Influence of geometric and geotechnical characteristics on the behaviour of an isolated pile in sand, under cyclic lateral stress

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Abstract - *This work presents the results of modelling the behavior of deep foundations subjected to cyclic lateral and static loads in sand. The behavior of deep foundations is modelled with the PLAXIS 2D software according to the geometric characteristics of pile and geotechnical of soil. Modelling is an alternative solution to the high cost of in-situ tests and allows the behavior of deep foundations to be described as accurately as possible. The results obtained show that piles subjected to lateral head loading cause a horizontal head displacement that depends on the geometric shape of pile and characteristics of soil. The cyclic loading of pile causes a progressive mobilisation of soil mass on surface. The lateral displacement increases from the first cycles until it stabilises and generates an irreversible residual displacement due to the progressive plasticisation of soil. Lateral cyclic loading has a positive influence on the behavior of pile under cyclic loading, due to reversible effect of pile displacement.*

Key Words: Cyclic loading, Geometry, Geotechnical characteristics, Sand, Pile modeling.

1. INTRODUCTION

Civil engineering structures such as bridges and tunnels for example are sometimes subjected to cyclic loading in normal or accidental situations. During this time, the deep foundations that support the structure are usually subjected to cyclic loading in the axial or transverse directions. The variable and repetitive loading is applied over several cycles with a constant magnitude and period. These loads can cause problems with the stability or durability of piles in the operational phase for foundations anchored in soils with low bearing capacity. The soil-pile connection under cyclic loading depends on the nature of the soil.

Indeed, Randolph et al.[1] note that during cyclic loading applied to a clay; there is an increase or dissipation of pore pressure causing the degradation of undrained shear strength and an accumulation of permanent displacements. The cyclically loaded sand under the effect of pile is associated with a potential for liquefaction, accumulation of displacements and a possible increase in pore pressure which depends on the frequency of loading and the permeability of sand.

The cyclic loading of deep foundations on piles or micropiles remains undetermined, or at least to be perfected according to geotechnical data. 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 variations in the normal stress of the soil on the pile, even for a small number of cycles [2-4]. The problem of cyclically stressed soils has been extensively studied. Soil-shrinkage interfaces have so far been studied in the laboratory, for a small number of cycles, typically <10^2 [5-10]. The use of the cyclic load behavior law is very complex to apply in large-scale tests. Few studies report on the modelling of cyclic loads important for the soil-structure interface and on pile in laboratory or in situ for a large number of cycles, due to the complexity of performing the tests [11].

To overcome the complexity and high cost of in situ testing, numerical modelling can be an alternative solution to the problem at hand. The objective of this work is to predict the behaviour of piles under cyclic loading, for a better understanding of the soil-structure behaviour 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 roadbed by means of pressuremeter surveys, carried out by the Control Office for Building and 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 layers, more or less cemented. The physic-mechanical characteristics of soils on the project site are contained in Table 1.

Table -1: Mechanical characteristics measured in nearby pressure wells

Training	Depth (m)	Pl (MPa)	EM (MPa)	Internal friction coefficient (ϕ)	Cohesion not drained (Cu)	Wet density γ_h (KN/m3)	Dry soil density γ_d (KN/m3)	Water content W (%)
Sylt-clay sediment	0-10 (River bank)	0.40	4		0			
Sands	10-20	0.70	7	28	5	21	18	17
Soft Sandstone	> 20	5	50					

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

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

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

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

Plaxis 2D, is a software package suitable for analysing the deformation and stability of the structure for various geotechnical applications. This program produces a plastic calculation, a consolidation analysis and a variable analysis. It allows the analysis of elastic, elastoplastic, elastoviscoplastic problems in 2D or 3D and in large displacements by the updated Lagrangian method. Table 2 shows the data for the Batéké series sand and the characteristics of pile treated with Plaxis 2D software.

