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EFFECT OF CYCLIC AXIAL LOADING ON THE DISTRIBUTION OF LOAD ALONG THE PILE

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ABSTRACT

In France, within a new research project SOLCYP (cyclic loading on piles), an experimental program with compression and tension full-scale pile test is undertaken to study the behaviour of piles under cyclic axial loading.

The main feature of these tests will consist in measuring the distribution of load (shaft friction and toe resistance) along the pile during static and cyclic tests. To achieve this scheme, the use of the LCPC (French Public Works Research Laboratory) removable extensometer is required. Although, it is specifically designed for static loading, it could be used for cyclic tests until a frequency of 1Hz.

The aim of this research project, is to point out pile bearing capacity degradation and cumulative displacement due to repetitive service loads.

This paper summarizes preliminary full scale compression tests achieved in 2008. It shows the good reliability of the monitoring method to get the distribution of load along the pile during cyclic loading from 0.1 to 1 Hz frequencies load controlled tests. From the measurements of the load segments, the load was fairly distributed along the pile. As far as cumulative displacement is concerned, the pile response depends on the number of cycles, the load amplitude and loading history.

1. INTRODUCTION

Getting in situ data from full scale tests still remains a key point in the progress that can be made in the foundation industry. Indeed, the determination of the distribution of load along a pile for different types of piles and different soils represents a key issue in pile design.

Instrumentation using the French extensometer technique (Bustamante and Gianceselli, 1996, 2001) constitutes a reliable means of measuring load transfer along the piles for static loading. It represents an alternative to the strain measuring devices (Fellenius, 2002 and 2004). Its advantages are found in its installation costs, its adaptability to different types of deep foundations and soil configuration and measurement quality. More than 200 tests were carried out in France in the last 25 years showing a good repeatability and reliability of this technique (Bustamante et al., 2009).

Indeed, as this system seems satisfactory for this application, a step forward would consist in using this convenient instrumentation technique for another type of loading such as repeated loading or cyclic loading for some applications like vibratory machines, windfarms, railway or road infrastructure.

The loads transmitted to the pile (due to the wind, traffic, etc.) fluctuate and can be considered as assimilated to cyclic loading on the piles. This axial cyclic loading on piles involves an evolution of the soil-pile system behaviour. The French onshore design practice does not take into account this type of loading. The design rules which consider cyclic loading, like the API (American Petroleum Institute) or the DNV (Det Norske Veritas), requires a design not adaptable to the onshore practice. New data on the effects of axial cyclic loads on the pile response are required, especially for two-way loading.

The French national project SOLCYP (Axial cyclic loading on piles) (2008-2012) precisely aims at studying the effect of cyclic loading on the pile response in terms of bearing capacity and cumulative settlement. A specific methodology will be developed to take into account this type of loading on the pile response, as well as calculation procedures (Puech et al., 2008).

Two tasks request a cyclic loading system to test piles. The first one is dedicated to the response of piles under cyclic axial loading in two different soils (overconsolidated clay and sand); that can be divided into several successive sequences with increasing/decreasing maximum load, followed at the end by a final static load to measure the loss or degradation of pile resistance after cyclic loading. These load sequences can show some similarities with the storm loading used for design in the offshore industry. Secondly, a testing procedure should be defined or developed in order to validate the design of pile under cyclic loading, from a cyclic load pile test. Therefore, opportunities of field work would be used to be able to achieve pile load tests and to develop that procedure. In addition, requests relative to typical structures submitted to cyclic axial loading are launched to be able to monitor the foundations that would be submitted to cyclic loading during their service life to get a better idea of the real repeated load they will withstand.

At last, for typical structures, cyclic load tests could be planned to check the design of pile under cyclic loading. Specific loading program could be defined according to the load cases the structure will face.

It can be mentioned that Several full scale pile tests campaigns were carried out in the 80s in Europe, in the Drammen clay (Karlsrud et al., 1986), in the test site of Plancoët (sand) and Cran (clay) in France (Puech et al., 1982), more recently in Dunkirk site (France) (Jardine et al., 2000) and in England within a railway building project (O'Riordan et al., 2003) with pile instrumented with strain gauges. This database has to be completed, especially in sands, to be able to propose reliable design rules for engineers.

The local shaft resistance can help the validation of simplified models such as t-z type transfer curves (Randolph, 1986, Chin and Poulos, 1992, Atkins, 2000) to describe the capacity degradation of the piles when they are submitted to cyclic loading. These models need load transfer data measurement to get validation.

Then, a feasibility study of the use of the removable extensometer was achieved to validate the choice of this technique for that application. It took place in Rouen in 2008 where two instrumented piles were tested under cyclic axial loading using a different pile test procedure modified from the usual LCPC procedure for static loading.

2. DESCRIPTION OF THE TESTS

2.1 Rouen test site

The pile test site is located near Rouen, France. The area was known as having a relatively homogeneous geology with clayey gravel soil underlain by weathered and intact chalk.

Two boreholes were done to characterize the geology of the test site. Two main soil layers were observed; clay with gravel on a thickness of 5-6m underlain by a weathered chalk.

The boreholes were ten meters away from the pile location.

Table 1 gives some soil characteristics of the two main layers (gravelly clay and weathered chalk).

Table 1 Soil Characteristics at the pile toe

Depth	W %	W _L %	W _P %	IP %
1-2m	6-14 %	48	21	27
5-6m	5-7 %	20-21	17-18	3,5 - 4

The clay with gravel was difficult to sample as the gravel size was greater than one centimetre. Therefore, the soil material was sieved so that mainly clay was submitted to soil identification tests.

2.2 Pile test layout

Two instrumented test bored piles and four reaction piles were built (Fig. 1). They were 250mm diameter and about 6 m long piles. The pile spacing was such that no group effect could occur between the test piles and the reaction piles.

