Piles under cyclic loading: study of the friction fatigue and its importance in piles behavior.

Pieux sous chargements cycliques: étude de la fatigue du frottement et son importance dans le comportement des pieux.

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ABSTRACT
The main point of this paper is to model the behavior of piles under cyclic loading, aiming with this to identify the key features and load transfer mechanisms controlling friction fatigue. The numerical modeling makes use of an advanced elastoplastic, state dependent constitutive model, the ECP model, also known as Hujeux's model. Therefore, the cyclic loading simulations allowed identifying three different mechanisms, depending on the amplitude of the first load cycle, that control the level of friction degradation. Furthermore, the analysis also offers useful insights regarding the modification of the pile static resistance once this one has been cyclically loaded. All analyzes are carried out on Toyoura sand.

RÉSUMÉ
Le principal objectif de ce papier est d'identifier les mécanismes de transfert de charge qui sont à la base du phénomène de la fatigue du frottement en utilisant la simulation numérique du comportement des pieux sous chargement cyclique. Ces simulations ont permis d'identifier trois types de mécanismes de transfert de charge qui aboutissent à des niveaux de dégradation du frottement différents. Ces mécanismes dépendent de l'amplitude du premier cycle de charge. En outre, la simulation des rechargements après une serie de chargement cyclique permet d'observer la modification de la résistance statique du pieu due à son histoire de chargement. Toutes les analyses sont effectuées avec le sable de Toyoura dont le comportement est simulé à l'aide du modèle élastoplastique de l'ECP connu comme modèle de Hujeux.

Keywords : Pile, friction fatigue, cyclic, non-linear, Toyoura sand

1 INTRODUCTION

Pile shaft capacity in sand has been observed to decrease significantly during the pile driving (Vesic 1970, Lehane et al. 1993, White & Lehane 2004). This effect was observed in model-scale as well as in full scale pile tests. Nevertheless, there is small understanding of the underlying mechanisms of the shaft friction degradation. Hence, the friction fatigue quantification methods are mostly based on experience and performance trends rather than on comprehension of fundamental soil mechanics.

The study of the pile's response under cyclic loading is not just important in terms of pile drivability but is also important in terms of the modification of the soil initial state after cycling and if this modification has repercussions in the pile's subsequent resistance. This leads us to the important role of pile installation effects on the pile's performance. Thus a first parallel could be established, between installation effects and the behavior of piles cyclically loaded.

Therefore, in this paper, the behavior of piles under cyclic axial loading is studied using a 3D numerical model and an elastoplastic cyclic soil constitutive model (Hujeux 1985). In the numerical simulations the effects of amplitude and number of the pre-loading cycles are studied, and their effects on subsequent pile static resistance are also quantified. Friction fatigue is, therefore, analyzed in terms of pile load settlement curves and soil stress paths.

The present analysis, underlines the importance of the soil initial state, in terms of initial relative density and initial confining stress, combined with the amplitude of the first pre-load cycle, as the major factors influencing different load transfer mechanisms that lead to different levels of friction degradation.

2 NUMERICAL MODEL

In the present work the GEFDYN finite element software is used to compute the soil-structure interaction problem, in which a three-dimensional finite element model is created to analyze a pile subjected to axial cyclic and monotonic loads. The studied model is based on a centrifuge model pile tested by Fioravante 2002 and Columbi 2005 (used for previous model validations in D'Aguiar et al. 2008). This prototype scale pile is 7.4 m long, 0.3 m diameter and is embedded in a 20 m depth homogeneous dense Toyoura sand layer. The pile and soil are modeled using 8-node solid three dimensional elements (details of the mesh can be found in D'Aguiar 2008).

The Toyoura sand is modeled with the 3D ECP multimechanisms soil model (Hujeux 1985). This model can take into account the soil behavior in a large range of deformations; the representation of all irreversible phenomena is made by four coupled elementary plastic mechanisms; takes into account the cyclic behavior through a kinematical hardening based on the state variables at the last load reversal.

Model parameters were calibrated using laboratory drained triaxial test results presented by Fukushima and Tatsuoka 1984 (details in D'Aguiar 2008). The sand density is Dr = 93%, for which the initial earth pressure coefficient is $k_0 = 0.5$ and $\gamma = 16\text{kN/m}^3$. Concerning the, soil-pile interface it is considered to be totally rough, and is modeled with using thin solid elements. The pile was modeled as linear elastic (Poisson's ratio: $\nu = 0.36$, Young modulus: E = 8.1 GPa). It is important to note that the modeled pile is a non-displacement pile, so installation effects are considered to be negligible. Loading is applied at the pile through the application of prescribed displacements and forces.

