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Load distribution along a pile – case of cyclic axial loading

A. Le Kouby,

Paris-Est University, GERS-SRO, IFSTTAR, F-77447 Marne-la-Vallée, France

M. H. J. Rakotonindriana,

Geolia, formerly IFSTTAR Paris, France

L. Thorel

LUNAM University, IFSTTAR, GERS-GMG, F-44340 Bouguenais, France

ABSTRACT: To study the behavior of a pile foundation subjected to cyclic axial loading, an instrumented pile was developed and centrifuge tests were undertaken. The pile was designed to be installed in flight by jacking and could provide the skin friction and the tip resistance of the pile during installation, monotonic and cyclic loading. Tension and compression monotonic tests were performed to validate the proposed experimental procedure. Pile response under cyclic loading show typical global response. In addition, some relevant features related to local responses of the pile in terms of load distribution and cumulative displacement.

1 INTRODUCTION

When the ground underlying a superstructure doesn't have enough resistance to support the structure, piles are usually used as foundations. The loads transmitted to the pile (due to the wind, road and railway traffic, etc.) fluctuate and can be assimilated as cyclic loadings on the piles. This axial cyclic loading on piles involves an evolution of the soil-pile system behaviour.

The axial cyclic loading of a pile may have a significant impact on the behavior of the soil-pile system. To investigate this behaviour, a series of centrifuge tests with an instrumented pile has been undertaken (Rakotonindriana, 2009). The details on the instrumented pile developed for centrifuge tests, with in flight installation by jacking to simulate a displacement piling method, have been presented in Rakotonindriana et al. (2008). It has been developed for the measurement of the load distribution along the pile (skin friction and the tip resistance).

The tests were performed in dry silica sand (Fontainebleau sand) which is prepared by pluviation technique to obtain relative density of 47% and 78%. The mean size (d_{50}) of the sand particle is 0.22 mm and the maximum and minimum densities are respectively equal to 1736 kg/m^3 and 1417 kg/m^3 .

The pile was designed in order to measure the resulting load distribution along the pile (shaft friction and tip resistance). The cases of tension – compression monotonic loading pile responses are studied for the two density ratio (47 and 78%). For cyclic

loading on pile response, only the case of tension is presented for the density ratio of 78%.

2 SOME INFORMATION ON PILE DESIGN

Different kinds of instrumented piles have already been developed for centrifuge tests. They were instrumented with protected external gauges (Nunez et al. (1988), Colombi (2005)).

2.1 Scale effect

Scale effects have been discussed in Rakotonindriana et al. (2008) and summarized in Garnier et al. (2007). When the ratio B/d_{50} is greater than 91 (i.e. $20/0.22$), no scale effect is observed. So, when the diameter of the pile is greater than 20 mm, the prototype values of the tension resistance remain relatively constant. In other words, no scale effect occurs in this case.

To consider a prototype pile diameter of 0.8 m, the scale of 1/40 was adopted and the corresponding g-level was thus equal to 40g.

2.2 Side effect and pile length

The centrifuge tests were undertaken in a strongbox whose plan dimensions are $1200 \times 800 \text{ mm}^2$ and whose depth is 360 mm.

It is recommended that the distance between the strongbox wall and the CPT (Cone penetration test) be higher than 10 B (Garnier et al., 2007). All the centrifuge tests were undertaken at a minimum distance of 13 B from the wall of the strongbox in order not to have side effect. On the other hand, Le Kouby

et al. (2013) have shown that the minimum distance between the tip of the pile and the bottom of the strongbox should be greater than $4 \times \text{diameter}$ from the tip in order not to have an influence of the bottom of the strongbox on the stress under the tip. In order to respect this criterion, an embedment depth of 260 mm was chosen (Figure 1).

2.3 Pile instrumentation

The design of the pile (20 mm diameter and 260mm long for the model and 800mm diameter and 10.4m long for the prototype) for the measurement of the skin friction is similar to the pile developed by Balachowski (1995). The pile model is divided into five sections, and each section has a length of 48 mm (1.92 m – prototype scale) (Figure 1).

The pile is cylindrical but it has different internal cross sections to insert the strain gauges. A cylindrical sleeve is then mounted at this section to protect the strain gauges and to obtain the same surface along the pile. These cylindrical sleeves have the same machined surface as the rest of the instrumented pile.

The instrumentation of the pile consisted of five strain gauges glued to the external surface of the pile. The strain gauge at the bottom of the pile (gauge 1) measures the tip resistance during the tests. The value of the skin friction for each section is obtained by subtracting the measurements of two successive strain gauges surrounding the section, and dividing this value by the surface of the section. For the upper part, the skin friction is obtained by considering the pile head force which is measured with a force sensor.

Table 1. Experimental program

V_m : mean load; V_c : cyclic load ; V_{uc} : compression bearing capacity; V_{ut} : tension bearing capacity, N: number of cycles.