All the piles were built on the same day in May 2008 :

- 2 instrumented piles equipped with the removable extensometer (P1 and P2)
- 4 non-instrumented piles; reaction piles with steel bars to withstand tensile loads (A, B, C, D)
- 1 unloaded pile to sample the concrete and perform unconfined compression tests (E)

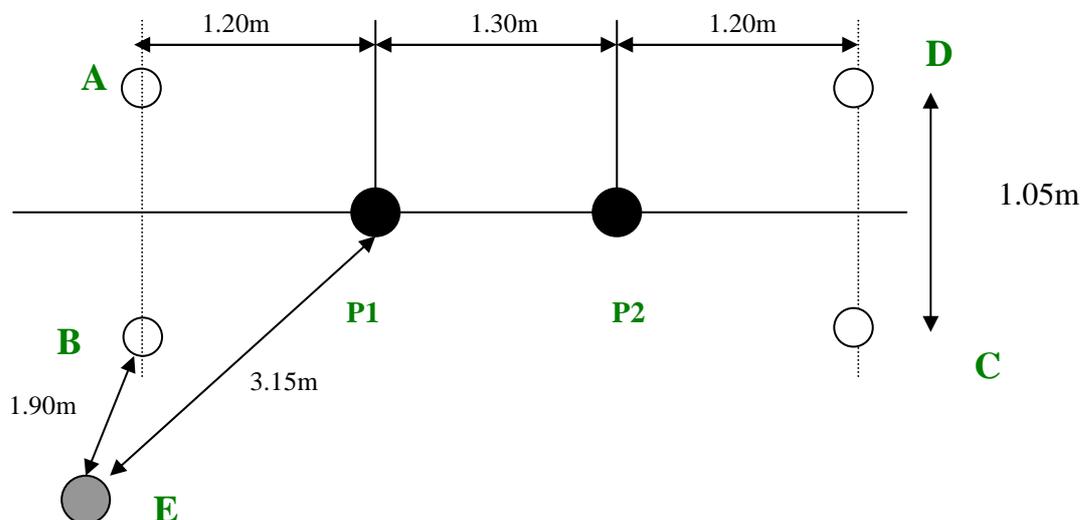


Fig. 1 Layout of site investigation and pile load test

2.3 Pile test procedure and experimental program

The chosen pile test procedure are as follows :

- a succession of load steps of 50 kN are applied until the average load is reached. Each load step is maintained during 30 minutes until the average load for the cyclic load sequence P_m (Fig. 2),
- at a maintained static load (average load), a succession of cyclic load sequences between minimum and maximum values (P_{max} and P_{min}) at different frequencies inferior to 1 Hz. Increasing load amplitudes ($2 P_c$) (difference between maximum and minimum) for each average load were applied. No unloading phases between two successive load sequences were applied. The applied load has to increase.
- at the end of the cyclic loading sequences, a static load, increasing by steps of 50 kN, is applied until the pile head displacement reached 10% of the diameter
- maximum corresponding to a displacement of 10% diameter relative settlement criterion. The bearing capacity of the pile is calculated from Chin – method (Tomlinson, 1995).

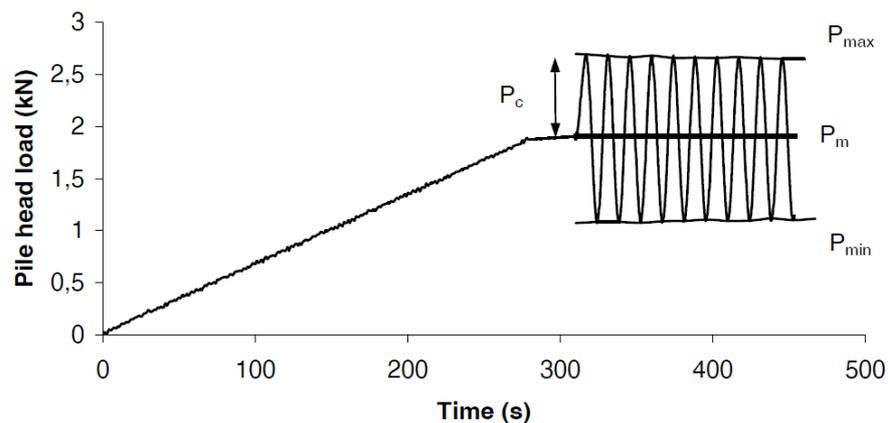


Fig. 2 Typical cyclic loading

3. INSTRUMENTATION DETAILS

The objective of a full scale pile test is to determine the forces Q_i acting along the entire length of the pile from the top to the base, together with the pile toe resistance Q_p . When the loads for each of the pile segments i are known, the corresponding shaft friction can be calculated as the difference between the loads at the top and at the bottom of the pile segment divided by the shaft surface.

The French extensometer technique is described in Fig. 3 (Bustamante and Doix 1991; Bustamante and Gianceselli 1996, 2001). The column (pile) is equipped with a close ended steel (or aluminum) tube during the construction of the column. The tube can be pushed or jacked through the column. The instrumentation is separated into four segments. Each segment is composed of two packers (1) with a strain gauge (2) stuck to a steel ribbon, allowing us to measure the average shaft friction on a portion of the column (pile). Each segment is connected to the other. Consequently, it is possible to determine the transfer of the load along the shaft to the soil with the evolution of strain measurements with depth. The

procedure is the following : the packers and the gauges are installed through the steel tube. The packers are swelled with the help of nitrogen at a certain pressure that block them against the tube ((5), (6) and (7)). All the gauges are connected to the connection box (10) and a bridge (11) with cables ((8) and (9)). The procedure for the packers is such that the toe packer is swelled at first and then blocked. Subsequently, the packers and ribbons are pulled with the string strainer so that all the elements are taut. The other packers are swelled and then the system is ready for measurement. The vertical displacement of the pile head can be measured with an accuracy of 0.01 mm by means of 4 displacement transducers (13) with 150 mm travel placed on 2 reference beams (15). The connection to the acquisition system is made through a displacement transducer reading (14).

