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Original Research Article

NUMERICAL MODELING OF THE DEGRADATION OF THE NORMAL STRESS UNDER LARGE NUMBER OF SHEARCYCLES

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Abstract

The evaluation of friction is an important element in the verification of stability and the determination of the bearing capacity of piles. In the case of cyclic stress, the soil-pile interface has a relaxation which corresponds to a fall in the horizontal stress which represents the normal stress at the lateral surface of the pile. This paper presents an explicit formulation to express the degradation of the normal stress after a large number of shear cycles as a function of cyclic parameters. In this study we are interested in the exploitation of the cyclic shear tests carried out by Pra-ai [1] with imposed normal rigidity (CNS) in order to demonstrate the phenomenon of falling of the normal stress. The approach presented in this paper consists in proposing a simple expression for estimating the degradation of normal stress as a function of cyclic shear parameters after a large number of cycles. The validation of this approach is verified by the application of this formulation to a real case where the comparison of the simulations made by this approach with those recorded on site shows the good adaptation of this approach to this type of problems.

Keywords: shear,friction , degradation, normal stress, number of cycles

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1. INTRODUCTION

Lim and Lehane [2] they said that the shearing resistance developed during displacement pile installation in sand is an important consideration for pile drivability assessments. Although laboratory interface tests have greatly improved understanding of the interface shearing characteristics, confidence in their direct application to the large displacement and rapid shearing induced during pile installation is limited, owing to the difficulty in replicating the correct boundary conditions in laboratory test set-ups.
To ensure the safety and durability of the structures, it is necessary to take into consideration the different types of solicitations possible during their life. Cyclic stresses are often having a significant impact on many structures are susceptible to cyclic loadings either in normal or transversal situations such as roads, bridges, railways, silos, tanks, foundations for vibrating machinery, etc. [3].The term "cyclic loading" refers to a variable loading mode over time. It applies for a number of cycles with a constant amplitude and a constant period. The deep foundations can undergo according to the structures that they support cyclic loadings in the axial or transverse directions [4].
These loadings are characterized by the loading direction, the number of cycles applied, the loading period, the average load, the cyclic amplitude applied and the type of loading (alternating or non-alternating).
The study of soil behavior under monotonic and cyclic loading (or under this type of solicitation) is the subject of numerous theoretical and experimental researches around the world [5].One of the most recent and complete works is the research presented by [1].The soil-structure interfaces for a small number of cycles typically < 102 have been studied in the laboratory by many researchers [6, 7, 8, 9, 10, 11]. Cyclic stress modeling is also quite rich for soil-structure interfaces [12, 13, 14, 15, 16, 17, 18].But the effect of high number of cycles on the behavior of soil-structure interfaces and on the response of piles have been relatively little studied in the laboratory and in situ for the large numbers of cycles, because of the heaviness of the test s[19].
The study of the behavior of soil-structural interfaces is an important factor in the study and verification of geotechnical structures (superficial foundations, pile foundations, tunnels, diaphragm walls, ...). In general, the piles under axial load is influenced by two important factors are the loading history and the displacement history [20].The degradation of the friction corresponds to a fall (or a reduction) of the level of normal stress along the shaft [21].The capacity of laterally loaded piles is mainly governed by the strength of soil at the proximity of top level of the piles [22].

2. CYCLIC BEHAVIOR

For a cyclic test, figure1shows the different cyclic parameters in the plane $\sigma_n - \tau$. where σ_n is the normal stress and τ is the shear stress.

$$\Delta\tau = \tau_{max} - \tau_{min} \tag{2.1}$$

$$\Delta\eta = \frac{\Delta\tau}{\sigma_{nav0}} \tag{2.2}$$

$$\eta_{av} = \frac{\tau_{av}}{\sigma_{nav0}} \tag{2.3}$$

Where:
η_{av} - the average cyclic level;
$\Delta\eta$ – the cyclic amplitude;
σ_{av0} – the initial average cyclic stress;
k – the cyclic stiffness.

