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STUDY OF THE BEHAVIOR OF DEEP FOUNDATIONS UNDER CYCLIC LOADING IN SAND

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ABSTRACT

This work presents the results of modelling the behavior of deep foundations subjected to different cyclic loads and their displacements in relation to the static load in the sand. The behavior of deep foundations is modelled with the PLAXIS 2D software based on data from geotechnical tests performed in situ and in the laboratory. Modelling is an alternative solution to the high cost of in-situ tests and to describe the behavior of deep foundations as well as possible. The results obtained show that piles under lateral head loading cause a horizontal displacement normalized to the diameter. The cyclic loading of the pile causes a progressive mobilization of the soil mass at depth. The lateral displacement increases with the cycles without stabilizing and generates an irreversible residual displacement due to the progressive plasticization of the soil. Lateral cyclic loading has a positive influence on the behavior of the pile under cyclic loading, due to the reversible effect on the pile displacement.

KEYWORDS: Cyclic loading; Drained condition; Sand; Pile modelling.

1. INTRODUCTION

Civil engineering structures (bridges, tunnels, silos, etc.) are sometimes subjected to cyclic loads in normal or accidental situations. During this time, the deep foundations in charge of supporting the structure are usually subjected to cyclic loading in axial or transverse directions. Cyclic loading is a variable and repetitive loading that is applied for a number of cycles with a constant amplitude and period. These loads may cause problems with the stability or durability of the piles in the operational phase for foundations founded in soil with low bearing capacity. The soil-pile connection under cyclic loading depends on the soil type. Indeed, Randolph and Gourvenec (2011) [1] (in their work on clay and sandy soils under stress) note that during cyclic loading applied to a clay; there is an increase or dissipation of pore pressure, a degradation of undrained shear strength and an accumulation of permanent displacements. Sand subjected to cyclic loading is associated with liquefaction potential, displacement accumulation and a possible increase in pore pressure which depends on the frequency of loading and the permeability of the sand. The cyclic loading of deep foundations on piles or micro-piles remains undetermined, or at least to be perfected by geotechnical engineering. Despite the fact that the soil-structure friction coefficient varies little, cyclic degradation is sometimes observed during the operation of structures. The degradation mechanism is related to the variations in normal soil stress on the pile, even for a small number of cycles [2, 3, 4]. The problem of cyclically stressed soils has been the subject of numerous studies. Soil-structure interfaces have so far been studied in the laboratory, for a small number of cycles, typically < 102 [5, 6, 7, 8, 9, 10]. The use of cyclic loading behavior laws is very complex in large-scale tests, which justifies the modelling of cyclic loading that is important for soil-structure interfaces [3, 11, 12, 13]. However, cycles on soil-structure interfaces and on piles have been relatively little studied in the laboratory and in situ for large numbers of cycles, due to the complexity of the tests [14]. To overcome the complexity and high cost of in situ tests, modelling can be an alternative solution to the problem at hand.

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The objective of this work is the prediction of the behavior of piles under load subjected to cyclic loading, for a better understanding of the soil-structure behavior in situ.

2. MATERIALS AND METHODS

The study site is located on the Brazzaville corniche along the Congo River between the cable-stayed bridge and the Mami Wata restaurant. This study was based on geotechnical studies of the pavement platform by means of pressiometric soundings, carried out by the National Laboratory of Public Works of Congo (BCBTP). The results of the investigations of the site identified during the drilling are described below:

At a depth of 10 to 15 m, silty-clay sediments at the edge of the Congo River, and sandy cover materials (sands) moving away from the river;

Beyond a depth of 15 m, the soft sandstone bedrock of the Stanley Pool, with marly or sandy, more or less cemented layers. The physic-mechanical characteristics of the soils on the project site are contained in Table 1.

Table 1. Mechanical characteristics of the soil, obtained with the Menard pressure meter

Training	Depth (m)	Pl (MPa)	E_M (MPa)	Internal friction coefficient (ϕ)	Cohesion not Drained (C_u)	wet Density γ_h (KN/m^3)	Dry soil density γ_d (KN/m^3)	Water content W (%)
Silty-clay sediments	0 to 10 (River bank)	0.40	4		0			
Sands	10 to 20	0.70	7	28	5	21	18	17
Soft sandstone	> 20 m	5	50					

The density is determined by soil mechanics formulas. The void index (e) and porosity (n) are determined by the following formulas:

$$e = w\,\% \times G_s \Rightarrow e = 0{,}17 \times 2{,}65 = 0{,}45 \qquad (1)$$

$$n = \frac{e}{1+e} \Rightarrow n = \frac{0{,}45}{1+0{,}45} = 0{,}3 \qquad (2)$$

The shear modulus (Gs) is taken to be Gs=2.65.