Then, (10), (11) and (14) are connected to a computer for data acquisition.

The jack used for this test was composed of a load cell (17) and a ball point (16) so that no bending is exerted on the pile head in the load cell. The load cell was in contact with the fixed beam at the top of the system to apply the loading force.

The ends of these reference beams should be supported at a distance of no less than 2.5-3.0 m from the center of the trial pile. One end of each beam shall be free to move horizontally as its length changes with temperature.

Special attention has to be paid to assembling and positioning of the extensometer housing tubes and constructing of the head column with special outlets; the success of the extensometer method depends on this factor.

The positions of the packers and their levels must be chosen by estimating the location of the different layers to find the response of one or several segments of each layer after the test columns were completed.

A certificate of calibration is usually provided by the LCPC for each ribbon.

To improve the “adherence” effect between cement/concrete and the steel tube, pieces of steel were welded on the steel tube to increase and improve the surface contact with the cement to withstand reversal loads due to cyclic loading (Fig. 4).

4. PILE LOADING SYSTEM

The loads are applied through a hydraulic jack of 1 MN capacity and 200mm displacement range. At the head of the jack, a load sensor is positionned. A steering joint is set up between the load sensor and the hydraulic jack to avoid bending moments.

An important requirement of the cyclic axial load testing was to achieve load-controlled repeated load tests which consist of applying a predetermined controlled load intensity to the pile in a specific wave shape at a specific frequency. To fulfil this requirement, an automated loading system with hydraulic loading was acquired. The electronic and mechanical control system is a fully automated closed-loop servo system consisting of a function controller, function generator, load cells and servovalve.

The cyclic vertical load was applied through a hydraulic system consisting of pumps, jacks, and accumulators, interfaced with the closed-loop system.

The automated closed-loop system consists of a function generator, a controller, strain gauge type load cells and a servovalve. The QUIRI C80/100 digital function generator is a high accuracy waveform synthesizer of ramp, sinusoidal and square wave functions.

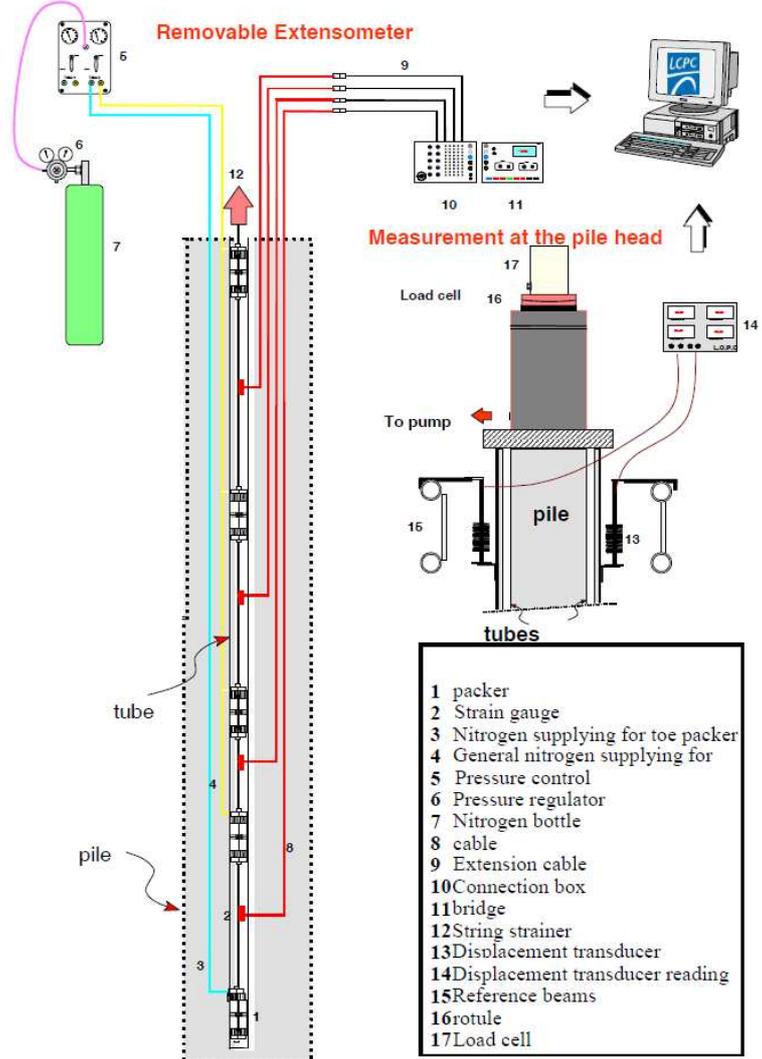


Fig. 3 Removable Extensometer details (Bustamante and Gianceselli 1996, 2001)



Fig. 4 Steel tube with welded pieces to improve the cement-tube contact

This generator is specifically designed as a programmer for closed loop servohydraulic testing system. The model controller is designed to control one or two channel of a closed loop servohydraulic testing system.

5. TEST SETUP

The construction steps were the following:

- Drilling to the fixed depth of 6m for a diameter of 250mm. The grouting was made without injection pressure. After the auger hole was filled with grout, it was vibrated from the base to the top to homogenise the distribution of grout along the pile ;
- A few hours later, the closed ended steel tube for the instrumentation was set up. For pile P1, it was not possible to make the steel tube go down to until the chosen depth of 5.5m; only a depth of 4.58m was reached. It is possible that the gravel was not completely withdrawn by the auger that stopped the downward process. For pile P2, it was possible to make the steel tube reach the depth of 5.50m.