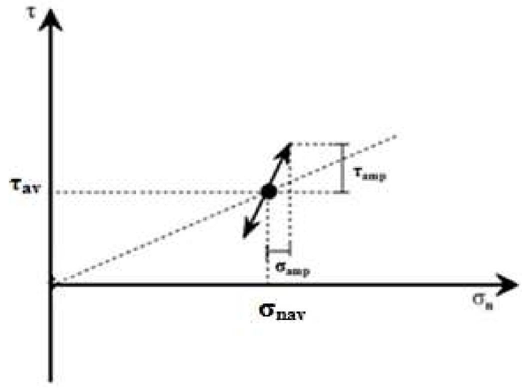


Fig.1 Cyclic stress path the $\sigma_n - \tau$ plane

Boulon and Foray [23]have also proposed the boundary conditions of direct shear tests in which the rigidity of the surrounding soil was represented by a pressuremeter modulus to simulate the elementary mechanism of mobilization of lateral friction at the soil-pile interface. Cyclic tests with imposed normal stiffness (CNS) are always contracting, leading to a reduction of normal stress on the pile. The CNS test has become more popular after it was realised that the degradation of shaft friction with cycling observed in the field [24, 25, 26] could only be replicated in laboratory interface tests if the CNS condition was used in place of the more generally employed CNL mode [2].

3. NUMERICAL SIMULATION

This study is interested in the exploitation of the cyclic shear tests presented by [1],who carried out tests on the sand of Fontainebleau, by considering two types of contacts (rough and smooth), and two types of paths, with constant normal stress (CNL, k = 0), and with normal stiffness imposed (CNS, k> 0), for each 10 000 cycles [1]. The purpose of this simulation is to formulate the normal stress degradation as a function of the cyclic parameters for stiffness k> 0. Table (1) presents the cyclical parameters of the experimental tests conducted by [1].
To express the influence of cyclic parameters on normal stress, the results of the experimental tests conducted by [1] were used, based on table 1 and the curves shown in figure 2.
Figure 2shows the normal stress (σ_n) as a function of the number of cycles (N). This dependence is a logarithmic form, It can be expressed by the general form of equation (3.1):

$$\sigma_n = A_i * Ln(N) + B_i \tag{3.1}$$

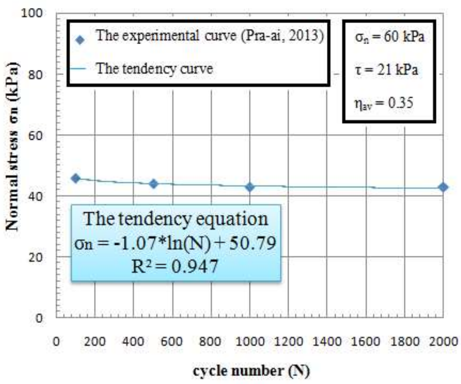
Table 1. CNS test series after [1]

N°	TEST	I_{D0} (%)	σ_{av0} (kPa)	k (kN/mm)	τ (kPa)	η_{av} (-)	$\Delta\tau$ (kPa)
1	10DM60-1000K	90	60	1000	16<τ<26	0.35	10
2	10DH60-1000K	90	60	1000	20<τ<30	0.42	10
3	10DM100-1000K	90	100	1000	30<τ<40	0.35	10
4	10DH100-1000K	90	100	1000	45<τ<55	0.5	10
5	10DM310-1000K	90	310	1000	105<τ<115	0.35	10
6	10DH310-1000K	90	310	1000	150<τ<160	0.5	10

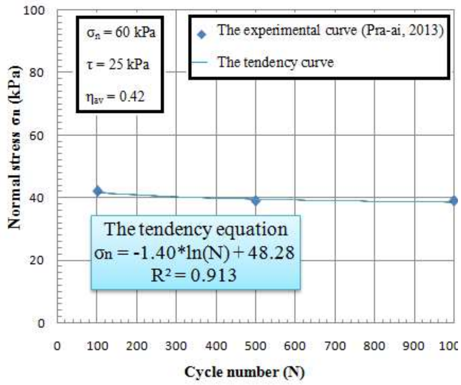
Table 2 summarizes the values of parameters of all tests and the constants A_i and B_i for each test. A_i and Bi are the constants of tendency function of the normal stress curve as a function of the number of cycles as shows in figure 2.