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3 CYCLIC LOADING ON NON-DISPLACEMENT PILES

Cycling was applied at the pile head for different load levels, 200, 400, 900, 1100 and 1300 kN and for different number of load cycles (N equal to 5, 10 and 15). From cycle to cycle the maximum total load, at the pile head, was maintained constant.

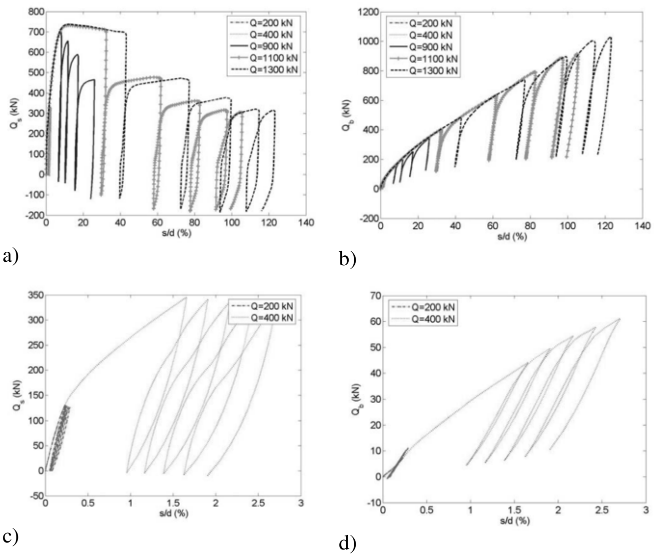
The goal is to study the effect of cyclic load on the shaft and base resistance mobilization separately, and to observe their joint effect on the final total resistance. A special attention is given, therefore, to the load settlement analysis and to the friction fatigue phenomena, in terms of shaft soil stress path.

3.1 *Load settlement analysis*

In Figure 1, comparative load settlement results are presented for the application of 5 cycles of different amplitudes, in terms of shaft (Figure 1a, c) and base resistance (Figure 1b, d).

One of the main aspects that can be pointed out from Figure 1 is that different evolutions of the shaft and base resistance with cycling are obtained, regarding the applied load level at each cycle. In terms of peak shaft resistance at each cycle, one can note that, for the higher load levels (900, 1100 and 1300 kN Figures 1a) there is a clear reduction of the peak friction with the increase of the number of cycles and, for the lower load levels (200 and 400 kN, Figures 1c) this friction degradation with cycling is very reduced or inexistent. Thus, what is observed in the shaft friction, for some of the applied loads, is the so called phenomena of friction fatigue. In addition, the base resistance mobilization load settlement curve is affected by cycling in terms of permanent displacements and peak base resistance at each cycle, so that the loss of shaft resistance due to friction fatigue is compensated by base resistance, and total pile head load remains constant (Figure 1b,d).

In sum, for the applied loads Q_T = 1300 kN, Q_T = 400 kN and Q_T = 200 kN, it was possible to identify that the friction degradation is very high, very smooth and inexistent, respectively. Nonetheless for a deeper understanding and even justification of this dependency of the friction fatigue on the load level, the soil stress path near the pile shaft has to be analyzed.



a) b) c) d)

Figure 1. Comparative load settlement results for the cyclic calculations at different load levels (QT equal to 200, 400, 900, 1100 and 1300 kN): a) Shaft resistance, b) Base resistance. c) Zoom - Shaft resistance, d) Zoom - Base resistance.

3.2 *Friction fatigue stress analysis*

Experimental investigations, DeJong et al. (2006) White and Lehane (2004), in piles and in interface Constant Normal Stiffness (CNS) tests have shown that the primary mechanism controlling friction fatigue is the cyclic history of the soil element at the pile-soil interface. According to the latter authors this cyclic history is translated in a net contraction of a thin layer that is confined by the far field soil.