The pile head was built with the following method :

- A square concrete frame is installed at the top of the pile,
- It is filled with concrete and steel bars, steel bars are inserted to make a good connection between the pile and the square head. A space is left the for the cables of the gauges,
- the steel tube is cut at the level of the pile head so that steel plate can be positioned at the top of the pile head to ensure a good contact between the hydraulic jack and the pile.

28 days later, the pile head is ready for the test (Fig. 5), the removable extensometer can be positioned within the pile. Then, a steel plate is placed between the pile head and the hydraulic jack.

The reaction frame was adapted to compression tests as the reaction piles were equipped with steel bars to withstand tensile forces. A transversal view of the whole system is shown on Fig. 6. The top of the piles reached the ground level and the two pile head were built with concrete above ground level with a height of 32 cm.

- The column head displacement are measured with the help of four dial gauges with a accuracy of 1/100 mm.
- The deformation $\Delta l/l$ are measured with the help of the removable extensometer of the LPC.

A general view of the loading frame is shown on Fig. 7.



Fig. 5 Pile head

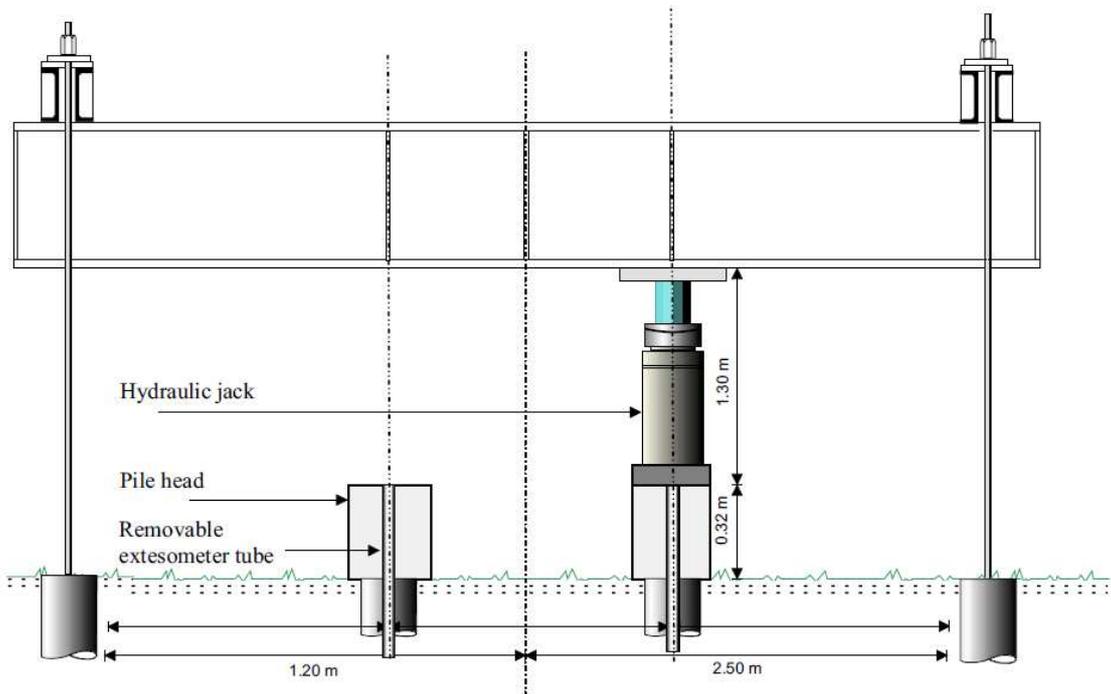


Fig. 6 Transversal view of the reaction load frame and on the right the loading jack before test – one-way cyclic loading



Fig. 7 Photo of the pile load test system

6. LOAD TEST

Two 250mm diameter pile were tested with a pile instrumented with the removable extensometer. As described above, a steel tube was installed in the middle of the column just after the soil-cement column is set up. For the test, a set of ribbons separated by inflatable packers is introduced in the tube. Once the packers are inflated, they follow the displacement of the steel tube. Steel ribbons are equipped with strain gauges (Fig. 8), making it possible to measure the vertical strain for each level located between two packers.

A reaction system was designed on the basis of the results of in situ geotechnical tests. In both cases, the frame consisted of a steel beam on concrete beams (Fig. 7) and linked to four vertical anchor bars DYWIDAG \varnothing 22 mm connected to four reaction piles that work in tension when the column is tested in compression. The limit traction force of the DYWIDAG bars was 2 MN.

During the static load tests, the vertical displacement of the column head was measured by four displacement transducers. Respectively four and five strain gauges for pile P1 and pile P2 inside the pile are installed (from top to the base: A, B, C, D and E) (Fig. 8 and Fig. 9).. They are associated with appropriate data acquisition and storage devices, to measure the vertical strains at the different levels during rapid loading.

From Fig. 8, the pile load test led to pile segment responses specific to their depth, the load distributions (Fig. 9 for static loading) are shown in terms of strain deformations and shaft friction distribution. All levels withstand deformations and respond to the cycle loading sequence.

6.1 Typical results for static loading

No focus is given on the load-displacement curves for both piles P1 and P2. Only the maximum displacement of 10% diameter represents has been considered as a relevant parameter. Nevertheless, the interpolation made from the Chin method (Tomlinson, 1995) gives evaluations of the bearing capacity of the pile with respectively 1300 kN and 1100 kN for piles P1 and P2.