Table 2. The different values of the parameters used

N°	A_i (-)	B_i (-)	η_{av} (-)	$\Delta\eta$ (-)	σ_{av0} (kPa)	k (kN/mm)	I_{D0} (%)
1	-1.07	50.79	0.35	0.166	60	1000	90
2	-1.04	48.28	0.42	0.166	60	1000	90
3	-0.49	101.6	0.35	0.100	100	1000	90
4	-5.59	120.6	0.50	0.100	100	1000	90
5	-5.86	322.5	0.35	0.0322	310	1000	90
6	-4.32	321.6	0.50	0.0322	310	1000	90



Test N° 1



Test N° 2

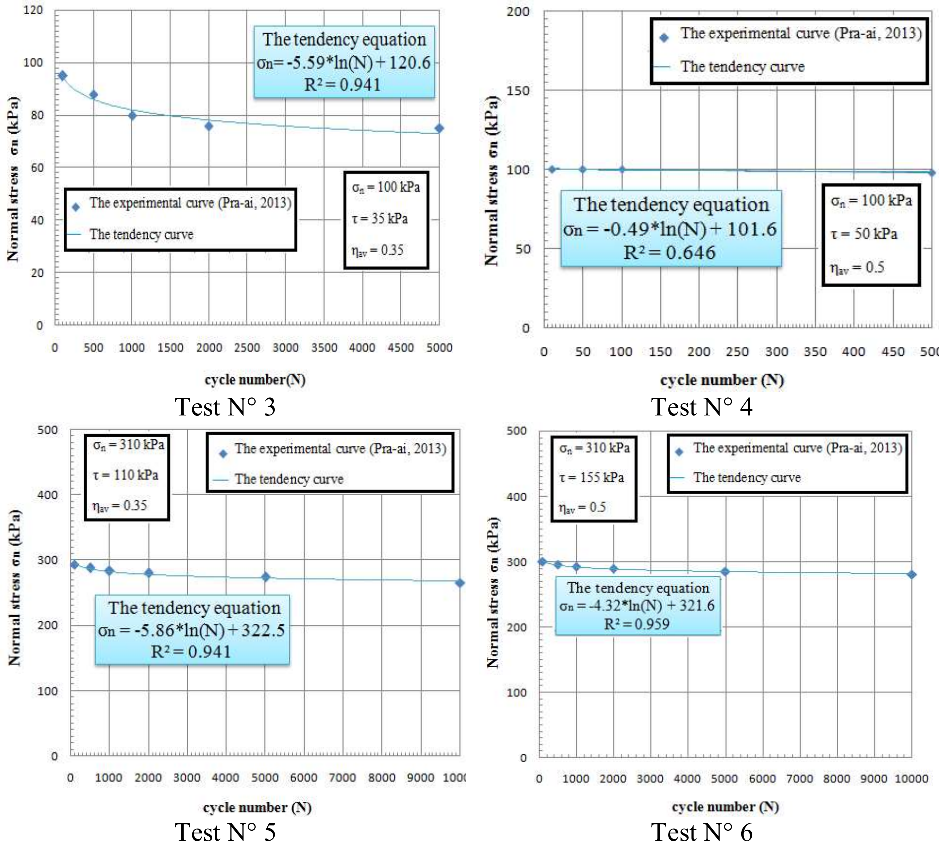


Fig. 2. Evolution of the normal stress as a function of cycles

For set of tests that have σ_n = cte we write a and b according to η_{av}. The tendency curves of A_i (B_i) as a function of η_{av} make it possible to write equations (3.2-3.7).

