Prieta earthquake for various suction scenarios.

The influence of soil suction is also incorporated into the p-y curves to consider the effects of moisture changes in soil-pile interaction. The p-y curves for various matric suction values were evaluated based on the apparent cohesion concept and using the Boulanger model. As shown in Table 1, the ultimate lateral soil resistance increased with the matric suction and then decreased after the suction reached 100 kPa.

Table. 1. Ultimate soil resistance (p_{ult}) in different suction values

Suction (kPa)	p_{ult} (kN/m)
0	27.3
40	34.8
100	37.6
300	31.7
400	28.8

From Figure 7 and Table 1 it can be seen that changes in moisture can influence the seismic response of a pile foundation due to two reasons: a) change in free-field soil displacement because of affected soil shear strength and shear wave velocity, and b) changes in p-y curves and lateral resistance for the pile due to the affected p_{ult}.

DYPAC analyses were next performed for various suction scenarios from fully saturated to nearly dry soil. The results show that soil suction can significantly affect the seismic performance of piles interacting with unsaturated soils. The seismic response of the pile foundation induced by the Loma Prieta earthquake is presented in Figure 8. The pile displacement-time histories show that the earthquake-induced displacement decreased with the soil suction and then increased after the suction reached 100 kPa. The results show that the peak value of the lateral seismic pile displacement in fully saturated soil is almost 150% of the minimum pile displacement, which happened for a matric suction value of 100 kPa.

As presented in Figure 9, the results show that the apparent cohesion and shear strength increased with soil suction to a peak value and then decreased when the suction was beyond a critical value (almost 100 kPa) corresponding to the peak shear strength. In fact, the apparent cohesion decreased to 20 kPa when the suction increased to 400 kPa, a value of apparent cohesion same as that of the saturated soil. It is important to note that the apparent cohesion versus suction graph in Figure 9 is for the 8th soil layer, that is the ground surface layer. Figure 9 shows that the best seismic performance of the pile interacting with the unsaturated soil happened in the transition zone. It means that the minimum lateral displacement of the pile happened in the transition zone in silty clay soils. The maximum pile displacement in matric suction of 100 kPa is 30 mm, while this value is 46 mm when the suction is 0 kPa (fully saturated soil).

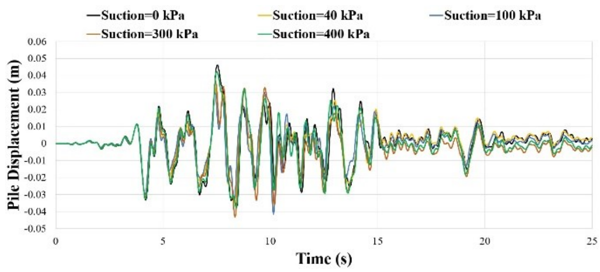

Fig. 8. Loma Prieta earthquake-induced lateral displacement for the top of the pile interacting with the unsaturated soil at different matric suction values.

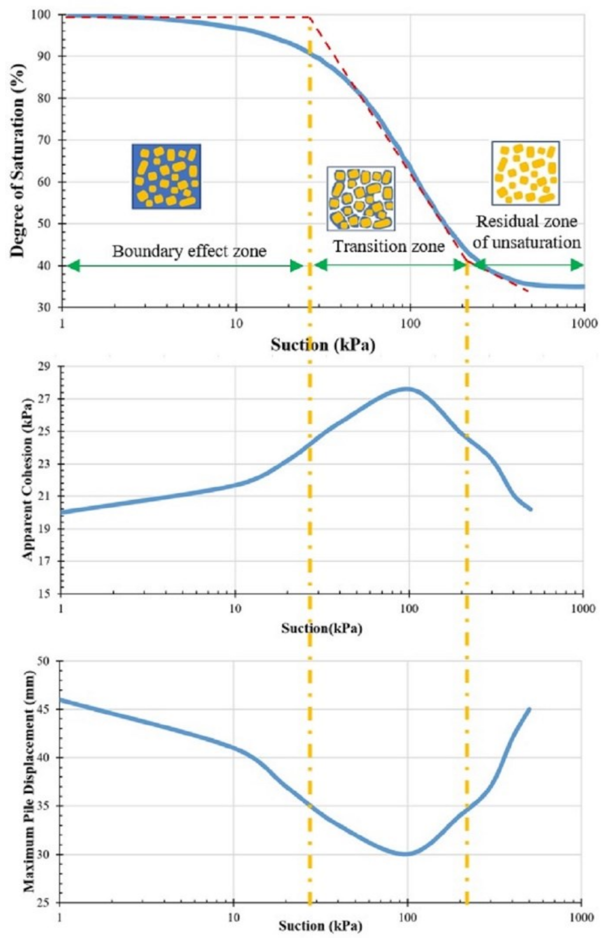

Fig. 9. Maximum pile displacement and apparent cohesion versus suction in three different saturation zones.

5. Conclusions

The main objective of this study is to investigate the effects of unsaturated soil conditions on the seismic response of the pile-soil system in silty clay soils. This

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study used a stand-alone finite element computer code called DYPAC (Dynamic Piles Analysis Code) developed using the Beams on Nonlinear Winkler Foundation (BNWF) approach.

Predicted suction values corresponding to different moisture contents were used to determine the apparent cohesion needed for defining the p-y curve parameters needed for DYPAC modeling. The free-filed soil displacements were also obtained using the affected soil shear strength and shear wave velocity values due to moisture content variation.

This study found that soil suction can significantly influence the seismic performance of piles interacting with unsaturated soils, especially as the soil becomes drier in the transition zone. Results showed that the best seismic performance of the pile and the minimum lateral pile displacement happened in the transition zone. The maximum pile displacement for a matric suction of 100 kPa was 30 mm, while this value was 46 mm when the suction was 0 (fully saturated soil).

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