Plaxis 2D, is a software package suitable for analyzing the deformations and stability of the structure for different geotechnical applications. This program produces a plastic calculation, a consolidation analysis and a variable analysis. It allows the analysis of elastic, elastoplastic, elasto-viscoplastic problems in 2D or 3D and in large displacements by the updated Lagrangian method. In Table 2, the sand and the characteristics of the pile treated with Plaxis 2D software are recorded.

Table 2. Processing of geotechnical soil data and mechanical properties of piles in plaxis 2D version 8.2.

Parameters	Symbol	Values	
	Pile property		
Normal stiffness (KN/m)	EA	100995,57e^3	227240e^3
Flexural stiffness (KN/m)	EI	25248e^3	127822,52e^3
Young's modulus (MPa)	E	32164,195	
Density of concrete (KN/m^3)	γ	25	25
Fish coefficient	υ	0,2	0.2
Pile section (2 m^2 à 3 m^2)	A	3.14	7.07
Properties	Plaxis data	HSM model	
Reference secant modulus (E_M : 4 ; 7 ; 50)	E_{50}^{ref}	32000	

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Reference unloading module	E_{ur}^{ref}	96000	
Odometer reference module	E_{oed}^{ref}	18000	
Fish coefficient	υ	0.2	0.2
Cohesion	C_u	0	5
Power	M	0.5	

The number of cycles is taken as 10, the length of the pile as 20 m, two diameters 3 m and 2 m are chosen for the study in a sand bed of (50 m2). The loads used for the modelling are: 250 KN, 450 KN, 650 KN, 900 KN. The behavior law used for the sand is the Hardening Soil Model (HSM). This law has a non-linear hyperbolic behavior based on the well-known model [15]. The plasticity surface is not fixed as in the Mohr-Coulomb (MC) perfect plasticity models. Hardening is allowed in shear and simple compression (isotropic hardening). This model was developed for the behavior of powdery soils. The HSM (Hardening Soil Model), implemented in the Plaxis calculation code, is a hyperbolic model that was originally established by Kondner (1963) [16], then taken up by Duncan and Chang (1970) [15], completed by the use of the theory of plasticity and the introduction of the load surface and soil dilatancy. It comprises 8 parameters (m: a fitting parameter that depends on the type of soil; E50ref: reference secant Young's modulus, at 50% of the deflector at failure, under a confining stress sigma 3 = Pref = 100 kPa; Eoedref: reference eddy modulus for sigma 3 = Pref; Euref: reference unloading modulus; upsilon{ur}: load-unload Poisson's ratio; c, ϕ and ψ, α = 0. 5: Mohr-Coulomb plastic parameters). The different moduli were evaluated at the mid-height of each layer, and the reference moduli were deduced from the formulae below and d{eq} the equivalence diameter proposed by the Plaxis finite element calculation:

$$E_{oed}^{ref} = \frac{E_{50}^{ref}}{\frac{E_{50}}{E_{oed}} \times \left(\frac{1}{K_0}\right)^m} \qquad E_{50} = \frac{2E_M}{\alpha} \qquad (3)$$

$$K_0 = 1 - \sin\varphi \qquad E_{oed} = \frac{E_{50}}{1,3} \qquad (4)$$

$$d_{eq} = \sqrt{\left(\frac{12E_P I_P}{E_P A_P}\right)} \qquad \upsilon_{ur} = 0,2 \qquad (5)$$

$$E_{ur}^{ref} = 3 \times E_{50}^{ref} \qquad E_{50}^{réf} = \frac{4E_M}{0,5} \qquad (6)$$

This study models the behavior of an insulated pile under monotonic and cyclic lateral loading based on geotechnical data using Plaxis 2D software.

3. RESULTS AND DISCUSSION

Figures 1 to 11 show the deformation curves of an isolated pile under monotonic and cyclic lateral loading.