$$A_1 = -10.26 * \eta_{av} - 0.72 \quad (3.2)$$

$$A_2 = 34 * \eta_{av} - 17.49 \quad (3.3)$$

$$A_3 = -4.714 * \eta_{av} + 0.58 \quad (3.4)$$

$$B_1 = 6 * \eta_{av} + 319.5 \quad (3.5)$$

$$B_2 = -126.6 * \eta_{av} + 164 \quad (3.6)$$

$$B_3 = -35.85 * \eta_{av} + 63.34 \quad (3.7)$$

From the curves of equations (3.2-3.7), the A_i and B_i can be expressed by equation (3.8 and 3.9):

$$A_i = C_i * \eta_{av} + D_i \quad (3.8)$$

$$B_i = E_i * \eta_{av} + F_i \tag{3.9}$$

From equations (3.8) and (3.9), the trend curve representing the coefficients C, D, E and F as a function of Δη can be written Eqs (3.10-3.13):

$$C_1 = -9262 * \Delta\eta^2 + 1877 * \Delta_\eta - 61.1 \tag{3.10}$$

$$D_1 = 3894 * \Delta\eta^2 - 762 * \Delta\eta + 19.77 \tag{3.11}$$

$$C_2 = 24894 * \Delta\eta^2 5246 * \Delta\eta + 149.1 \tag{3.12}$$

$$D_2 = 5541 * \Delta\eta^2 - 3012 * \Delta\eta + 410.7 \tag{3.13}$$

After substitution of the Eqs. (3.2-3.13) into Eq. (3.1) we will have Eq.(3.14):

$$\sigma_n = [(-9262.\Delta\eta^2 + 1877.\Delta\eta - 61.1).\eta_{av} + (3894.\Delta\eta^2 - 762.\Delta\eta + 19.77)] * Ln(N \\ [(24894.\Delta\eta^2 - 5246.\Delta\eta + 149.1).\eta_{av} + (5541.\Delta\eta^2 - 3012.\Delta\eta + 410.7)] \tag{3.14}$$

The eq (3.14) makes it possible to determine the normal stress as a function of the several cyclic parameters, and also to determine the maximum friction as going up to L'eq (17).

4. APPLICATION OF THE PROPOSED FORMULATION TO PREDICT THE DEGRADATION OF THE FRICTION OF PILES

To validate the proposed formulation, a study of degradation of the friction of the piles under cyclic vertical loads is presented. In this study, we are interested in determining the degradation of the friction of a reinforced concrete drilled pile placed in a sandy soil. The case studied is presented in the thesis of Benzaria [20]. According to Benzaria the pile F5 is made of reinforced concrete with a diameter of 420 mm whose mechanical characteristics of the pile are summarized in Tab.3. The sand samples had a dry density γd=20 kN/m^3, young's modulus Eref=50000 kN/m^2, an angle of friction φ=38.1°a cohesion of c=0 kN/m^2, a dilatancy angle ψ=8°, and poison ratio ν=0.2.The pile is loaded with a force at the head: maximum cyclical vertical loading Q_{max}=700 kN, minimum cyclical vertical loading Q_{min}=100 kN, medium cyclical vertical loading Q_m=400 kN, and cyclic amplitude Q_c=300 kN.

Table 3. Mechanical characteristics of the pile

Mechanical characteristics	**Volume weight γ_d (kN/m^3)**	**Young's module E (kN/m^2)**	**Poison ratio ν (-)**
Pile	24	$3*10^7$	0.1

Numerical simulations are done by finite element calculation using an axisymmetric model (Fig.3) Soil behaviour is described by Mohr Coulomb's model.