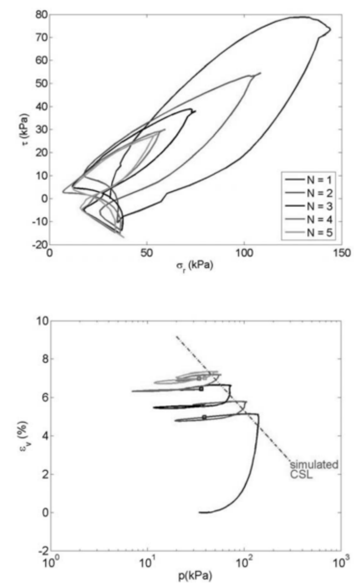
Thus, the three identified different cyclic load transfer mechanisms are studied hereafter in terms of soil stress path adjacent to the pile shaft, at 4.4 m depth. They are presented for each cycle (plotted with different colors), and each load level (Q_T = 1300 kN, Q_T = 400 kN and Q_T = 200 kN), in Figures 2, 3, and 4. In the latter figures Toyoura sand Critical state line (CSL) is also represented and one can notice that initial load cycle can place differently the soil state regarding the critical state line depending on the applied load amplitude. Therefore, the different stress paths, for a given number of cycles, show that it is the first cycle amplitude that determines the rate of the friction degradation due to whether the critical state or transformation phase is reached or not. Therefore, friction fatigue phenomena, for a small number of applied load cycles, can be summarized by three different cyclic mechanisms:

- **Cyclic mechanism 1**, where during the initial load cycle, the critical state is reached. So, in the subsequent cycles:

• Soil experiences compaction and dilation;

• The mean stress increases (Figure 2a);

• Therefore, the soil state moves towards the **CSL** (Figure 2b), so to less dense state. So at each cycle, the critical state is reached again, but there is a progressive increase in compaction and decrease in dilation. Consequently there is a clear reduction of the normal stress so of the maximum shear stress mobilized at each cycle.



a)

b)

Figure 2. Cyclic soil stress path for N=5 at Q_T=1300 kN, for a point adjacent to the pile shaft at 4.4 m depth: a) shear and normal stresses; b) volumetric strain and mean stress (CSL– critical state line).

- **Cyclic mechanism 2**, where the critical state is not reached but the transformation phase line (passage from contractive to dilative behavior) is reached by the first cycle stress path. So, in the subsequent cycles:

• Soil experiences compaction and dilation (Figure 3b);

• The mean and normal stresses decrease; (Figure 3a);

• The initial state moves farther from the **CSL** with progressing accumulation of permanent dilation volumetric strain (Figure 3b) and shear stress decreases smoothly.

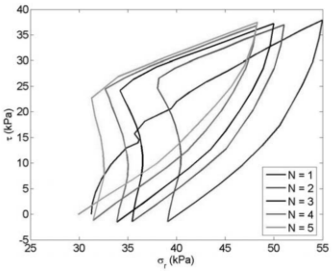
- **Cyclic mechanism 3**, where the transformation phase is not reached during the first load cycle. So, in the subsequent cycles:

• Soil experiences compaction (Figure 4a);

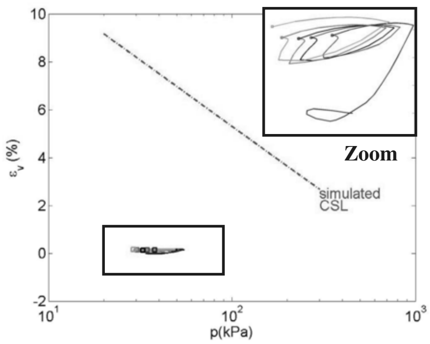
• The mean stress decreases. There is no friction fatigue until the stress path touches the intrinsic line: cyclic mobility. As far as this M (M = 6sinφ/(3−sinφ)) curve, perfect plasticity, is not achieved, there is a total stress reversal during cycling.

• The initial state moves farther from the CSL with progressive accumulation of permanent compaction. Thus, the soil is densified by cycling (Figure 4b).

These findings provide an initial insight into the primary mechanisms that lead to the friction fatigue. It was possible to see that the cyclic rate of degradation is primarily dependent on the load level applied during the first load cycle, on the initial confining stress and on the relative density of the soil, which will determine the position of the soil regarding its critical state.

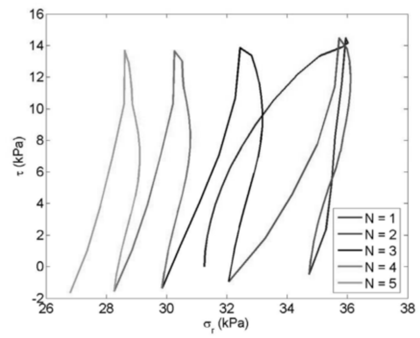


a)

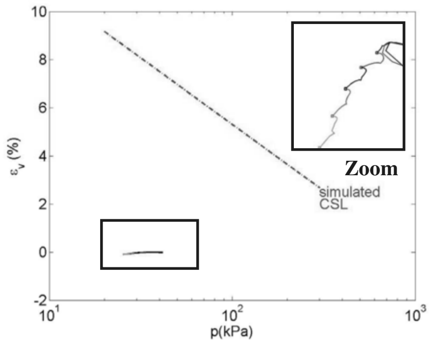


b)