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

Parameters	Symbol	Values	
Normal stiffness (KN/m)	EA	100995,57e3	227240e3
Bending stiffness (KN/m)	EI	25248e3	127822,52e3
Young's modulus (MPa)	E	32164,195	
Density of concrete (KN/m3)	γ	25	25
Fish coefficient	υ	0,2	0.2
Pile section (2 - 3 m2)	A	3.14	7.07
Properties	Plaxis	HSM model	
Reference secant modulus	E_{50}^{ref}	32000 96000 18000	
Reference unloading module	E_{ur}^{ref}		
Reference odometer module	E_{oed}^{ref}		
Fish coefficient	υ	0.2	0.2
Cohesion	Cu	0	5
Power	M	0.5	

The number of cycles is taken equal to 10 cycles, the length of the pile equal to 20 m, two types of pile geometry circular (2 m) and square (2x2 m ; 3x3 m), as well as the different variations of geotechnical characteristics (cohesion and internal friction coefficient) 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 behaviour law used for the sand is the Hardening Soil Model (HSM) and Mohr Coulomb for the influence of Young's modulus. This law has a non-linear hyperbolic behaviour based on the well known model [12].

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 behaviour of powdery soils. The HSM (Hardening Soil Model), implemented in the Plaxis calculation code, is a hyperbolic model that was originally established by Kondner [8], then taken up by Duncan and Chang [12], completed by the use of the theory of plasticity and the introduction of the load surface and soil dilatancy. It has 8 parameters (m: a fitting parameter which depends on the soil type; E50 ref: reference secant Young's modulus, at 50% of the deflector at failure, under confining stress σ^3 = P^{ref} = 100 kPa;

E_{oed}^{ref} : reference odometer module for $\sigma^3 = P^{ref}$;

E_{ur}^{ref} : reference unloading module;

υur : Poisson's ratio in loading and unloading;

c, ϕ et 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 following formulae and from the equivalence diameter proposed by the Plaxis finite element calculation:

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

Where: $E_{50} = \frac{2E_M}{\alpha}$; $K_0 = 1 - \sin\varphi$;