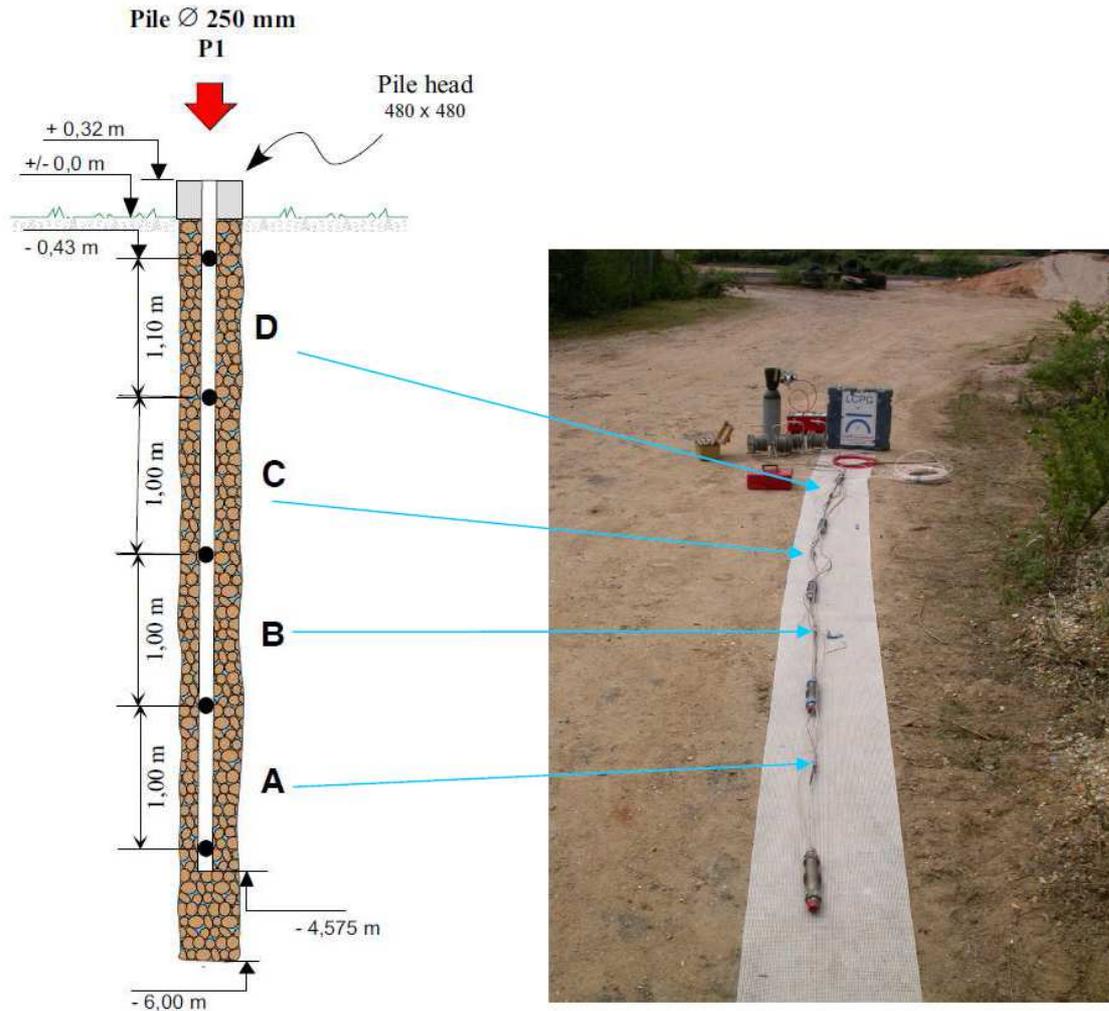


Fig. 8 Monitoring for pile P1

The analyze of the distribution of loads along the pile P2 and their mobilization were made from the unit deformations ϵ and the corresponding distribution of loads (Fig. 9). The results showed a small decrease of the load from the top to the depth of 3.5m. Beyond this depth, the shaft friction mobilized was much higher.

As far as shaft friction is concerned (Fig. 9), for pile P2, 92.5% of the maximum load applied (750 kN) was taken from the shaft ($Q_s = 694$ kN) and 7.5 % of the load by the tip ($Q_p = 56$ kN). The mobilization curves of shaft friction for the different levels A – B – C – D – E of pile P2 are represented on Fig. 10 ; calculated for the theoretical side surface (for a diameter of 250mm) of the pile. The values of shaft friction at different levels calculated from the deformation of gauges are : levels E, $q_s \approx 51$ kPa D $q_s \approx 84$ kPa,, level C $q_s \approx 127$ kPa, level B $q_s \approx 184$ kPa, level A, $q_s \approx 229$ kPa. It can be considered that theres no weakness in the sealing of the tube to the pile during the higher load steps.

Nevertheless, for pile P2, the load carried by the two levels D and E was low and increased a lot from level C to the tip. However, the mobilized toe resistance was very low as the shaft friction of the pile segments above the tip is not fully mobilized.