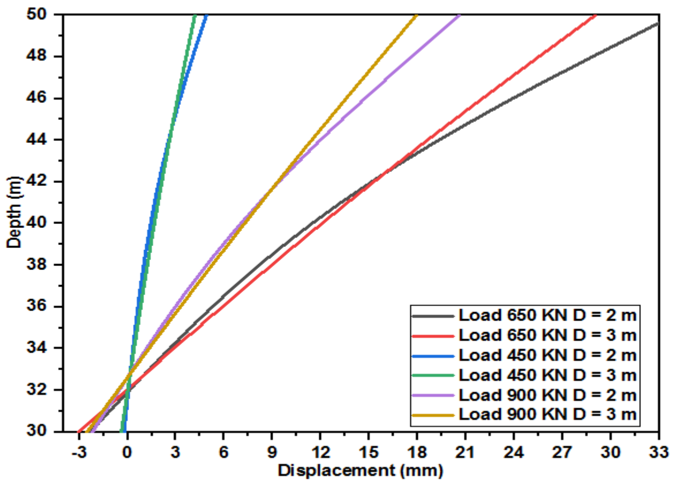

Fig.1.Comparative deformation curve of the isolated pile under lateral loading and post-cyclic loading for different pile diameters

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Figure 1 shows the lateral deformations of an insulated pile under static lateral loading (pre-cyclic and post-cyclic) as a function of (pre-cyclic and post-cyclic) as a function of the depth and diameters of the pile's diameters in the sand. The displacements of the pile before cyclic loading are high compared to the pile displacement after cyclic loading. The geometric shape of the geometric shape of the pile has a considerable influence on the pile design. As the pile diameter increases, the displacements tend to decrease. The diameter increases the resistance of the pile to the stresses applied to it. The difference in displacement between the two diameters (3m and 2m) under pre-cyclic static lateral loading (for a load of 650 KN) is 4.46%. The difference between the initial loading of the 2m diameter pile and the final loading of the same diameter is 39.34%. This suggests that the cyclic lateral loading in the sand has a positive influence on the pile behavior. There is a decrease in the lateral displacement of the pile despite the variations in the load applied to the pile head (as a result of the cyclic lateral load applied to the head of the deep foundation). It can be said that the lateral cyclic loading has a positive influence on the behavior of the pile under cyclic loading. There is a reversible effect on the pile displacement. There is a decrease in the displacement of the pile after the lateral cyclic loading. This result is in agreement with the studies of Schoefs F. and Levacher (1994) [17], who studied the effect of cycling on a laterally loaded pile in dense sand. Schoefs F. (1993) [18] shows that the pile tends towards equilibrium under the applied cyclic lateral loads. The soil consolidates around the pile and tends towards a state that changes relatively little with the number of cycles. The effect of the cyclic loads has an elastic behavior.

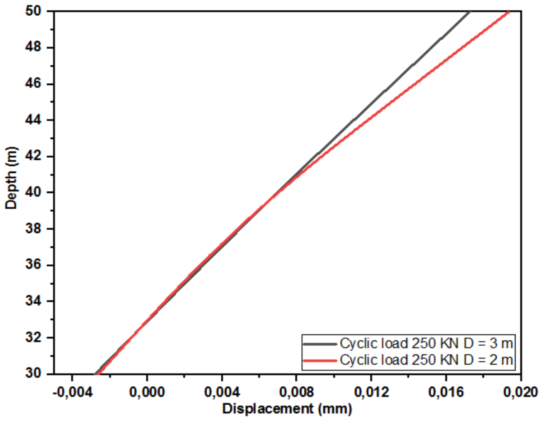

Fig.2. Lateral deformation curve of an insulated pile under cyclic lateral loading versus pile diameter

The curve in (Figure 2) shows the difference in displacement of isolated piles under cyclic lateral loading of 250 KN as a function of the diameter. This curve shows identical linear deformations at pile depth and from the surface (50 m^2) of the natural ground to a depth of 40 m, a slight lateral deformation is noted. The difference in diameters has a very significant influence on the design of the pile behavior under lateral cyclic loading. When the diameter is increased to 3 m, the displacement at the head of the pile is 0.0172 mm compared to the 2 m diameter of the first test where the displacement at the head of the pile was 0.0172 mm. When the diameter is increased to 3 m, the displacement at the head of the pile is 0.0172 mm compared to the 2 m diameter of the first test where the displacement is 0.0193 mm. Under cyclic lateral under cyclic lateral loading, there is a 12.21% difference in displacement between the two diameters.