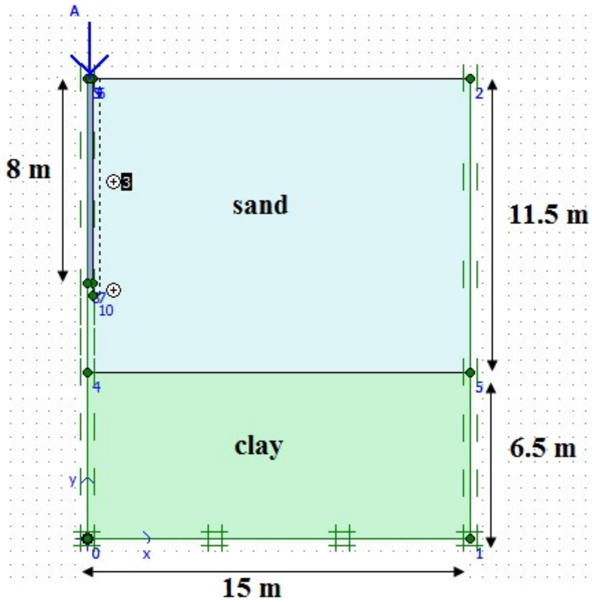


Fig. 3. Geometry model

4.1. Results and interpretation

According to API-RP2 GEO [27], the friction for each layer along the piles can be calculated from equation (4.1) :

$$\tau = \sigma'_v.\beta \tag{4.1}$$

Burland [28] proposes that the coefficient β calculated by equation (4.2):

$$\beta = K.\tan\delta \tag{4.2}$$

Where:
K – an earth pressure coefficient relating the effective normal stress acting around the piles at failure to the in situ effective over burden stress σ′v0 and $K_0 = \frac{\sigma_h}{\sigma_v}$;
δ – ground-pile interface angle (1/3φ or 2/3φ).

After substitution of the Eq. (4.2) into Eq. (4.1) we will have Eq. (4.3):

$$\tau = \sigma'_h \cdot \tan\delta \qquad (4.3)$$

In the analysis of friction τ (tangential stress in the soil-pile interface), the normal stress on the pile is presented by the horizontal stress in the soil (σ'h). The study of degradation of the friction around the piles amounts to simulating a cyclic shear test in which the horizontal stress applied to the pile at a given depth represents the normal stress in a shear test and consequently the soil-pile friction represents the shear stress in a direct shear test. Therefore to determine the cyclic parameters of equation (3.14) for a given depth, a pile load-unload cycle will be performed by a finite element calculation according to the model in Figure 3.This simulation allows the determination for each depth of the horizontal stresses on the pile which are the equivalent of the normal stresses in the shear test and the vertical stresses at the soil-pile interface which are the equivalent of the shear stresses in the test.Table4 summarizes the cyclic parameters used in this simulation. From equations (3.14), (4.3) and Table (4) it can be obtained the results shown in Figure 4. Figure 4shows the simulated and experimental curves where we observe a good convergence between simulated and experimental curves, which reinforces the basic idea of this work.
To determine the cyclic parameters at layer (3, 4, 5, 6, and 7), a simulation of the first load-unload cycle will performed and then the necessary parameters are extracted which are summarized in the table (4).

Tabl 4. Parameters of the simulated tests

Layer (m)	σ_{nav0} (kPa)	τ_{av} (kPa)	$\Delta\tau$ (kPa)	η_{av} (-)	$\Delta\eta$ (-)
3m	70.52	52.89	3.10	0.75	0.044
4m	92.2	69.15	3.69	0.75	0.040
5m	119	92.82	4.76	0.78	0.040
6m	135	81.00	13.5	0.60	0.100
7m	170	105.4	13.6	0.62	0.080