Figure 3. Cyclic soil stress path for N=5 at Q_T=400 kN, for a point adjacent to the pile shaft at 4.4 m depth: a) shear and normal stresses; b) volumetric strain and mean stress (CSL– critical state line).



a)



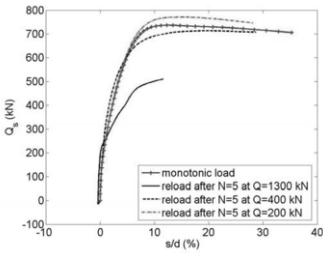
b)

Figure 4. Cyclic soil stress path for N=5 at Q_T=200 kN, for a point adjacent to the pile shaft at 4.4 m depth: a) shear and normal stresses; b) volumetric strain and mean stress (CSL– critical state line).

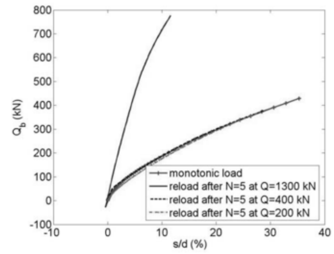
4 MONOTONIC TESTING AFTER CYCLING

4.1 *Effect of the cyclic amplitude for a given number of cycles*

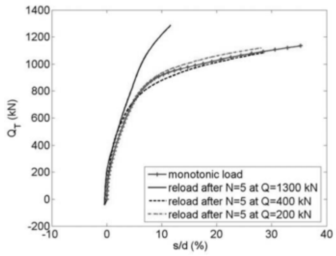
Figure 5 shows the load settlement curves for the static reload, subsequent to the application of five cycles of different amplitudes (Q_T = 200 kN, Q_T = 400 kN and Q_T = 1300 kN), compared with the monotonic results with no previous cycling. The load settlement curves presented are apparent ones (relative to the initial state). This is to say, that residual loads are not taken into account and displacements are set to zero after cycling, as it is done in common *in-situ* practice.



a) Q_s - s/d



b) Q_s - s/d



c) Q_s - s/d

Figure 5. Apparent load settlement curves; Effect of cyclic pre-loading loading (N=5, QT = 200 kN, QT = 400 kN and QT = 1300 kN) on the subsequent static response compared to the monotonic load settlement curve (in red); a) Shaft resistance, b) Base resistance, c)Total resistance.

After the application of 5 cycles with different amplitudes the soil initial state was modified, so now the second question is how important is the soil loading history in the pile resistance mobilization and whether it is improved or not by the previous cycling.

In terms of shaft resistance, Figure 5a, in the case of cyclic mechanism 3 (Q_T=200kN), there is a small increase in resistance due to the cyclic densification; cyclic mechanism 2 (Q_T=400kN) presents a small degradation of the shaft and the cyclic mechanism 1 (Q_T=1300kN) looses about half of its maximum shaft resistance when compared to the monotonic one. It is evident that the soil has a "memory" and in cyclic mechanism 1 and 2 shaft resistance is not recoverable. Nonetheless, the effect of the soil densification, observed in the cyclic load transfer mechanisms 3, justifies the small increase of the maximum shaft resistance during the static reload.

Considering the base resistance, this one is clearly reinforced by the application of cycling with high amplitude. On one hand due to the residual loads locked in, and on the other hand due to the high base stiffness increase due to pre-loading that the base had to undergo to compensate the great amount of the friction fatigue (Figure 1). As seen previously, the base resistance mobilization during cycling is dominated by the generation of the friction fatigue, because the pile has to settle more during cycling to compensate the lost of friction.

Therefore, as the pre-load cyclic amplitude increases, the shaft resistance, in a subsequent reload to failure, tends to decrease. Concerning the base, the opposite effect is observed. Thus, for the final mobilized total resistance (Figure 5(c)), the effect of the friction fatigue is compensated by a large gain in base resistance mobilization. Thus, the application of previous cycles before testing to failure, with higher amplitude, can be beneficial to increase resistance, despite the friction fatigue generated during cycling.

