Small-scale model testing of cyclically axially loaded piles

Extended Abstract

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Abstract: Throughout the years, the need for heavier and more complex structures have stimulated the development of pile foundations, which may be subjected only to monotonic loading, but also to cyclic loading. However, the deterioration effects of cyclic loading have only been studied in the last five decades and these remain largely unknown. The offshore structures' foundations are often more susceptible to cyclic axial loading, driving the research in this field, where the addressed cyclic periods are relatively low. In that regard, this work explored the overall cyclic pile-soil system behaviour when longer periods were considered, supporting the study of the long-term cyclic performance of energy piles.

Featuring an experimental campaign in the framework of studying the effects of cyclic axial loading on piles, a small-scale pile and various equipment were used. Several variables were taken into account and the hypothesis of the increasing stiffening effect of a tensioned and compressed soil is made. The demystification about the soil initial state is discussed, being concluded it can be considered partly irrelevant, only after running a number of cycles. Lastly the pre-cycling is considered beneficial since it is a step further in the prediction of the cyclic pile-soil behaviour.

Keywords: Pile foundations; cyclic axial loading; shaft resistance degradation; small-scale testing

1 Introduction

In the framework of considering cyclic loading, numerous experimental research has been devoted to it by various authors; nonetheless, the periods of loads considered in existing studies suggests that little has been done to address longer periods and large numbers of cycles. In that regard, this work explored the overall cyclic pile-soil behaviour when longer periods of mechanical loading were considered, supporting the study of the long-term cyclic performance as well of energy piles. These energy piles are submitted to cyclic thermal loading as a result of being exposed to daily (i.e., day and night) and seasonal (i.e., summer and winter) temperature variations during their lifetime, which may cause axial displacements and additional axial stresses. A theoretical and experimental publications review of existing studies around cyclic pile-soil behaviour took place and, while it is extensive, the parameters studied vary significantly from author to author. The work also features an experimental campaign in the framework of studying the effects of cyclic axial loading on piles, where a small-scale pile and various equipment were used. Several variables were taken into account and possible suppositions are discussed.

2 Pile foundations under axial monotonic loading

Pile foundations are commonly used for structures' foundations to transfer load to deeper layers of soil or rock, that have improved bearing capacity as well as acceptable settlement behaviour. And depending on the construction method and ground conditions, they can be categorised into: displacement and replacement piles, or end-bearing and friction piles, respectively.

Axial loading of piles may be either compression or tension and there are a number of ways in which the resistance load may be established. Two types of resistances can be mobilised in piles: base and shaft resistances. There are two ways to estimate the resistances: (1) by calculation of the shaft and base resistance components, or (2) by measuring it directly through undertaken static and/or dynamic load testing. Based on the equilibrium of vertical forces in Figures 1.a) and 1.b), the equations Eq. 1 and Eq. 2 can be used to evaluate the ultimate compression and tension resistance, respectively.

$$R_{c;u} = R_b + R_s \tag{1}$$

$$R_{t;u} = R_s \tag{2}$$

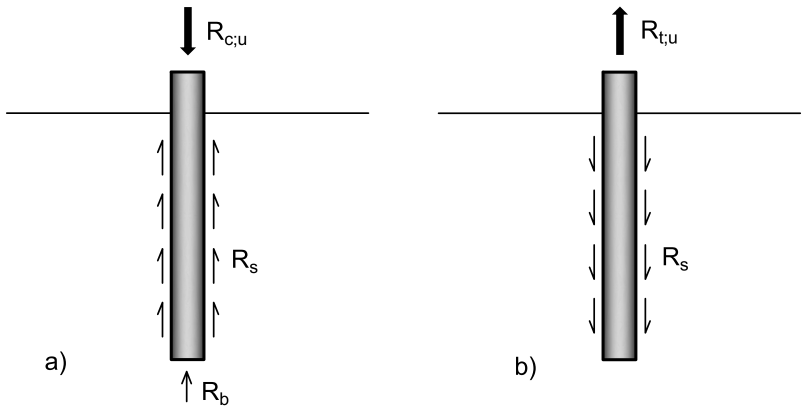

Figure 1 - (a) Pile in compression; (b) Pile in tension

3 Piles under axial cyclic loading

The term *cyclic* loading is defined as a repetitive and regular type of loading that follows a certain pattern, where variables such as amplitude, period and frequency can be easily determined by analysing the behaviour of the source of the cyclic loading (Andersen et al., 2013). Traditionally, the focus has been on offshore structures, with cyclic loading being imposed by natural influences i.e., wind, waves and earthquakes that correspond to relatively small periods, varying from as short as 1-second to as long as 10^2-seconds.

In real-world scenarios, cyclic loading is non-regular, meaning the amplitude and/or period of loading are irregular, making it difficult to characterise it by means of regular, periodic functions. However, such simplifications are made to facilitate analysis as well as to undertake experimental testing. Consequently, it is necessary to define certain parameters to indicate a range of cyclic values. The cyclic load parameter Q_{mean} is the mean load or mean component of the cyclic load, while Q_{cyclic} is the axial cyclic load amplitude increment or half-amplitude of the cyclic load, providing the peak cyclic loads Q_{max} and Q_{min}. T is the period of the cycles (thus $f = 1/T$ corresponds to the frequency) and lastly, N is the number of cycles applied. In pile behaviour studies, cyclic loading is classically distinguished between *one-way* and *two-way* loads as follows:

- *one-way* load tests, either in tension or compression, where $Q_{cyclic} < Q_{mean}$;
- *two-way* load tests, alternating tension-compression, where $Q_{cyclic} > Q_{mean}$.