$$E_{oed} = \frac{E_{50}}{1,3}$$

$$d_{eq} = \sqrt{\left(\frac{12E_P I_P}{E_P A_P}\right)} \quad (4)$$

$$E_{ur}^{ref} = 3 \times E_{50}^{ref} \quad (5)$$

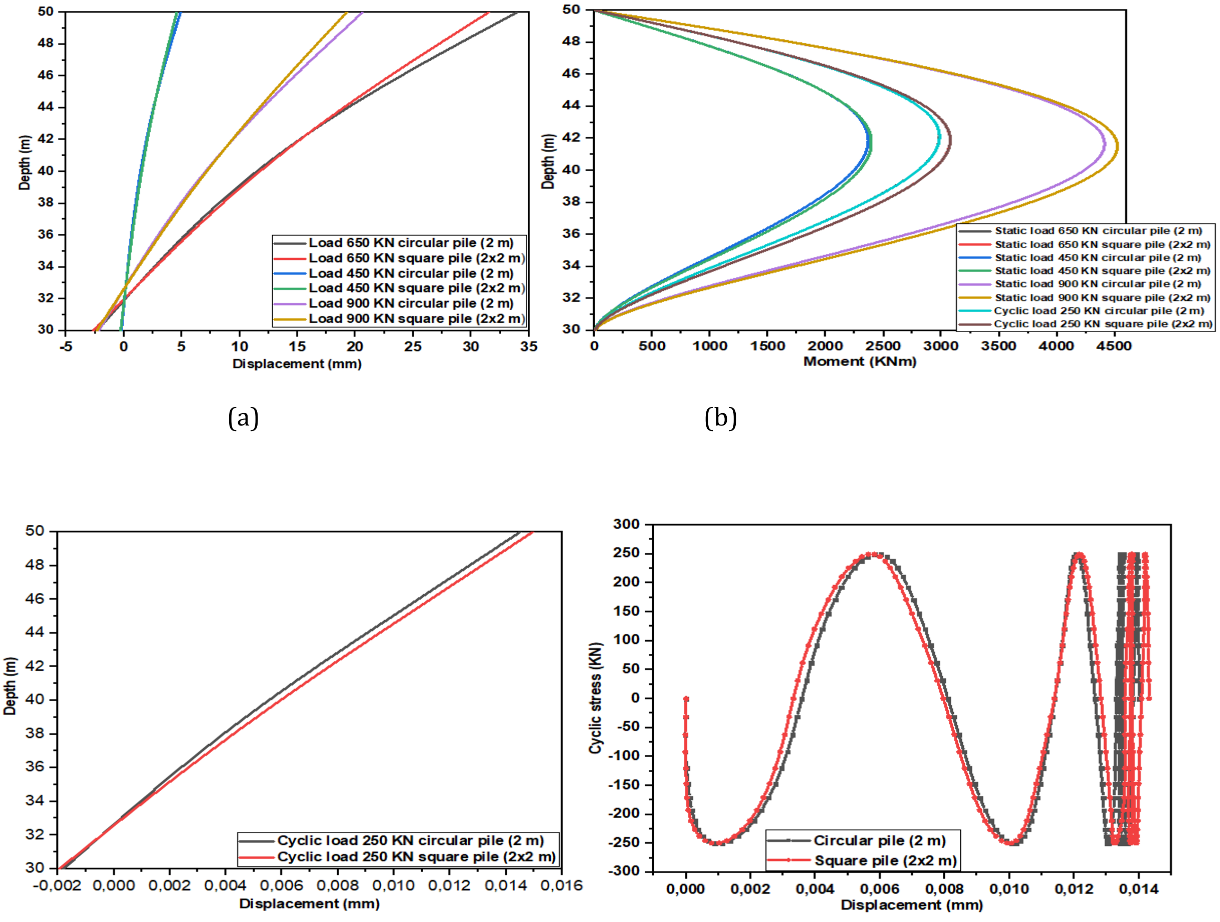
With, $E_{50}^{ref} = \frac{4E_M}{0,5}$

This study modelled with Plaxis 2D software the behaviour of an isolated pile under monotonic and cyclic lateral loading on the basis of geotechnical and geometrical form data.

3. RESULTS AND DISCUSSION

3.1 Influence of the geometric shape of the pile

Fig.1 show the different deformation and moment curves of an isolated pile under monotonic and cyclic lateral loading in of sand.



(c) (d)

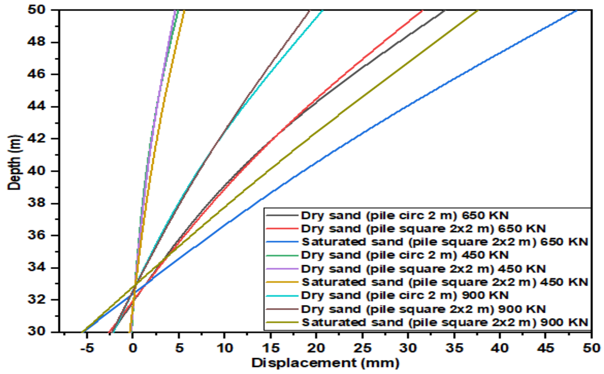
Fig.-1: Comparative curve of insulated piles under static (pre- and post) cyclic lateral loading and cyclic loading as a function of different geometric shapes (circular and square)

Fig.(1a) shows the evolution of the lateral deformations at the pile head, including the geometric shapes under static lateral loading (pre and post) cyclic in the sand. It can be seen that the maximum displacements are in the vicinity of pile head and then decrease with depth, this is valid for both geometric shapes. The circular pile has a displacement of 33.96 mm for a load of 650 KN, which is greater than the square pile 31.50 mm, that is a difference in deformation of about 7.23%. The final static lateral load of 450 KN, gives a difference in displacement between the two types of circular and square piles of the order of 4.88 mm and 44.55 mm respectively, a difference of 6.76%. The same phenomenon is observed when the static load is increased to 900 KN. In this case, the deformation between the circular and square pile shapes is of the order of 20.61 mm and 19.24 mm respectively, a difference of 6.64%. It can be concluded that the square pile has good resistance to cyclic lateral load (before and after) due to the interlocking action with the surrounding soil, unlike the circular pile.