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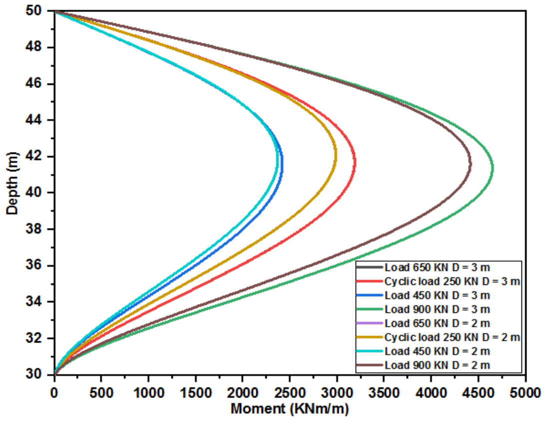

Fig.3. Comparison curve of different bending moments of piles under pre-cyclic and post-cyclic pre-cyclic and post-cyclic lateral loading as a function of diameters

The bending moment curves in Figure 3 show a certain cohesion in the behavior of piles under static and cyclic loading. The pre-cyclic bending moment for a load of 650 KN and two pile diameters of 3 m and 2 m and the bending moment under lateral cyclic loading for a load of 250 KN are identical. Craig and Kan (1986) in their work, centrifugally tested a 1:25 and 1:44 scale model under cyclic lateral loading and compared the results with the analytical approaches of Hudson Matlock and Reese (1960) [20] and Harry G. Poulos (1971) [21]. The model pile is darkened during centrifugation in dense sand (ID = 88%). In addition to comparisons with existing analytical methods, the tests showed that the maximum moment generated by cyclic loading was greater than that due to static loading. The difference is almost zero in our case. However, when comparing the final loading moment with a load of 450 KN, the moment of the lateral cyclic load is greater than that of the final unloading with the same load and for both diameters. However, the bending moment curves vary according to the applied load and its diameter. The cyclic lateral loading has a very considerable influence on the bending moments of piles, with a reduction in the increase of the pile moment in the sand. The bending moment is high when increasing the pile diameter, as a result of pile-soil contact and soil-pile deformation in the sand.

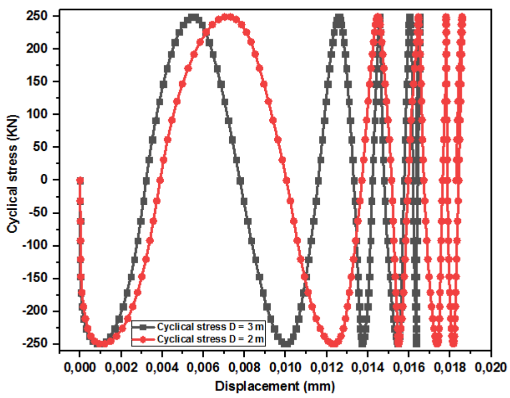

Fig.4. Comparative stress-displacement curves of cyclically loaded piles for different diameters

Figure 4 shows the stress-displacement curves at the pile head during the cyclic lateral loading. During the first cycles, large displacements are observed for diameters of 2 m and 3 m. The diameters have an influence on the cyclic behavior of the pile. When the diameter is increased, the displacements decrease as a result of the rearrangement of the sand in the vicinity of the pile; it can be said that there is an equilibrium in the soil-pile relationship. For both types of diameters, there is an accommodation effect which is a progressive increase in deformation that tends to stabilize after a certain number of cycles. The difference in displacement between the two diameters is of the order of 25%.