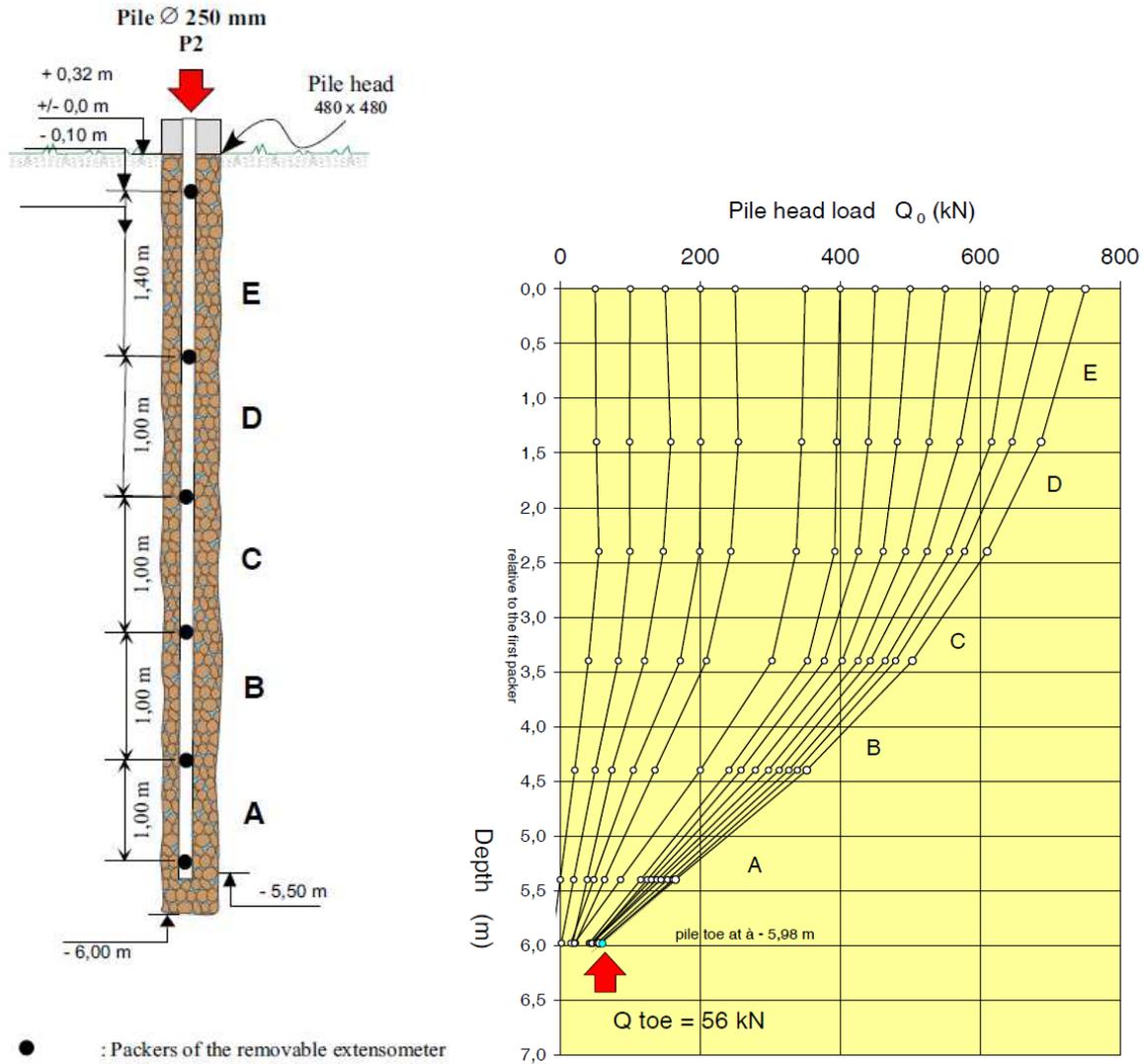


Fig. 9 Load distribution along the pile

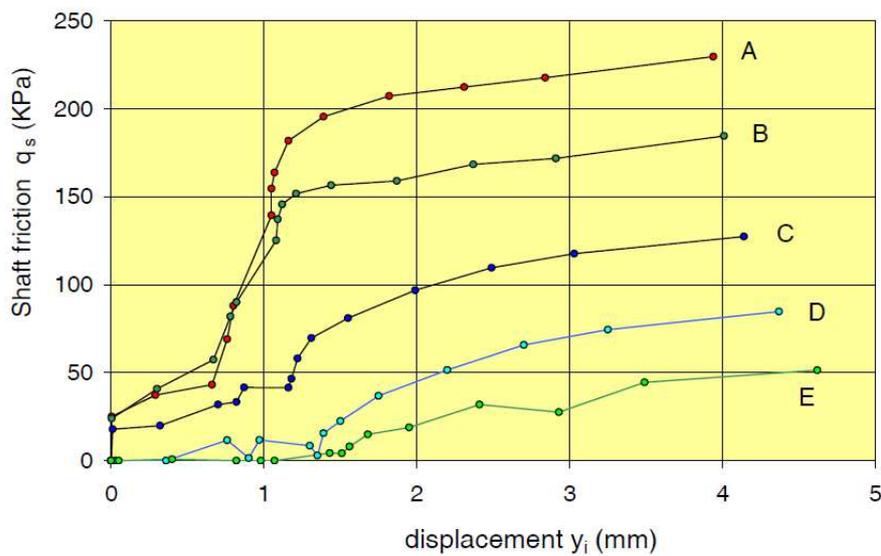


Fig. 10 Shaft friction of the different pile segments (levels A, B, C, D, E) for pile P2

6.2 Cyclic loading

As far as pile response under cyclic axial loading is concerned, a specific experimental program as carried out for each pile (Table 2). The test procedure was defined with the help of tests carried out with pile P1. Loading and unloading phases were achieved between two following cyclic load sequences to observe the influence of the history of loading on the pile response. A static load of 500 kN i.e. greater than the maximum cyclic load of the sequence of 200 kN was applied to check the good response of the soil pile system. For pile P2, the chosen test procedure was followed so that the results can be explained more precisely.

Table 2 Experimental program for the cyclic load sequences

Pile	P1	type	Cyclic Maximum load (kN)	Cyclic Minimum load (kN)	Average cyclic load (kN)	frequency	N
P1	100 kN	Cyclic load sequence	105	85	95	0,5	60
	100 kN	Cyclic load sequence	150	50	100	0,2	1000
	150 kN	Cyclic load sequence	190	104	147	0,5	40
	150 kN	Cyclic load sequence	170	107	138,5	1	40
	200 kN	Cyclic load sequence	245	140	192,5	0,08	40
	200 kN	Cyclic load sequence	245	140	192,5	0,01	40
P2	150 kN	Cyclic load sequence	200	100	150	0,2	1000
	250 kN	Cyclic load sequence	350	150	250	0,05	100
	250 kN	Cyclic load sequence	375	120	247,5	0,5	450
	250 kN	Cyclic load sequence	309	180	244,5	1	1000
	350 kN	Cyclic load sequence	455	270	362,5	0,05	50

For a given applied load at the pile head, the response of each pile segment seems satisfactory (Fig. 11). The deformations in mm are presented along the pile for the loading sequence with $P_{min} = 105$ kN and $P_{max} = 170$ kN.