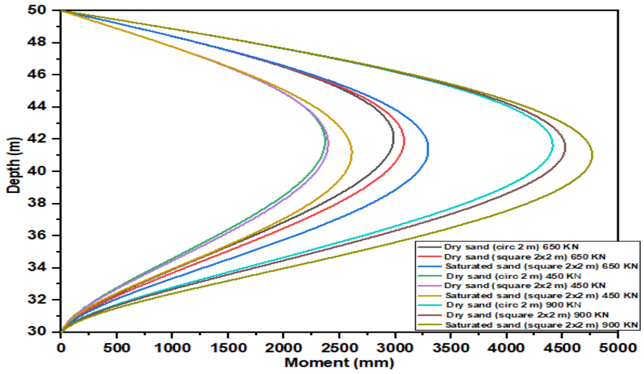
Fig.(1b) shows the evolution of pile moments for both geometric shapes. The observed results illustrate that the bending moments developed in the square piles are more pronounced than the moments found in the circular shaped piles, both under static lateral loading and under cyclic loading, the effect of cycling on the maximum moment is small [13-14], the difference is 3.02% for an initial load of 650 KN, as well as in the case of cyclic loading.

Fig. (1c) shows the influence of two geometric shapes on a pile in sand under cyclic lateral loading. The curves in Fig.(1c) show a slight difference in lateral deformation between the square pile and the circular pile at the head. The square pile has a smaller lateral displacement of 0.0149 mm while that of the circular pile is 0.0144 mm under a cyclic load of 250 KN and a static load of 650 KN, depending on the change in radial stresses in the soil. Thus, the difference is of the order of 6.04%.

Fig.1d shows the cyclic stress-displacement behaviour as a function of the geometric shape of the pile. The square pile shows a more excessive displacement than the circular pile. The difference in displacement between the two types of pile is 0.0140 mm and 0.0143 mm respectively, i.e. a percentage displacement of 2.09%. Therefore, the square pile fails during the cyclic stress displacement. Fig.2a and 2b show the influence of the water table on the square and circular pile under static and cyclic loading.



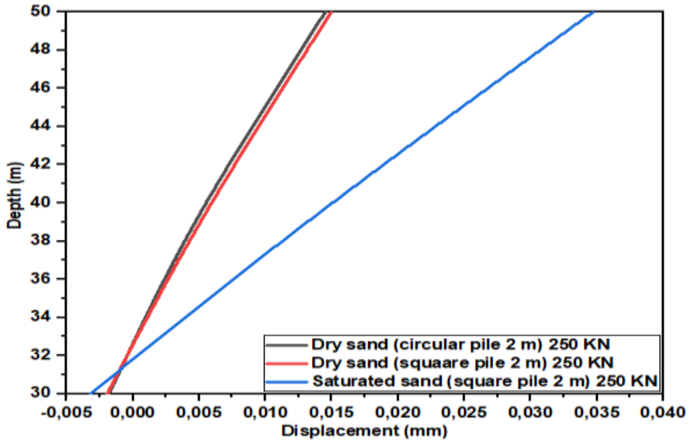
(a)



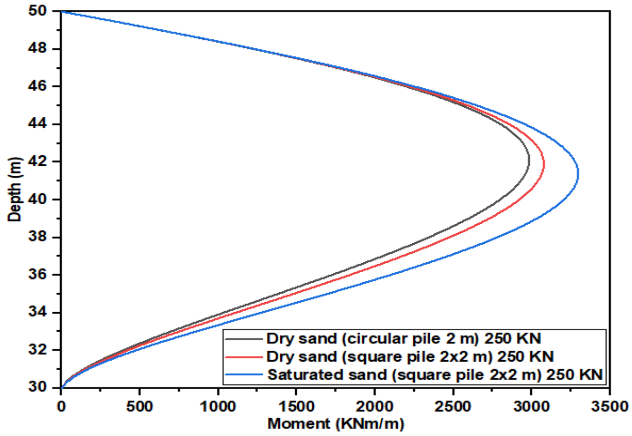
(b)