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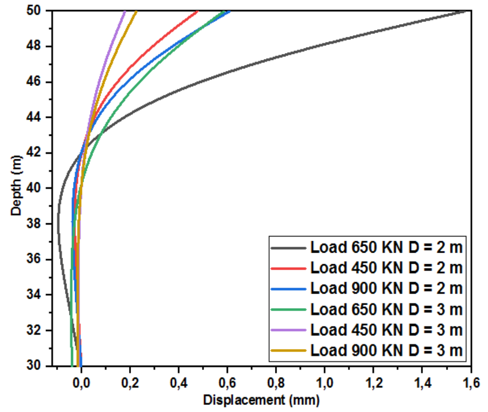

Fig.5. Deformation curve of insulated pile under static (pre and post) cyclic loading in saturated sand as a function of different diameters

Figure 5 shows the behavior of the insulated pile in saturated sand under static pre- and post-cyclic lateral loading. The pile in saturated sand shows a different behavior than the pile in dry sand in displacement and deformation. In saturated and stable sand, the pile undergoes less considerable displacement than in dry sand. Figure 5 clearly shows that the piles underwent very large displacements during the pre-cyclic static lateral loading of 650 KN, with both diameters of 3 m and 2 m. The cyclic lateral loading has an influence on the behavior of the pile and the soil surrounding the foundation through the pore pressure exerted around the pile.

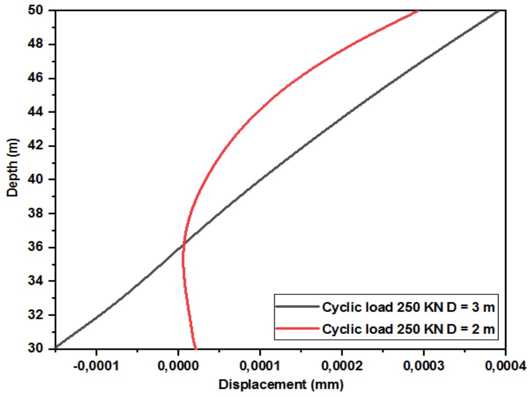

Fig.6. Representative image of pile formation under cyclic lateral loading in saturated sand for different diameter types

Figure 6 above shows the behavior of a pile under cyclic lateral loading. A slight increase in displacement can be seen for the 3 m diameter, while the 2 m diameter experienced less displacement. This difference is due to the increase in diameter and pore pressure, which has a great influence on the functioning of the soil-pile bond.

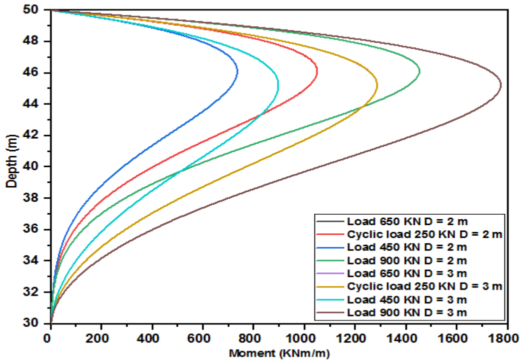

Fig.7. Comparison curve of different bending moments of piles under pre-cyclic and post-cyclic lateral loading as a function of diameters in saturated sand

Figure 7 shows the development of the bending moment curves in saturated sand, which illustrates a pile in a sand, which illustrates a pile in submerged sand. This figure shows maximum moment curves for the large diameter (3 m). However, these moments are lower compared to the moments observed in dry sand. The pre-cyclic bending moment under 650 KN load for the 3 m and 2 m pile diameters and the bending moment under lateral cyclic loading under 250 KN load are identical. It can be said that the soil reaction during monotonic pre-cyclic sand loading reacted to the pile displacement under static lateral loading. The change in pile diameter affects the pile behavior and the bending moment. As the applied load increases, the moment also increases. The moment with a diameter of 3 m is greater than that with a diameter of 2 m.

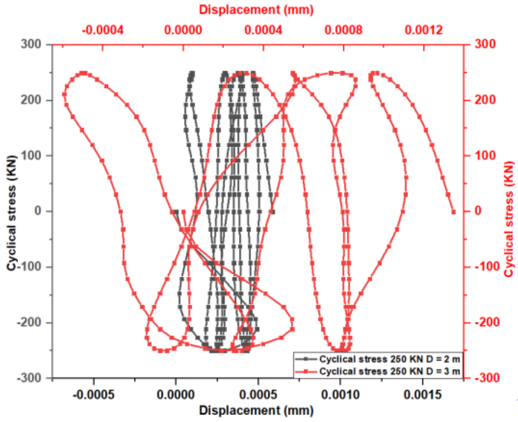

Fig.8.Representative cyclic stress-displacement curves of pile in saturated sand as a function of diameters

Figure 8 shows the behavior of the pile in saturated sand as a function of different pile diameters. The curve with the 3 m diameter shows a larger displacement than the one with the 2 m diameter. This is due to the pore pressure of the water contained in the soil during its dissipation, which has modified the soil stresses by interacting between the pile and the surrounding soil.