3.1 Concept of Cyclic Stability Diagram

Poulos (1988) described the effect of cyclic loading through a cyclic stability diagram where the results were presented in terms of the ratio $Q_{cyclic}/Q_{ult,t}$ as a function of $Q_{mean}/Q_{ult,t}$,for a fixed number of load cycles, N (Figure 2). $Q_{ult,t}$ is the ultimate monotonic compression resistance, while $Q_{ult,t}$ is the ultimate monotonic tension resistance (pull-out capacity). Such a normalised representation allows the results from various studies under the same conditions to be compared.

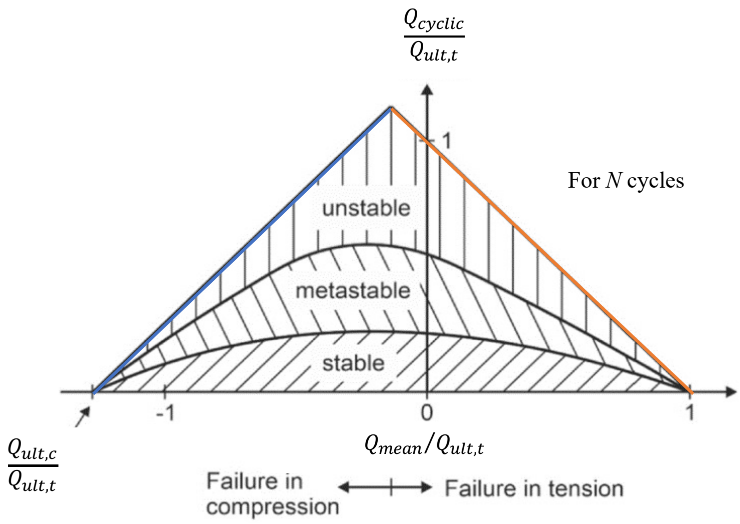

Figure 2 - Cyclic Stability Diagram, Poulos (1988)

The definition of *failure* under cyclic loading refers to the development of a limiting accumulated displacement. For the design of offshore structures, it is considered that failure takes place when a displacement equal to 10% of the pile diameter, *D,* is attained (Puech & Garnier, 2017). Within the diagram, three behaviour categories are defined: *stable*, *unstable* and *metastable*:

- The *stable* zone as the one in which only small deformation accumulation might occur without occurring failure;
- The *unstable* zone, where cyclic loading will result in failure of the pile within a specified number of cycles;
- The *metastable* zone lies between the *stable* and *unstable* zones and, in this zone, cyclic loading causes a limited accumulation of deformation, leading ultimately to failure.

The diagram developed by Poulos (1988) considers a two-way cyclic load, hence the pile response can be either in compression or in tension. The diagram is then asymmetrical in relation to the vertical axis because the compressive capacity is usually greater than the tension capacity, as the base resistance is mobilised in addition to the shaft.

3.2 Effects of cyclic axial loading on piles - Degradation of the shaft resistance

It follows naturally from this that any loss of capacity on the pile shaft must be compensated by the transfer of loads to the other parts of the shaft and the base of the pile. Cycle by cycle, the friction (shaft resistance) degradation tends to propagate along the shaft from the head, towards the base of the pile. Experimental tests made by Poulos (1991) showed that pile foundations under cyclic loading have a smaller shaft capacity when compared to that of monotonic loading. Fioravante (2002) explains the interface behaviour between the pile shaft and soil by the conceptual model shown in Figure 3.

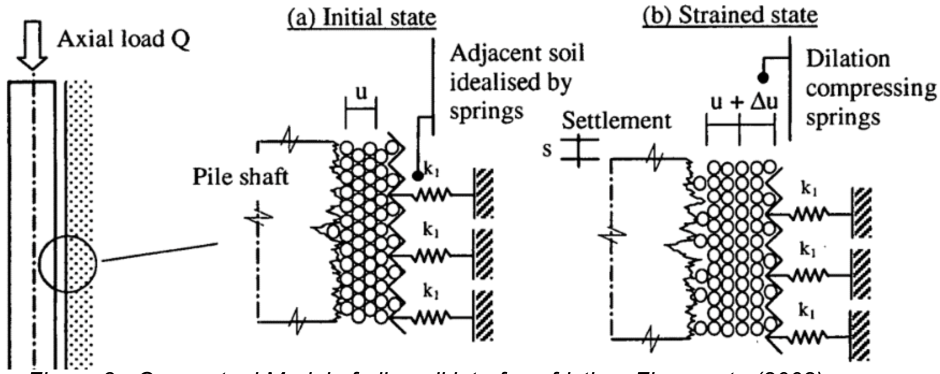

Figure 3 - Conceptual Model of pile-soil interface friction, Fioravante (2002)

In this conceptual model, the author describes that, in the interface between pile shaft and the surrounding soil, any volume change in this zone is constrained by the surrounding soil, acting as an "elastic spring". In other words, the tendency of the interface layer to change its volume interacts with the behaviour of the surrounding soil, which imposes the normal stiffness condition on the interface between the pile and soil.