Fig.-2: Displacement curve and bending moment of isolated pile under influence of geometrical shape in comparison to square pile in saturated sand

Fig.2a shows the deformation pattern of a square pile in saturated sand under static lateral load of 650 KN, 450 KN and 900 KN (pre and post) cyclic depending on the geometry of piles (circular or square) in dry soil. The square pile in saturated sand has large deformations of 48.31 mm compared to the circular and square piles which are about 33.96 mm and 31.50 mm in dry soil. The deformation is less than the head after cyclic loading in both dry and saturated soil conditions. For an applied load of 450 KN and 900 KN at the pile head (circular and square), gives a difference in displacement of 18.01% and 48.77% between the two soil characteristics (dry and saturated). Even when increasing the final load to 900 KN, the displacement decreases under cyclic loading, for the square pile in saturated soil is 37.56 mm and the other two are 20.61 mm and 19.24 mm. The cyclic lateral loading stabilises the displacements and changes the stresses around the pile, causing the soil to invert and dissipate pore pressure in the soil. Fig.2b shows the development of the bending moments of different pile shapes (circular and square) taking into account the rheological state (dry and saturated) of the soil. The development of the moment is always a function of the increase of the applied loads. Fig.2b shows a difference between the moments in dry and saturated soil. The saturated square pile develops large moments compared to the (circular and square) pile in dry soil which have small moments.



(a)



(b)

Fig.-3. Curves of cyclic lateral displacements and bending moments as a function of pile geometry and soil rheology under post-static cyclic lateral loading

Fig.3a shows the difference in displacement of the circular pile of 0.0144 mm and the square pile of 0.0149 mm, all drilled in dry sand compared to the curve of the square pile of 0.0347 mm in saturated sand under post-static cyclic loading. The difference in displacement between the circular pile and the square pile in saturated sand is 58.50%. Fig.3b shows the evolution of the bending moments in dry, saturated soil as a function of geometric shape.

The moment is greater for the square pile in saturated sand, which is 3295 KNm, two shapes of circular and square piles of 2984 KNm and 3077 KNm respectively. Pore pressure plays an important role in the behavior of square piles installed in saturated soil. Square piles develop excessive moments compared to circular piles in dry and saturated soils. Fig. 4 shows the cyclic force-displacement of an isolated pile as a function of geometric shape and soil condition (dry and saturated) in the sand of the Batékés series.

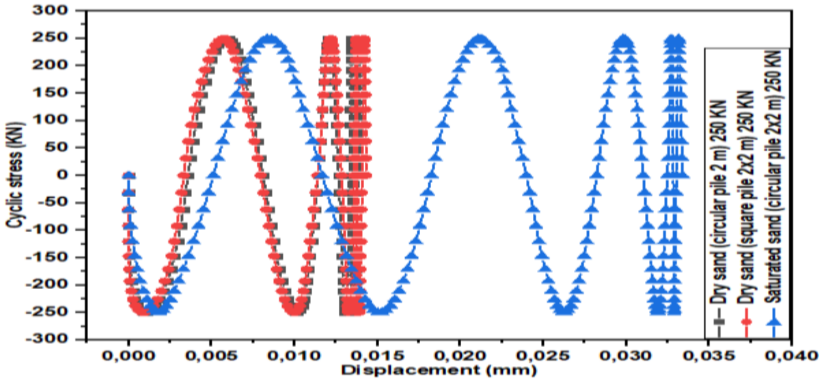
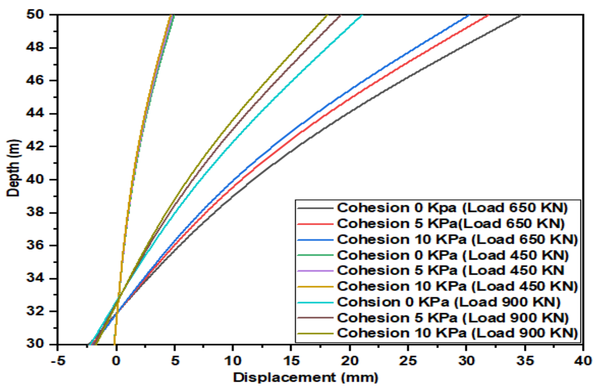


Fig.-4: Cyclic force-displacement of an isolated pile as a function of geometric shape and soil condition (dry and saturated) in sand.