4.2 *Effect of the number of cycles for a given cyclic amplitude*

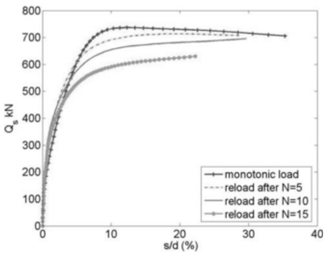
Load settlement curves for the monotonic loading, and reload after cyclic loading, with different number of cycles are presented in Figure 6. After the five cycles at Q_T=400 kN, the monotonic reload reaches almost the same maximum shaft resistance as that for the monotonic load (Figure 6(a)). Nonetheless, a total load reversal is observed for the base resistance (Figure 6(b)).

Normal stress decreases with the application of cyclic load. However, subsequent monotonic loading causes dilation as the "steady-state" strength is being mobilized. Hence for an applied load level in which the maximum shaft resistance is not reached, there is almost complete stress reversal in terms of the shaft shear stress.

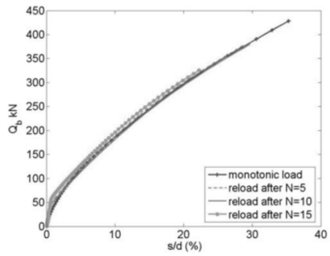
In addition, from the load settlement curves plotted in Figure 6, one can observe that shaft resistance decreases when the preceding number of applied load cycles increases. For base resistance, as expected, the initial stiffness increases due to the increase of the previous pre-load during cycling, to compensate friction fatigue. In terms of total resistance, the loss of shaft resistance, with increasing number of preceding load cycles, is not compensated by the base resistance mobilization, so total resistance is smaller than the monotonic total resistance mobilized with no preceding cycles (Figure 6c). This is in contrast with the effect of cycling when higher load levels are applied, such as in case of cyclic mechanism 1 (previous paragraph).

Nevertheless, for relative head displacements that vary from 0 to 4–5%, cycling produces a small increase in initial stiffness, both due to base and shaft resistance.

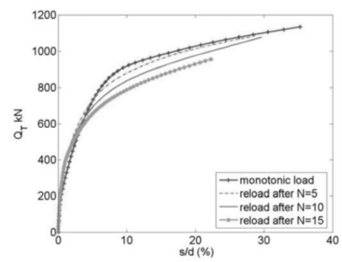
In sum, increasing number of cycles of Q_T = 400 kN - cyclic mechanism 2 - applied previously to the monotonic loading to failure, leads to a small reduction of the pile total resistance mobilization subsequent to cycling. Because total reversal of shear stress mobilized is not possible and this reduction is not compensated by the base "overconsolidation" or pre-loading during cycling.



a) Q_s - s/d



b) Q_s - s/d



c) Q_s - s/d

Figure 6. Effect of number of cycles at Q_T = 400 kN, on the subsequent reload response compared to the monotonic load settlement curve; a) Shaft resistance, b) Base resistance, c) Total resistance.

Another important aspect is that base mobilized resistance increases with the number of cycles, and the initial stiffness and strength of the reload increase, regarding the monotonic loading (due to the high pre-loading), but final base resistance, at the perfect plasticity remains unchanged. This feature is observed when base resistance of bored pile is compared with that of driven or jacked piles under very large displacements (Fioravante et al. 1994). Thus a first parallel can be established between installation effects and the behavior of piles cyclically loaded.

5 CONCLUSIONS

Numerical results show that, cycling decreases the maximum shear stress, due to the accumulation of soil contraction and the consequent reduction of the normal stress. The main mechanisms governing the friction fatigue are analyzed and well captured by the soil model.

Changes in lateral stress on the pile shaft arise from changes in volume of the shear zone. Therefore, if the mechanisms that control the volume changes during cyclic loading are clarified, the friction fatigue phenomenon is understood. Thus, the initial state of the soil and the amplitude of the first pre-load cycle are determinant for the rate of friction degradation. This is due to the modification of the soil state at the beginning of each pre-load cycle in respect to the critical state. If the critical state is reached during the first load cycle, friction fatigue will be more important in the subsequent cycles.

After cyclic loading, the soil memory and the previous stress path will influence the subsequent reload cycles by moving the initial state at the beginning of each cycle closer or further to the critical state. These changes will affect the monotonic reload resistance of a pile that has been previously cyclically loaded. Thus it is possible to point out some analogies with installation effects. The Base is first loaded to failure during installation and then reloaded. The base "overconsolidation" can be easily obtained by the cyclic loading of the pile and when reloaded, base will have a stiffer load-settlement response. The cyclic loading of the shaft leads to friction fatigue. That is why jacked and driven piles present different shaft capacities, because different levels of friction fatigue are attained with the number and the amplitude of the cycles, imposed during installation.

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