When cyclically loaded, the particles of soil surrounding the pile will crush and consequent degradation of shaft and base resistance take place, leading to soil fatigue. This is understandably the same reason for higher accumulation of permanent displacement, since particle crushing will allow particle rearrangement and, subsequently, the pile will have the freedom to relocate little by little until reaching failure.

3.3 Experimental literature of cyclic axial load testing of piles

Although there is a vast number of experimental literature of small-scale and full-scale cyclically and axially loaded piles, the process of reviewing and creating a database of the existing tests on pile foundations, for the present dissertation, has proven to be quite challenging. It has been found that the parameters involved in the tests vary from article to article e.g., most do not mention the period/frequency of the cyclic load – one of the key factors influencing the cyclically loaded piles; the soil initial state nor its properties; providing either relative or absolute of Q_{mean} and Q_{ult}; varying failure criteria, among others. Hence, it complicates the comparison between tests and the development of a consistent framework for describing cyclic axial loading effects on piles.

After careful examination of Puech & Jezequel (1981), Benzaria et al. (2013) and Blanc et al., (2015), it is evident that the main factors contributing to failure are the loading applied, as well as its frequency, since for higher values of Q/Q_{ult} and higher frequencies, failure tends to take place at lower levels of N_f. On the other hand, the soil density little modifies the bearing capacity, once for similar values of load ratio and frequency, but opposite soil density conditions, N_f remains unchanged. Logically speaking, a dense sand will have a higher static resistance when compared to a loose sand and, therefore, for any given load ratio, a larger load cycles take place. Nonetheless, it may be that, for cyclic loading, the effect of initial state of the soil is not so important, as it is altered from cycle to cycle.

4 Experimental small-scale pile under axial loading campaign

A series of tests were conducted on a single pile at the geotechnics laboratory of Instituto Superior Técnico, University of Lisbon. The goal of this experimental campaign was to simulate, through a small-scale model, the behaviour of a single pile installed on sand, under cyclic axial loading.

The testing setup is rather simple, in fact, it is similar to various experimental setups described in the literature, e.g. Li et al. (2012). The materials and equipment consisted of (Figure 4): a steel loading frame (repurposed from an existing consolidation frame), a large steel tank, a sandy soil, a small-scale aluminium pile, a linear stepper motor, a 1000N load cell, a displacement transducer (POPT), a data logger, a computer with the data acquisition system and motor control software installed.

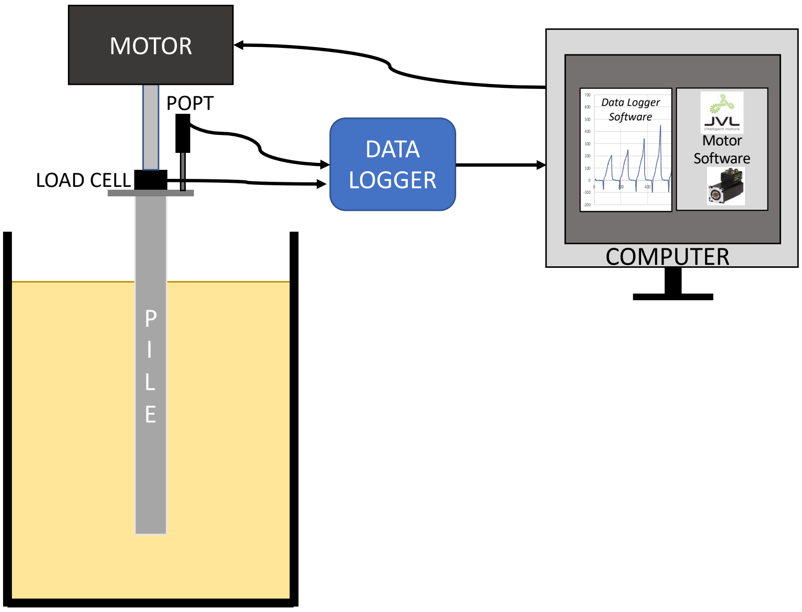

Figure 4 - Schematic of laboratory setup

The philosophy adopted in this study was that, while it is acknowledged that testing under 1g (one gravity) conditions implies that many model scaling effects are not satisfied, the testing is, however, undertaken within a consistent and controlled system, which will allow the stability of a single pile under cyclic mechanical (this study) and thermal loading (not approached in this study) to be appraised.
It was also important to ensure that the tests were undertaken in a consistent manner, to ensure the soil initial state was achieved repeatedly and to ensure the pile load test was executed in a repeatable manner too. The small-scale model testing of the pile consists of the co-ordinated use of all the mentioned equipment and materials. In fact, to run a test, the following steps were followed:

1) The tank is filled with sand until the level reaches the base level of the pile, then the pile is hung centrally in the tank and the remaining sand deposited while pile verticality is checked at intervals;

2) The POPT and load cell sensors are connected to the data logger;

3) The Stepper motor is programmed to load the pile in the planned manner;

4) The data logger is started and the motor program is executed: while the POPT measures the pile head displacement, the load cell measures the load generated at the pile head, in response to the imposed displacement;

5) The sensor data is captured, at a rate of 20 samples per second, and transferred from the data logger to the computer, where it is visualised as the test proceeds and converted directly to excel format for later analysis;

6) The motor program stops automatically as programmed, the data logger is stopped manually, and the next test is readied – returning to either Step 1 or Step 3.