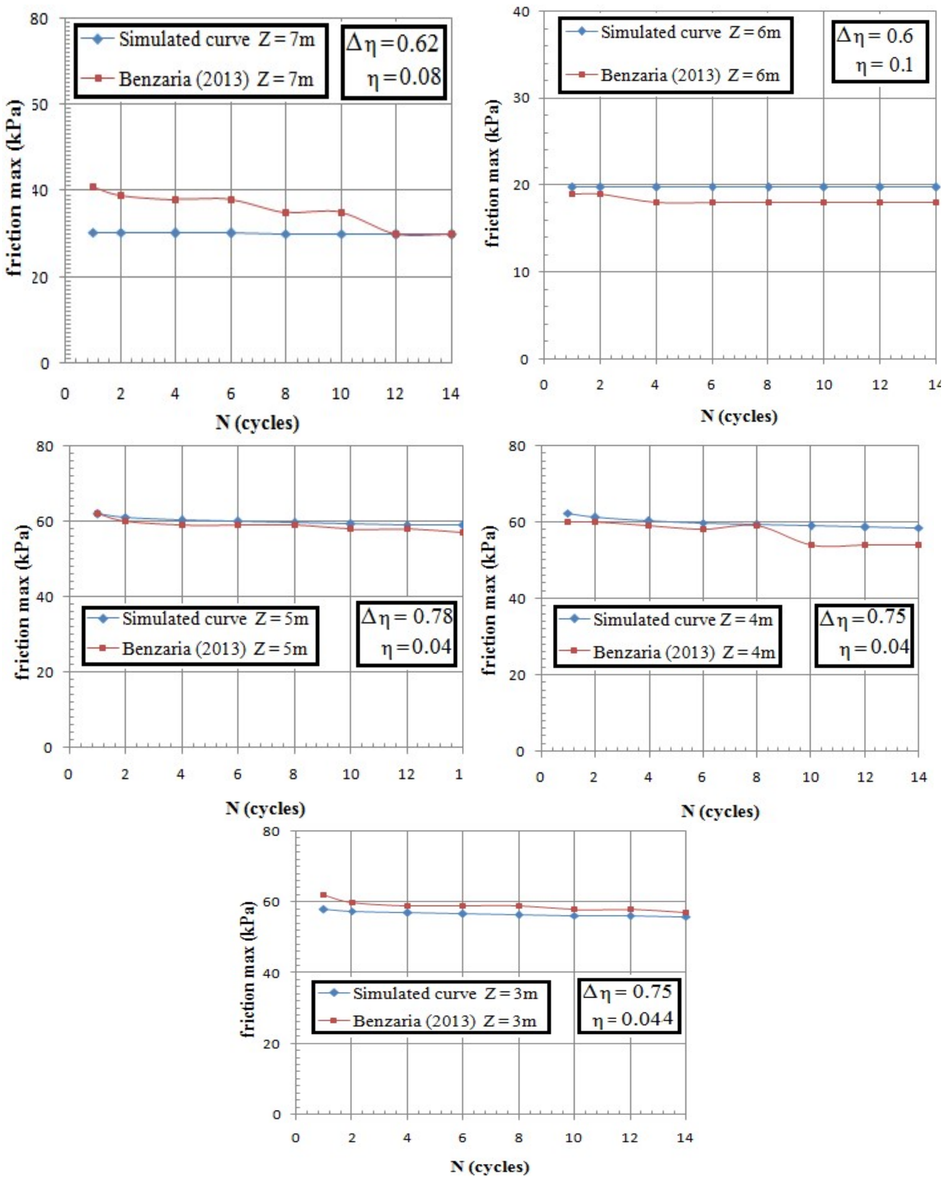


Fig. 4. Comparison of simulated curve and experimental results

5. PARAMETRIC STUDYOF THE CYCLIC BEHAVIOR OF SOILS

In this section, the parametric study we will examine the influence of cyclic parameters on the evolution of normal stress.

5.1. Influence of cyclic level average η_{av}

To study the influence of variation of the average cyclic level on the normal stress, The effect of mean cyclic stress ratio is typically presented byfor three levels of ηav (0.17, 0.35 and 0.5) with a cyclic amplitude $\Delta\tau = 10\ kPa$ and $\sigma_n = 310\ kPa$ (see also Figures5 and 6).