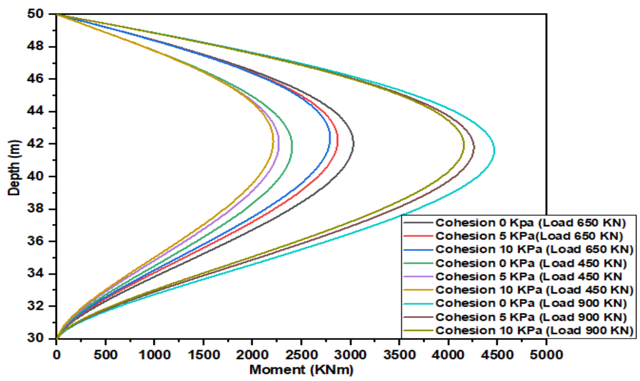
Fig.4 shows the cyclic stress-displacement behavior. The square pile in the saturated condition has a large cyclic displacement of 0.0333 mm, compared to the circular and square piles in dry soil which have displacements of 0.0140 mm and 0.0143 mm respectively. The difference between the square pile in saturated sand and the circular pile in dry sand is 57.95%.

The square pile in saturated sand undergoes large displacements from the first cycles until stabilisation by the accommodation effect. The hydrostatic water table influences the behaviour of the square pile under cyclic loading. Fig.5 shows the influence of cohesion on the behavior under static lateral load and cyclic load.



(a)

s



(b)

Fig.-5: Influence of cohesion on displacement and moment in an isolated pile under static (pre and post) cyclic lateral loading in Batéké series sand

Fig.5a and 5b show the displacement and bending moment curves as a function of cohesion and the evolution of lateral displacements and the decrease in bending moments under monotonic loading (pre- and post-cyclic). The deformations recorded at the head of the piles for a cohesion of 0 KPa, 5 KPa and 10 KPa are respectively 34.64 mm, 31.81 mm and 30.19 mm, that is, a difference of about 12.84%.

The moments change with the variation of cohesion; a large moment is observed with an equal cohesion of 0 KPa and the smallest with a cohesion of 10 KPa. The cohesion therefore has a significant influence on the behaviour of the isolated pile under lateral loading (pre and post) and under cyclic loading.The Fig.6, shows the lateral displacement and the lateral force-displacement curves under cyclic loading as a function of cohesion.