In order to distinguish the different tests, from this moment forth, the following nomenclature is used:

ABC / T or C or TC - #

MON: Monotonic test
CYC: Cyclic test

T: Tension
C: Compression
TC: Tension+Compression

Test number in same conditions

For example: CYC/TC-3 corresponds to a cyclic test, composed by tension and compression stages (*two-way*), having been the third test to be run in these conditions. In this experimental campaign, all the cyclic tests that took place were *two-way* tests, therefore, every CYC test will be, inevitably, TC tests as well.

In addition, two different soil preparation methods were considered: a dense one (where maximum dry unit weight, γ_d^{max} =14.14 kN/m^3 and relative density D_r =77%) and a loose one (γ_d^{max} =13.87 kN/m^3 and D_r =39%).

4.1 Monotonic load response

A series of 8 monotonic load tests was performed. One thing to bear in mind is that the test setup had a malfunction, since the commanded displacement does not correspond to the actual displacement, therefore varying randomly.

4.1.1 Loose soil preparation

For this set of three tests, MON/C-1, MON/T-1 and MON/C-2, the sand was prepared in a loose state, with an initial unit weight of 13.87 kN/m^3 (D_r = 39%). The three tests were run one after the other, which means that the final conditions of the first test are the initial conditions of the second test, and so forth.

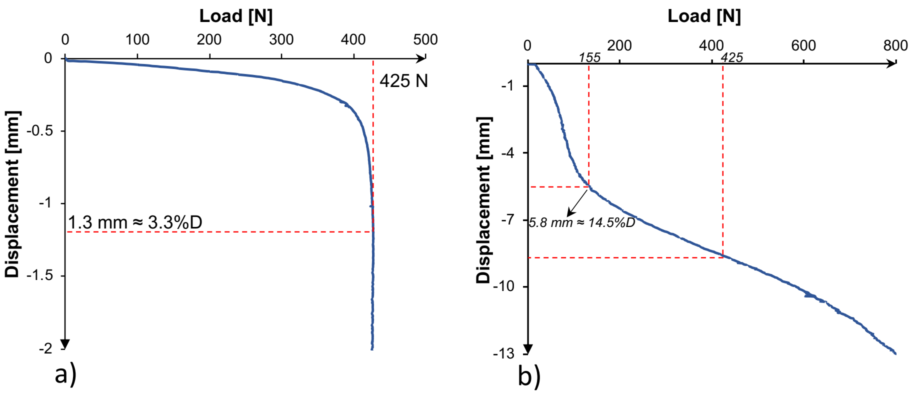

Figure 5 – (a) MON/C-1 and (b) MON/C-2 Test Displacement-load plots

In MON/C-1 (Figure 5.a), the motor was instructed to move 15 mm in compression, at a rate of 0.082 mm/s, or 4.9 mm/min. Right after running test MON/C-1, the small-scale pile is pulled out another 15 mm creating the MON/T-1, the first monotonic load in tension test to be run. The test did not go as planned and the corresponding Displacement-load graphs is noisy and unstable. Since no explanation seemed to be suitable, test MON/T-1 is considered irrelevant and, therefore, shall be ignored.
Right after running test MON/T-1, the pile and soil underwent another compression test about 2 minutes later, MON/C-2. By not altering the soil between tests, this means that the soil final conditions of MON/T-1 are the initial conditions of MON/C-2, which is crucial to understand the load-displacement graph (Figure 5.b).

At first, the curve shape was found to be peculiar, because being this another monotonic compression test, it would be expected the curve to be similar to the first compression monotonic test, MON/C-1. However, when comparing these two tests, MON/C-2 displays a stiffer behaviour by attaining higher loads for equivalent displacements. Even though failure is never attained, it seems to start taking place around 700 N, because beyond it, the response appears to be softening, which may be an indicator of approaching failure.

In Figure 5.b), the load and displacement corresponding to the failure of MON/C-1 were marked, demonstrating the difference in behaviour between these two monotonic tests. What differs MON/C-1 from MON/C-2 is that the pile has

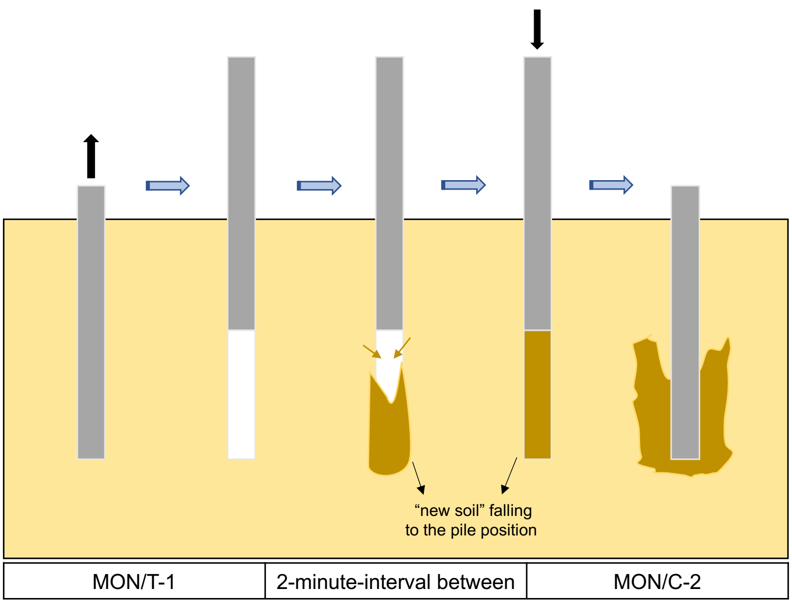

Figure 6 - Explanation of soil behaviour between MON/T-1 and MON/C-2

been pulled out before (tension test MON/T-1), altering the soil conditions. It is evident then, the contrast between an "intact" soil and a "flawed" one.