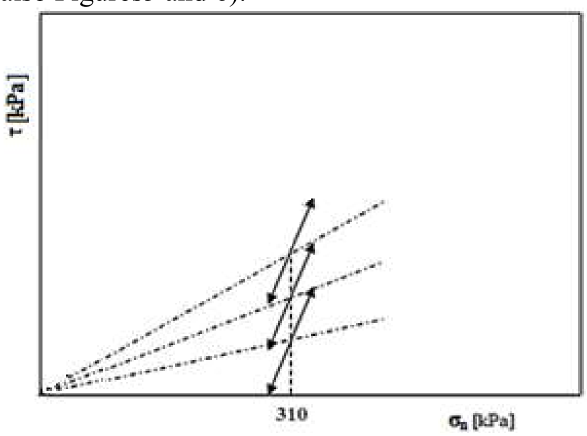


Fig. 5.Variation of the cyclic average level ηav

Figure 6 presents the curves of the evolution of the normal stress according to the cyclic average level. The Examination of the curves shows that the importance of the evolution of the normal stress decreases with the increase of the cyclic mean level (fig. 6).

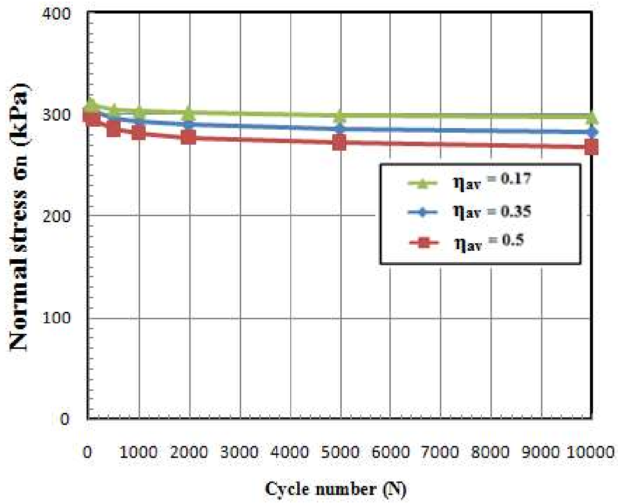


Fig.6. Influence of cyclic mean level on the evolution of the normal stress

5.2. Influence of the cyclic amplitude Δη

In the same way the study of the potential effect of the cyclic amplitude on the normal stress was carried out by the realization of the same cyclic average level of $\eta_{av} = 0.5$ but a cyclic amplitude variable of 0.1, 0.2 and 0.4 (fig 7).

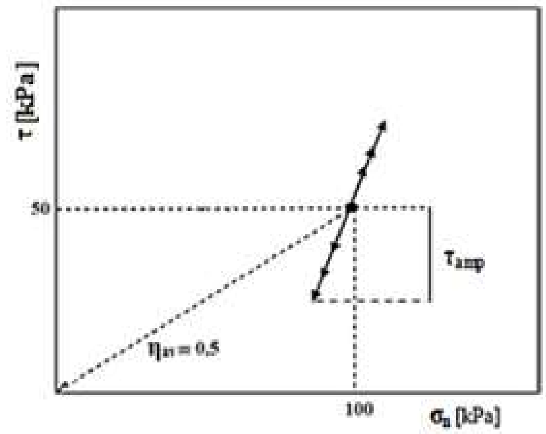


Fig. 7. Cyclical path with different amplitudes Δη

Figure 8 shows the results of evolution of the normal stress in dependence on the cyclic amplitude. This evolution is more important if the amplitude is larger.