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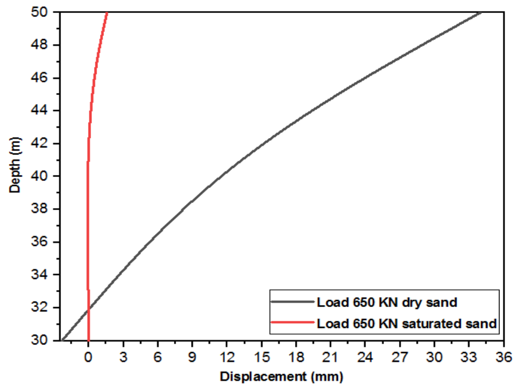

Fig.9. Displacement curves of insulated piles under pre-cyclic static lateral loading in dry and saturated sand

Figure 9 shows a very considerable difference in lateral displacement between dry and saturated sand. In dry sand the displacement is considerable and less in saturated soil. The difference between the two soil types is 95.37%. This can be explained by the dissipation of the pore pressure generated in the saturated soil, which changed the stresses in the soil. This can be explained by the dissipation of the pore overpressure generated in the saturated soil, which changed the stresses around the pile, by increasing the effective stresses around the pile, which allowed to enclose the structure.

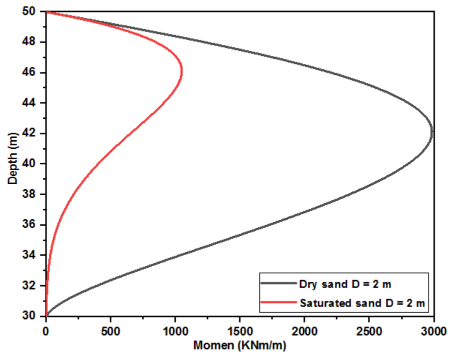

Fig.10.Comparative bending moment curves of piles installed in dry and saturated sand

Figure 10 shows the evolution of the bending moment curves in dry and saturated sand. The moment curve in dry sand is larger than in saturated sand. The maximum moment in the dry sand is 2983 KNm/m, whereas the maximum moment in the saturated sand is 1048.84 KNm/m, that is a difference of about 64.83%. The maximum moment in the saturated sand is closer to the surface than in the dry sand.

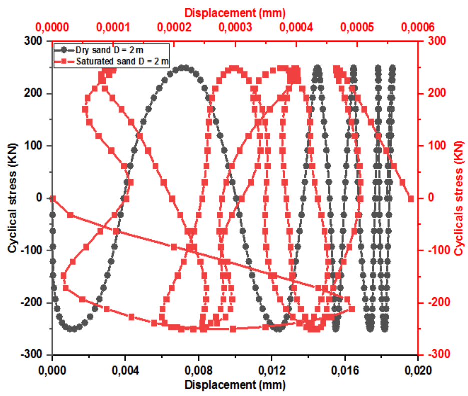

Fig.11.Comparative stress-displacement curve for cyclic lateral loading in dry and saturated sand

The curves shown in figure 11, clearly show a big difference between the two soils used. In the saturated sand (hydrostatic), the displacement of the pile in relation to the cyclic lateral load of 250 KN and the static lateral post load of 650 KN, the displacement is less in relation to the cyclic lateral load (250 KN) applied at the head of the pile in dry sand, that is a difference of 96.84%. This phenomenon can be explained by the fact that the water contained in the sand was dissipated by the cyclic stresses in the sand. The alternating cyclic loading of the pile induces a much higher densification than in the non-alternating case. Densification of the sand mass by squeezing the pile leads to an increase in soil resistance [22]. These voids are indeed filled by the sand grains if the soil is non-cohesive [23].

4. CONCLUSION

This work characterizes the modelling of the behavior of the soil-pile system under cyclic loading. The results obtained have allowed the understanding of the complexity of some of the problems involved in the design of isolated piles under static (pre and post) cyclic lateral loading; and the analysis of the behavior that influences the pile under cyclic lateral loading. The diameter of the pile has a very considerable influence on the design and behavior of the pile under different cyclic loading. Increasing the diameter decreases the deformations and displacements within a pile.

5. ACKNOWLEDGEMENTS

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