The shape of the displacement-load curves starts assuming a "belly" form, reaching the maximum compression load at 800 N. It was perceived that the "belly" shape start is evident at 155 N, or 5.8 mm. A possible conjecture for the shape of the curve can be that the soil below the pile is compacted and, as the pile goes upwards and downwards, a blank space is left, so there is "new" soil falling to the pile position as it is being pulled, as simply demonstrated in Figure 43. So, when a compression test is performed after pulling out the pile, the "new" soil is brutally pushed out of the way, to make room for the pile. The "new" soil right after falling to the pile position is loose, so, when compressing it, there will be a first stage (0 to 155 N) of penetrating through the "new soil", which will eventually compact. Once it is compacted, there is the stiffening of the curve (155 to 800 N), that corresponds to the compactation of the soil that is being compressed.

Before tests MON/T-2 and 3, the tank was emptied out and refilled back in, so that the sand was prepared in a loose state again. Since MON/T-1 was disregarded because of its irregularity, a MON/T-2 was run, Figure 7.a). In this test, a failure load of 388 N was recorded at about 3.5%D. Being a tension test, which means only the shaft resistance is mobilised, and considering the soil state (with low confining stress and stiffness of the soil adjacent to the pile), this recorded load was not expected, being almost identical to that obtained in the MON/C-1 (which should include base and shaft components of resistance). Therefore, out of the two scenarios, only one is possible in MON/T-2: either a large portion of the resistance is being mobilised at the base (not only because of the soil preparation, but also because APAS 30 is a very cohesionless sand), or there is none/very little base resistance in compression (which may be due to the way the test was prepared).

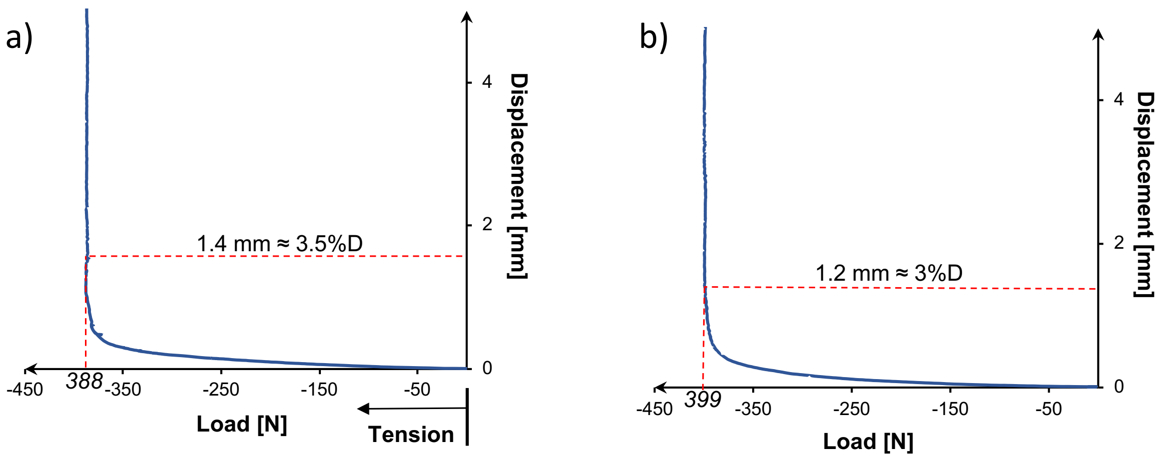

Figure 7 - (a) MON/T-2 and (b) MON/T-3 Test Displacement-load graphs

4.1.2 Dense soil preparation

In contrast to the previous tests, for this set (MON/C-4 and MON/T-4) the sand was prepared in a dense state, with an initial unit weight of 14.14 kN/m^3 (D_r = 77%).