The Equivalent Young modulus (steel and concrete) was assumed as constant with the number of cycles in our study. A further study could figure out the evolution of the Young modulus with the repeated loading which could provoke resistance and stiffness reductions.

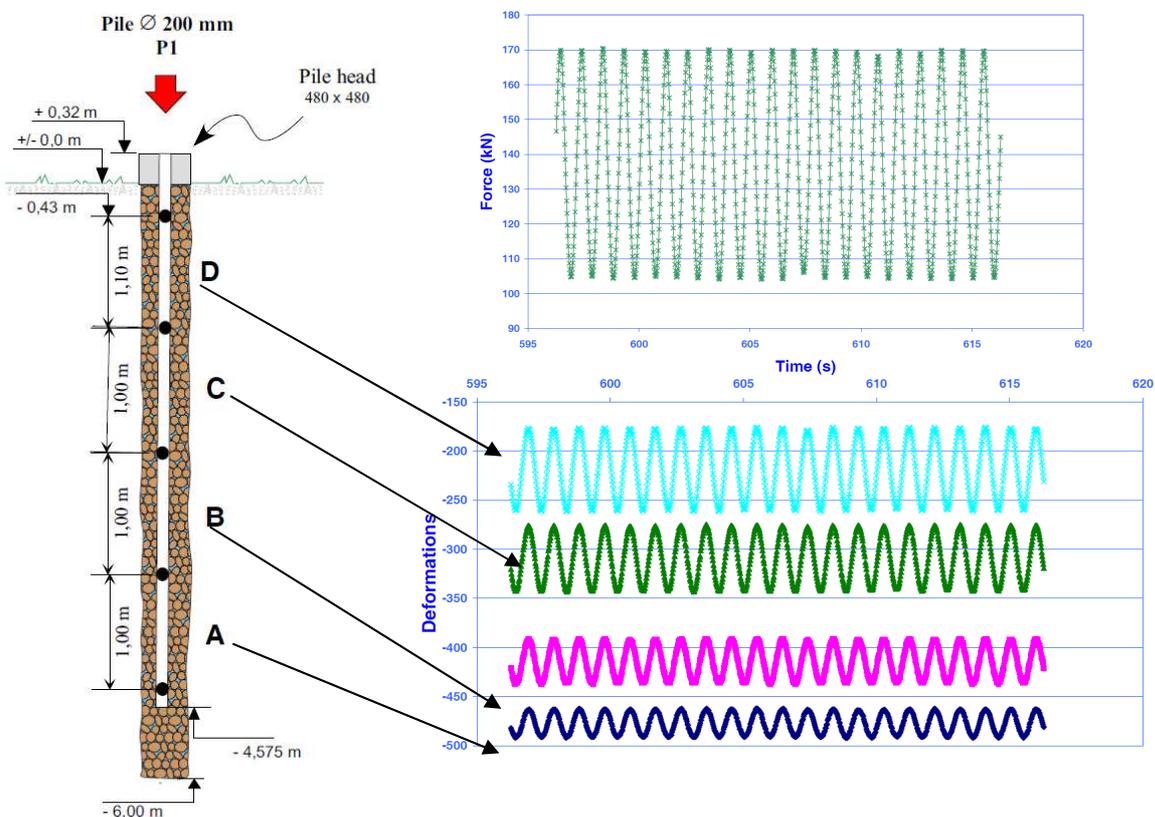


Fig. 11 Distribution of load (deformation)