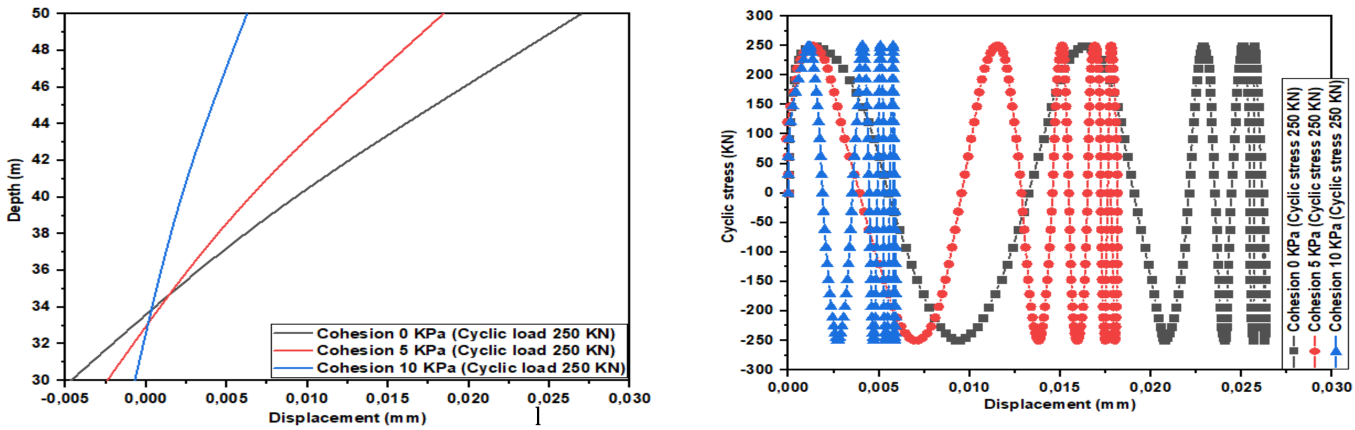


Fig.-6: Lateral displacement and the lateral force-displacement curves under cyclic loading as a function of cohesion

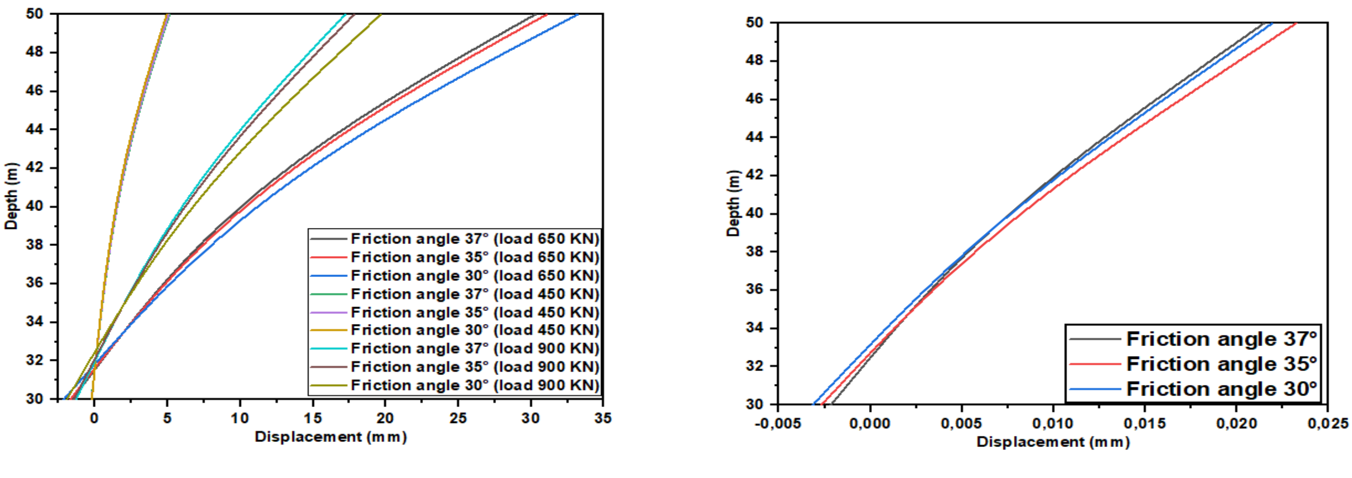
Fig. (6a) shows the evolution of the lateral displacement of the pile as a function of the cohesion under cyclic loading.

For a change in cohesion of 0 KPa, 5 KPa and 10 KPa, the lateral displacement decreases by 0.0269 mm, 0.0184 mm and 0.00624 mm respectively, a difference of 76.80%.

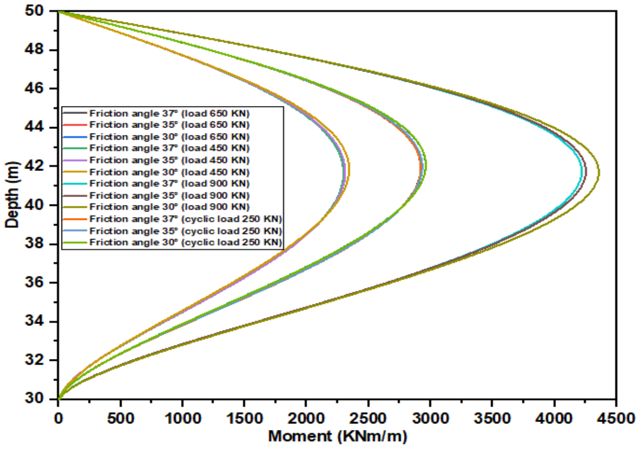
The cyclic lateral displacement decreases with increasing cohesion (Fig.6a). Fig.6b shows the decrease in cyclic stress-displacement as a function of cohesion change.