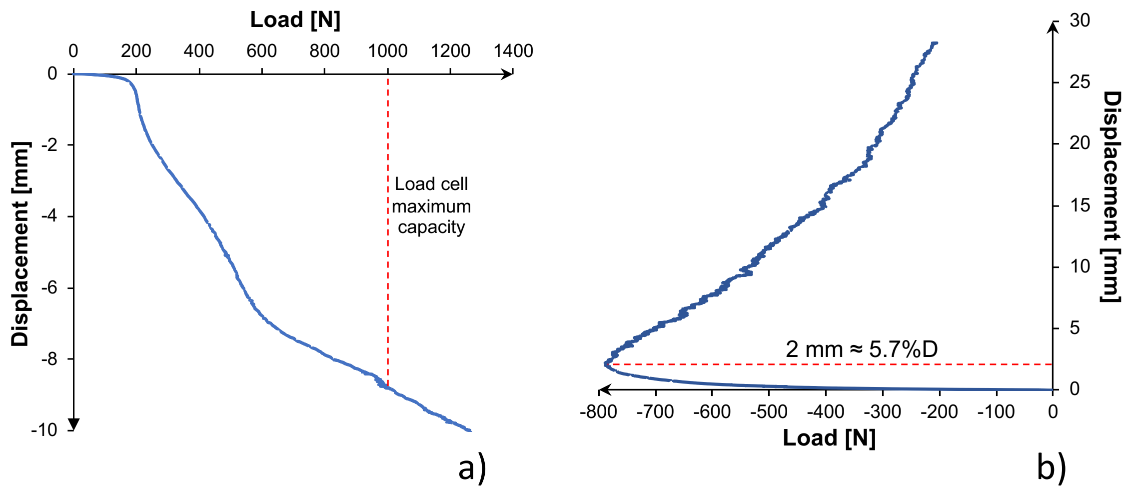

Figure 8 – (a) MON/C-4 and (b) MON/T-4 Load-displacement plot

In Figure 8.b), a load of 800 N is attained at 2 mm displacement, more than twice the recorded ultimate resistance in tension in MON/T-2 and T-3, and therefore not comparable to the estimation of 196 N. However, the response stiffness (load/displacement ratio) is similar to the previous tension tests with an initial loose preparation. The shape of the load-displacement curve is different, exhibiting significant softening after the peak resistance is reached.

By analysing the MON/T-4 curve, it is understood that, due to the method of placement of the sand, the initial confining stresses in the soil adjacent to the pile are higher than in initial tests. So the load necessary to displace it (800 N) will be higher than 390 N obtained previously in the loosen soil. Once the pile moves upwards, the load instantaneously decreases at a rapid rate until the test is finished at 205 N, a reasonable value for failure. Further testing would clearly be needed, as to check whether failure would take place around these values.

Afterwards, the test MON/C-4 (Figure 8.a) was run. Since the response in tension attained already more than twice the monotonic capacity, and, on top of it, the pile has been pulled out (which has proven to result in a stiffer response), the curve behaviour in compression was expected to attain even higher loads and form the "belly" format. Although the motor was programmed to induce a 15 mm displacement in compression, the test had to be interrupted at 10 mm, shortly after recognising that the load cell maximum capacity of 1000 N had been surpassed.

4.2 Cyclic load response: effect of soil initial state

4.2.1 Dense soil preparation

A series of 4 cyclic load tests in dense soil conditions was performed.

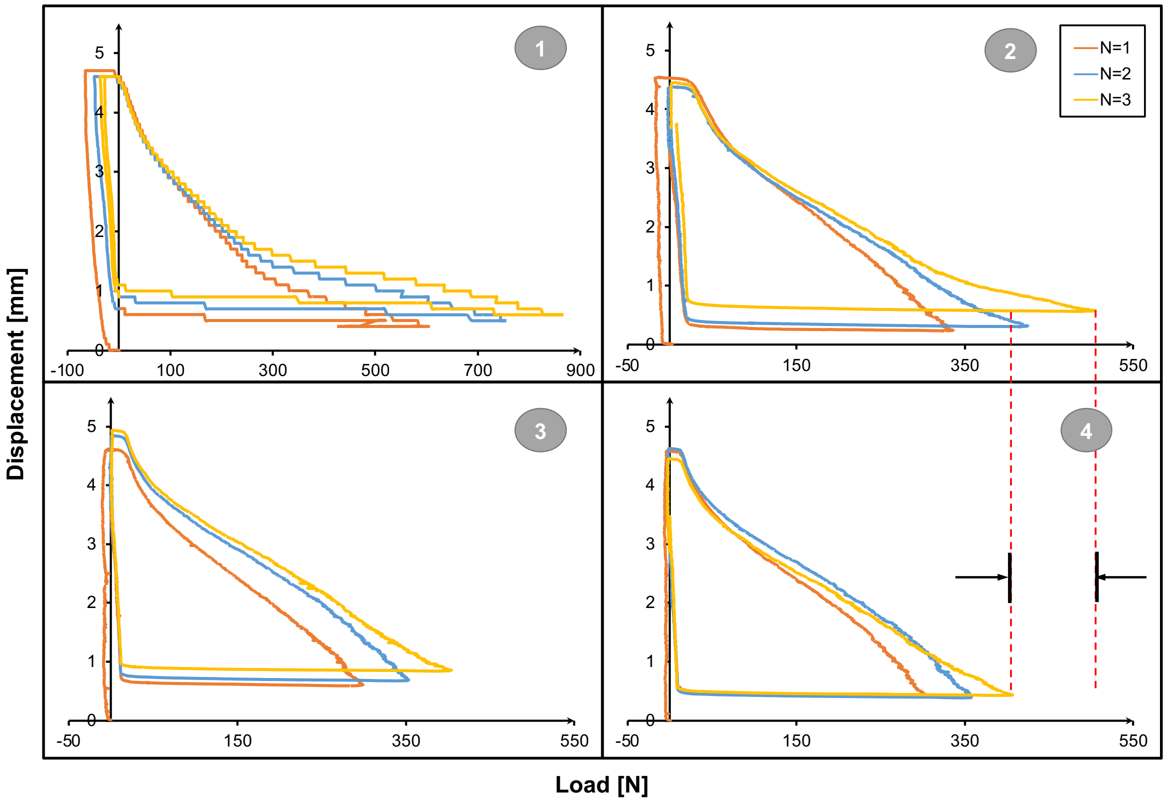

Figure 9 - Load-Displacement graphs for tests CYC/TC-1 through 4 in dense sand

After running the first cyclic tests in dense sand and plotting the corresponding graphs, numerous aspects were noted:

1) As shown in the figures, the compression load mobilised is significantly larger than that for tension, because, as discussed previously, the axial compression capacity derives from both the base and shaft resistances, while in tension on the shaft resistance can be mobilised;

2) The period of the cyclic load is 123 s and is kept constant in all 3 cycles of the 4 tests. Since the existing experimental data does not go further than 10 s, this is considered to be a large period;

3) Considering this is a displacement-controlled investigation, it is seen the measured displacement, although a somewhat irregular, is consistent. On the other hand, the maximum measured load, within the same test, increases from cycle to cycle;

4) Therefore, with the increasing number of cycles, there is a rearrangement of particles, which results in an increase in resistance;

5) On tests CYC/TC-2, 3, and 4, the maximum load attained in each test is significantly lower than that of CYC/TC-1. This fact is certainly related to the initial soil conditions, since the first test was the only one to take place right after compaction, hence attaining a higher load;

6) Knowing that the period is constant and that a larger displacement takes place in CYC/TC-1, there will be less coordinates to be recorded in between, hence explaining why there is some turbulence when compared to the others;

7) There is a permanent increase in stiffness, from test to test, meaning that the load/stiffness ratio increases. As it is noticeable, for a fixed displacement, the corresponding load is higher form test to test, in other words, the behaviour is stiffer;

8) From the test CYC/TC-1 to 2, a large fall is seen in maximum load attained, meaning the initial conditions are rapidly degraded. Therefore, this indicates that the graphs will shrink, which they do;

7) While within a test, the maximum load attained increases from cycle to cycle, in Figure 9 it is clear that the maximum load attained decreases from test to test. However, as the number of cycles *N* and number of tests increase, the maximum load tends to stabilise, especially on the last 2 tests. Further cycles would need to be run, to understand whether this stabilisation is merely apparent or not;

8) Even though the motor is instructed to move 5 mm, the recorded displacement is different, varying in all cycles and tests. The load cell, in its turn, can present somewhat varying values. The reason for this is not clear, nonetheless it is suspected this is related to the approach used for zeroing the load cell and POPT. In the approach used, the initial recording values are just set to 0, not considering or interpreting which values were being recorded by any sensor, especially the load cell.

4.2.2 Loose soil preparation

A series of 4 cyclic load tests in loose soil conditions was performed.