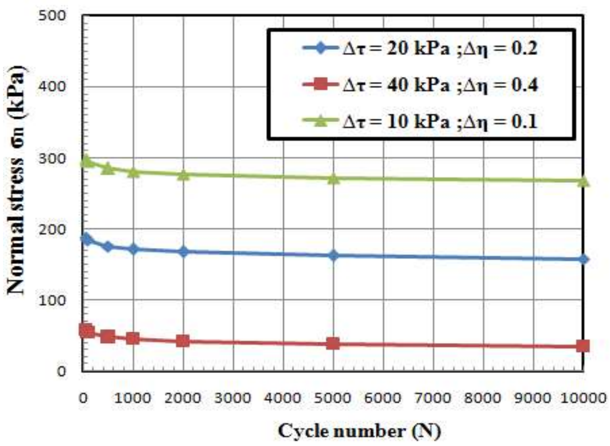


Fig. 8. Influence of cyclic amplitude on the evolution of the normal stress

5.3. Influence of the average stress

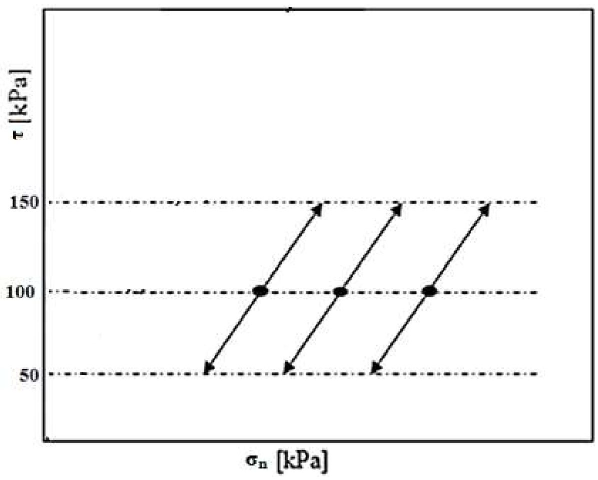


Fig. 9. Variation of the mean stress with τav = cst

In this section the influence of the variation of the average normal stress will be tested. This variation is taken within the interval $310\ kPa \leq \sigma_{av} \leq\ 400\ kPa$ with constant cyclic amplitude. Figure 10 shows the results of numerical simulations according to the cyclic plan of Fig. 9. Fig. 10 shows that the more high the average normal stress is, the evolution of the normal stress degraded.

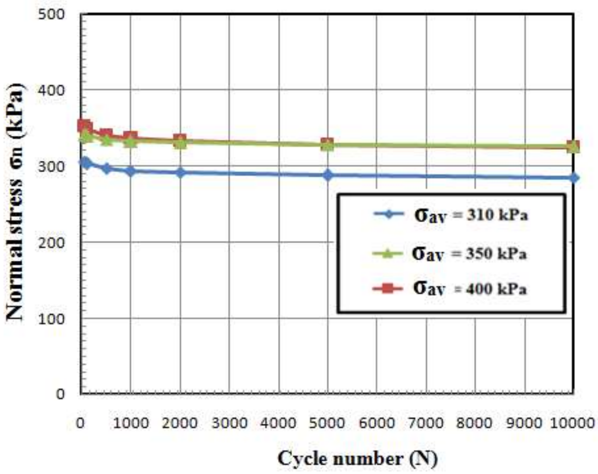


Fig.10. Influence of the mean normal stress on the evolution of the normal stress

6. CONCLUSION

The study presented in this paper aims to express the degradation of the normal stress as a function of the number of shear cycles. In this research we are interested in the large number of cycles, which imposes an explicit formulation. The study was based on the exploitation of cyclic shear tests presented in the Pra-ai PhD thesis, made on the sand of Fontaine Bleau.

This research has made it possible to propose a simple formulation of the degradation of the normal stress during the shear cycles as a function of the cyclic parameters. This approach was used to estimate the variation of friction of pile as a function of the number of cycles.

The comparison of the experimental results [27] and the simulated curves using the present formulation shows a good concordance, which confirms the good adaptation of the proposed formulation for estimating the degradation of the normal stress during cyclic shear tests [1]. Figures 5, 6, 7, 8, 9 and 10, illustrate the importance of the influence of the average cyclical level, average stress and cyclical amplitude on the evolution of normal stress.

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