In other words, the strain decreases with increasing cohesion and for cohesion of 0 KPa and 10 KPa, the displacements are 0.0263 mm and 0.0059 mm respectively, a difference of 77.56%.

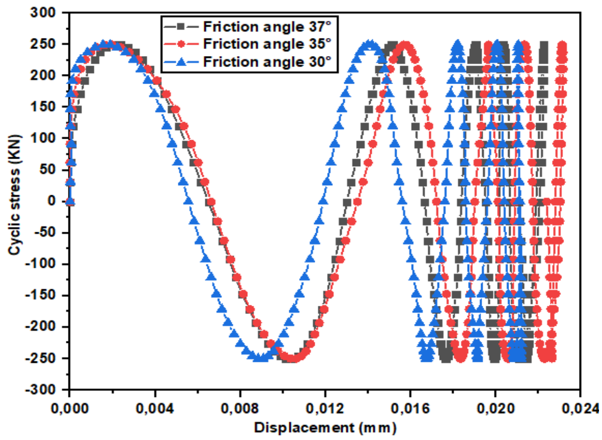
Thus, cohesion plays a very important role in the stabilisation of cyclic lateral displacements. Fig.7 shows the behaviour of an insulated pile under static (before and after) and cyclic lateral loading under the influence of the variation of the internal friction angle of (30°; 35° and 37°).



(a) (b)



(c)



(d)

Fig.-7: The behaviour of an isolated pile under static and cyclic lateral loading as a function of the internal friction angle

Fig.7a shows a large lateral displacement for the 30° angle under monotonic cyclic lateral loading (before and after). Thus, under static lateral loading, the lateral displacement as a function of the 30° angle is 33.20 mm, and the displacement decreases with increasing friction angle. By increasing the friction angle from 35° to 37°, a deformation at the pile head in the range of 31.08 mm to 30.29 mm is observed.

Fig.7b shows a different behaviour under cyclic loading than that observed in Figure 7a. The 35° angle shows a small lateral displacement of 0.0232 mm at the head compared to the other two angles of 30° and 37° which have lateral displacements of the order of 0.0219 mm and 0.0214 mm respectively. The difference in displacement between the 35° and 37° friction angles is 7.75%, whereas it is around 2.28% for the 30° and 37° angles.

It can be seen from Figure 7c that the moment varies with the friction angle. In other words, as the angle of friction increases, the moment decreases, whether under static or cyclic loading. At an angle of friction of 30° the maximum moment is 2959 KNm/m, at 35° the moment is 2930 KNm/m, while at 37° the maximum moment is about 2920 KNm/m. The difference between the angle at 30° and 37° is 1.31%, i.e. the cyclic load after the static load has no great influence on the moment. The bending moment is influenced by the highest load applied to the pile head.

Fig.7d shows the influence of the friction angle on the cyclic force-displacement. The displacement is very considerable with increasing friction angle. For angles 35° and 37°, the large lateral displacements are close and at 0.0231 mm and 0.0222 mm respectively. However, for a friction angle of 30°, the displacement is 0.0211 mm, which is a difference of 4.95% for angles 30° and 37°. On the other hand, the difference in displacement for the friction angles of 30° and 35° is about 8.65%. Finally, the increase of the friction angle has an influence on the cyclic force-displacement, it develops excessive displacements as a function of the friction angle increase.

3. CONCLUSION

In this study, the geotechnical parameters as well as the geometrical shape of piles are varied, in order to assess their impact on the lateral displacements and moments under cyclic loading. It was found that each parameter acts differently and influences the behaviour of the pile. The plaxis code was used to highlight the influence of square piles in saturated soil and to identify the influence of certain geotechnical parameters on the pile under cyclic loading.

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