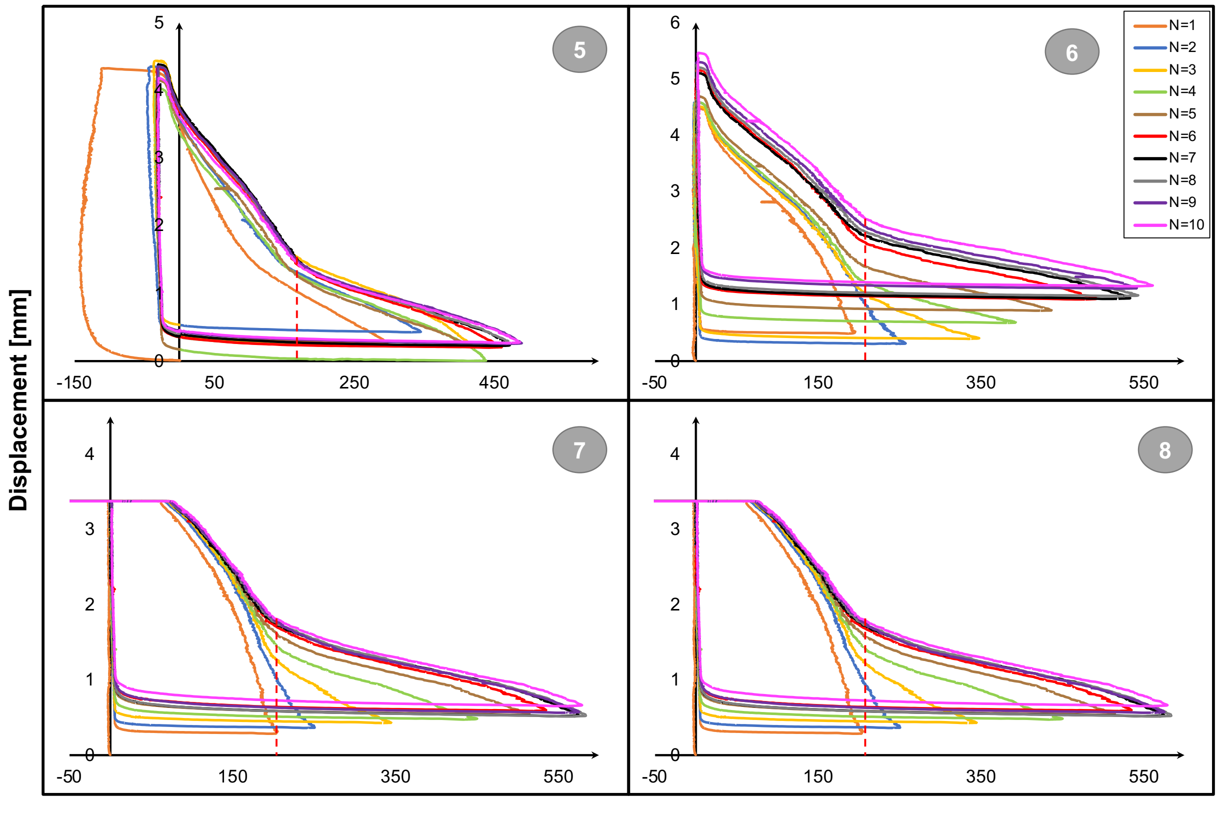

Figure 10 - Load-Displacement graphs for tests CYC/TC-5 through 8 in loose sand

1) The shape of the load-displacement curves assumes the same “belly” form, when reaching the maximum compression load. Though this time, it is evident that the shape of the curve changes around the 200 N threshold, as marked in Figure 10;

2) Unlike the previous tests, the maximum attained load in the last cycle increases from test to test, as shown in Figure 10. This means that the graphs will successively stretch, as opposed the dense ones, where the graphs would successively. So, the maximum attained load is greater than the monotonic tests’ values as well as the cyclic tests with initial dense soil conditions;

3) Surprisingly, the mobilised shaft resistance on *N* = 1 of CYC/TC-5 is higher in loose conditions than in dense conditions, being around 110 N. Nonetheless, it degrades faster, being almost totally lost by *N* = 3 of the first test;

4) Throughout these tests, the stepper motor is commanded to displace 5 mm, either in tension or compression. Even though in tests CYC/TC-5 and 6 the measured displacement is around 4.2 mm, it is not constant. In fact, in tests CYC/TC-7 and 8, the measured displacement does not even surpass the 3.4 mm. For now, it remains unknown the

reason why the motor would stop moving, since its thrust is approximately 2000 N. In later tests, this is an important aspect to be addressed since it might need to be fixed;

5) Even so, with increasing *N*, stabilisation appears to be attained around 580 N in last 4 cycles.

5 Conclusions and recommendations for future work

The aim of this work was to provide relevant knowledge regarding the pile-soil behaviour under cyclic axial loading and the resulting effects with regard to failure, since it has been proven that cyclic loading is very damaging in terms of resistance, as reviewed in many publications. In the pursuit of new discoveries about the unknowns related to cyclic behaviour of piles, the experimental campaign took place. It allowed several evidence to be observed and conjectures to be made, namely:

- In the monotonic tension and compression tests run in loose soil, the behaviour was identical, having resulted in similar failure loads and displacement. The reason for this remains unknown, but two scenarios were questioned: either a large portion of the resistance is being mobilised at the base, or there is none/very little base resistance in compression;
- It was observed the effect of a *two-way* cyclic test, where the pile is pulled out (tension) and pushed in (compression) afterwards. In these compression series, the witnessed behaviour is, in fact, stiffer and therefore capable of attaining higher resistances, than the compression tests where the soil is "intact". The conjecture made about this was that there is a "new" soil falling to the previous pile position as it is being pulled out. So, when a compression test is performed afterwards, the "new" soil is brutally pushed out of the way, to make room for the pile, hence demonstrating a stiffer behaviour;
- Unexpectedly, the first cycle in tension, in which the soil is still intact, the recorded resistance is less than 50% of what had been observed in the monotonic tests, but providing more equivalent values to the estimation obtained with the EN 1997-1 calculations. Therefore, to fully comprehend the mobilised shaft resistance, further testing would be required;
- Generally speaking, the main difference observed between the two initial soil states considered – dense and loose – was that, while in the dense soil the resistance is higher in the first cycle, it decreases until some stabilisation is achieved. On the other hand, the loose state corresponded to lower resistances in the first cycle, but it keeps increasing until stabilisation is achieved. To sum up, the initial soil state is, in fact, important regarding to the mobilised resistance, contradicting the results found in the literature, in this case;
- Considering the very limited number of cycles tested, i.e. 3 and 10 cycles, it could be anticipated that pre-cycling is beneficial in the sense that, although there might be a loss in resistance (especially in dense conditions), a stabilisation of the resistances with further cycling appears to take place, helping with the prediction of the cyclic pile-soil behaviour;
- The quick degradation of the mobilised shaft resistance is well observed, being almost all dissipated within the first cycle;
- The accuracy and poor performance of the test setup used was also a considerable hindrance, especially, the Stepper Motor. Even after the calibration of the displacement transducer, the induced displacements did not match with the ones commanded to the Motor. Naturally, 1 or 2 mm would not have an impact on a full-scale testing, however, on a small-scale testing, it is no longer true.

Confronted by the fact that the results could be, evidently, improved, further testing was attempted to be run. However, the equipment turned out to be faulty and fixing/replacement was not possible in the remaining time available for the work. All things considered, the experimental campaign had an adequate start and seemed to be promising, until the motor started to show it was possibly faulty, impeding further testing. Evidently, further experimental testing should have taken place in order to comprehend some suspicions and reservations that were left unanswered.

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