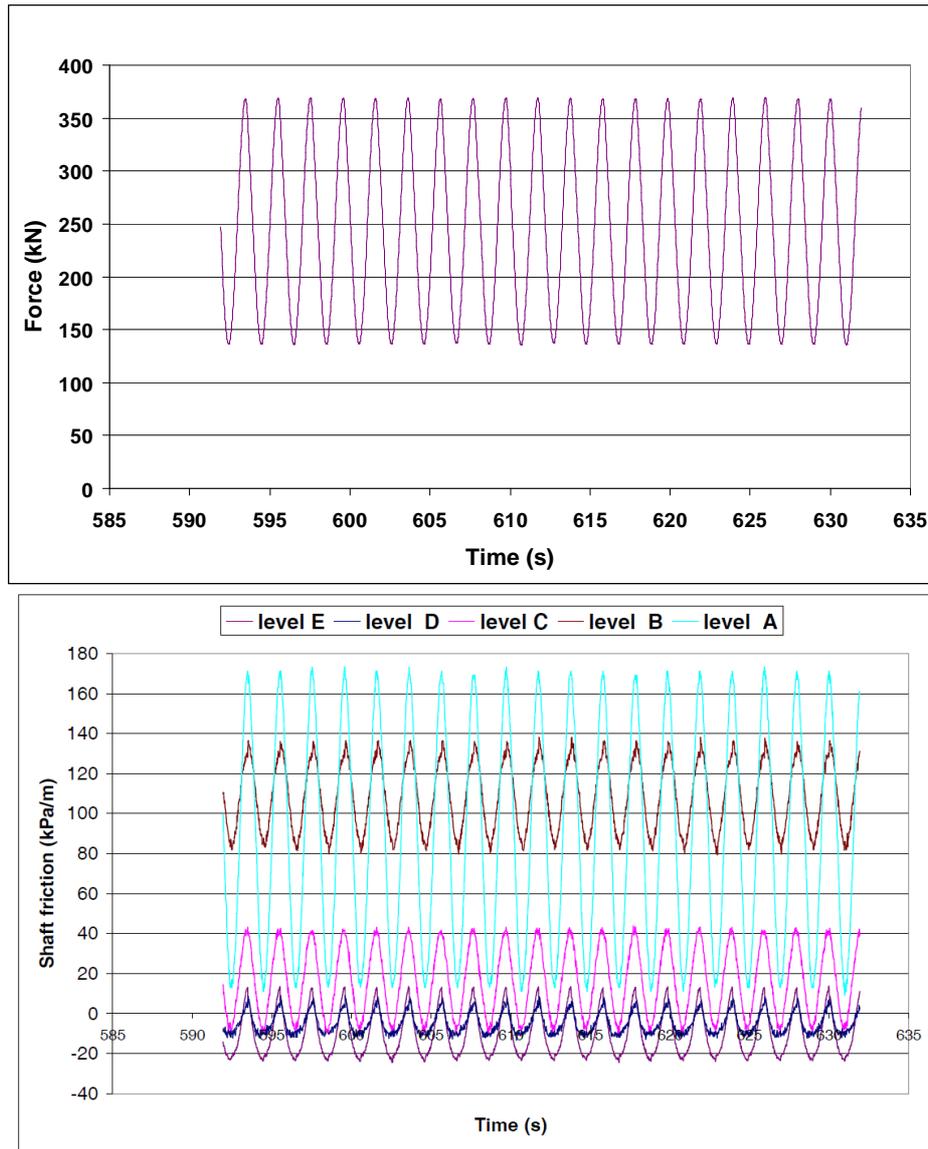


Fig. 12 Distribution of loads (shaft friction) along pile P2

On the two first pile segments, two way cyclic loading are observed whereas the two (three) deeper pile segments showed one-way loading. As far as shaft friction is concerned, the two-way loading at the top of the pile are typical response (Karlsrud et al., 1986) due to large movements and reverse movements at the top of the piles.

Near the top of the pile, the soil could withstand large strain – controlled type of cyclic loading due to pile flexibility.

Shaft friction along the pile may evolve as the value of maximum shaft friction resistance may be reached leading to a degradation of the latter for the subsequent cycles of loading as this pile segment at the top faces displacement – controlled solicitations that provoked the most important capacity degradation of piles. In addition, the pile segments underneath should carry more and more loads as cyclic loading proceeds to make up for the loss of pile capacity at the top.

The excess of load at the pile toe can probably be explained by the proximity of the tip and the high mechanical characteristics from 2m depth.

For a same average load of cyclic load sequence, the pile head displacement seems more sensitive to the load amplitude than the load frequency in the experimental program (Fig. 13).

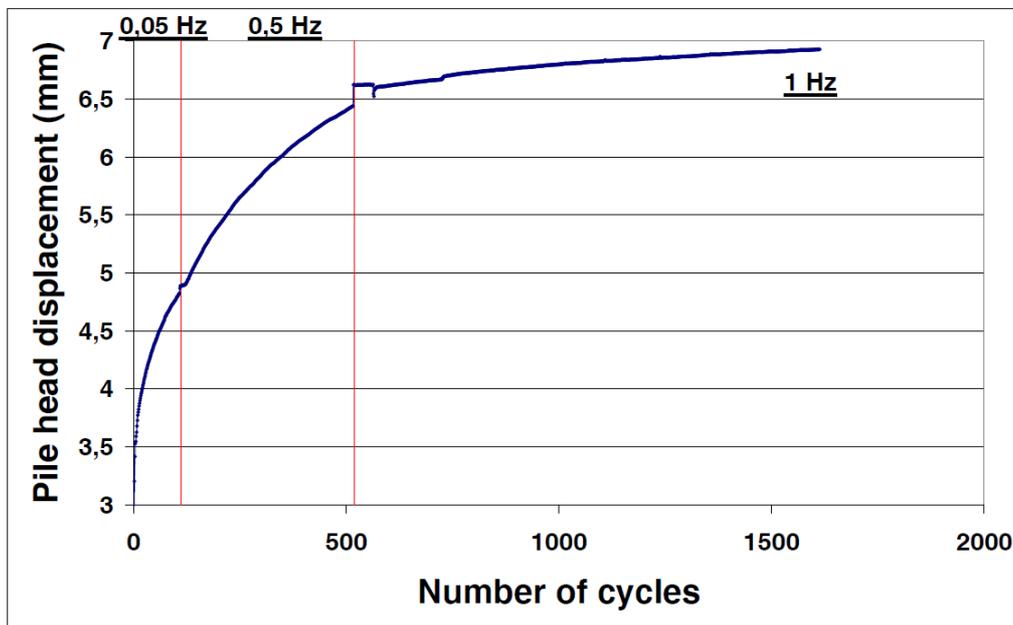


Fig. 13 Evolution of pile head displacement with the number of cycles

7. CONCLUSIONS AND PERSPECTIVES

Full scale tests carried out on piles to study the effect of cyclic loading on the bearing capacity are scarce. Besides, piles in clay submitted to cyclic loading have already been investigated regarding a limited amount of loading cycles.

Nevertheless, the effect of cyclic loading on piles in sand remains an interesting research topic as no clear means of taking this type of loading into account exists today. In addition, the tests will allow us to get the distribution of loads along the piles during the loading cycles and observe and analyse the local cyclic degradation.

The project SOLCYP aims at studying the effect of a great number of cycles on the soil-pile system as well as the evolution of the pile modulus during these repeated loadings. Three types of piles will be tested ; driven, screw and bored piles in two different soils (sand and overconsolidated clay). Laboratory tests will provide parameters to implement the different models that will be developed.

Several interesting parametric study could be investigated for further research such as the pile installation methods to study the influence of the soil-interface on the pile response under cyclic loading, as well as the type of soils to widen the database of the behaviour of piles under cyclic axial loading and give some tools for the design engineer.

The results will help the validation of the simplified models like t-z transfer curves and complex models developed in finite element models.

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