C	test	C/T	static / cyclic	V_m	V_c	N
C47	C47-1	T	static	Maximum		
C78	C78-1	T	static	Maximum		
			cyclic	$0.15 V_{ut}$	$0.3 V_{ut}$	1000
		C	cyclic	$0.4 V_{ut}$	$0.2 V_{ut}$	3
			static	Maximum		
C78-2	C	cyclic	$0.1 V_{uc}$	$0.1 V_{uc}$	200	
		cyclic	$0.4 V_{uc}$	$0.1 V_{uc}$	200	
		cyclic	$0.5 V_{uc}$	$0.2 V_{uc}$	100	
		cyclic	$0.05 V_{ut}$	$0.05 V_{ut}$	200	
C78-3	T	cyclic	$0.1 V_{ut}$	$0.1 V_{ut}$	200	
		cyclic	$0.2 V_{ut}$	$0.1 V_{ut}$	200	
		cyclic	$0.3 V_{ut}$	$0.1 V_{ut}$	200	
		cyclic	$0.4 V_{ut}$	$0.1 V_{ut}$	3 (failure)	
C78-4	C	cyclic	$0.2 V_{uc}$	$0.2 V_{uc}$	5000	

C : Container, C : Compression, T : Tension

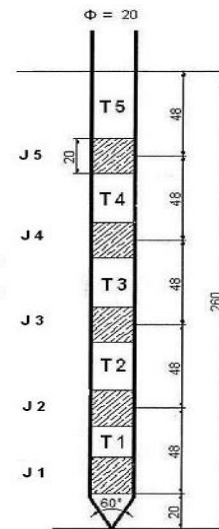


Figure 1. Cylindrical sleeve for the J2 gauge protection.

3 EXPERIMENTAL DEVICE, TEST PROCEDURE AND EXPERIMENTAL PROGRAM

3.1 Experimental device

The installation and the loading of the pile were undertaken with a jack which can move with a 300 mm stroke hydraulic jack. The pile head was fixed to the jack with a screw. A force sensor mounted at the pile head allows one to measure the force at the pile head (Figure 2).

Two displacement sensors were fixed close to the pile head to measure the pile head displacement during the loading. At the end of the installation, these displacement sensors were in contact with an abutment which was independent from the loading system and therefore can be considered as a fixed reference.

3.2 Test procedure

The adopted test procedure is described here. First of all, the pile was installed in flight by jacking, at a constant rate of 1 mm/s. When 260 mm of the pile

was embedded in the soil, the jacking was stopped and the pile head unloaded to obtain a force close to 0 kN. The unloading of the pile was undertaken step by step, each step corresponding to a vertical displacement of 0.1 mm. Finally, after the unloading, the different loading sequences were applied.

3.3 Experimental program

Two strongboxes have been used in this study (Table 1). In the strongbox C47 with a density ratio of 47% only one tension monotonic loading test is considered. In the strongbox C78 with a density ratio of 78%, four pile tests were performed, namely tension and compression monotonic loading respectively for C78-1 and C78-2. In the paper, the pile response under cyclic loading for tests C78-2, C78-3 and C78-4 is studied.

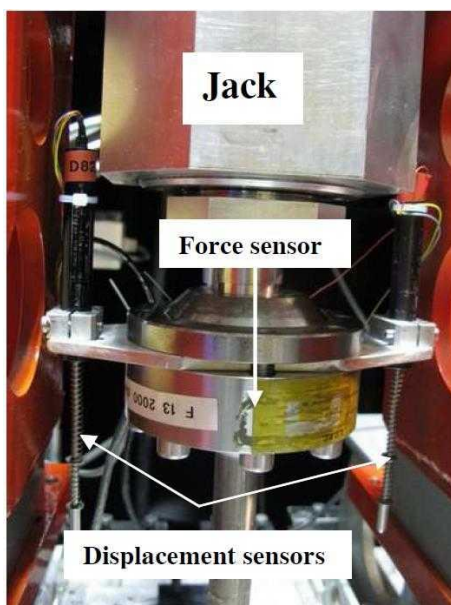


Figure 2. Experimental device at the pile head.

4 PILE INSTALLATION

The installation of the pile was undertaken in flight by jacking. All the values shown here are at model scale unless otherwise mentioned.

During the installation, the variation of the pile head force versus its displacement is given in Figure 3. Two phases can be observed during the installation: a first phase that corresponds to the penetration of the tip of the pile into the soil. Within this phase, the value measured by strain gauge J1 is similar to that measured at the pile head (up to an axial displacement of about 20 mm). The second phase shows the mobilization of the skin friction along the pile. Within this phase, the pile head load becomes greater than the load measured by the Gauge J1. At the end of the installation process, the pile tip resistance represented 70% of the total resistance.

4.1 Repeatability

Repetitive tests were performed to check the procedure. Four tests are compared for repeatability of the results obtained during jacking. All these tests were carried out in the same strongbox, at the same density ratio and at the same displacement rate.

For the pile head force, it has been observed that the four curves representing the four tests were almost the same (Figure 4).

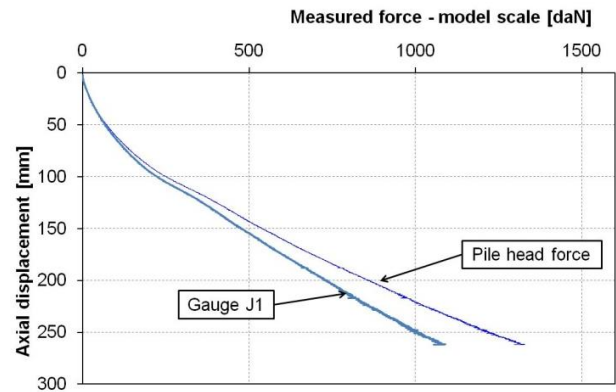


Figure 3. Pile head force versus displacement during installation. $B = 20\text{mm}$, $D = 260\text{mm}$, $I_D = 78\%$.

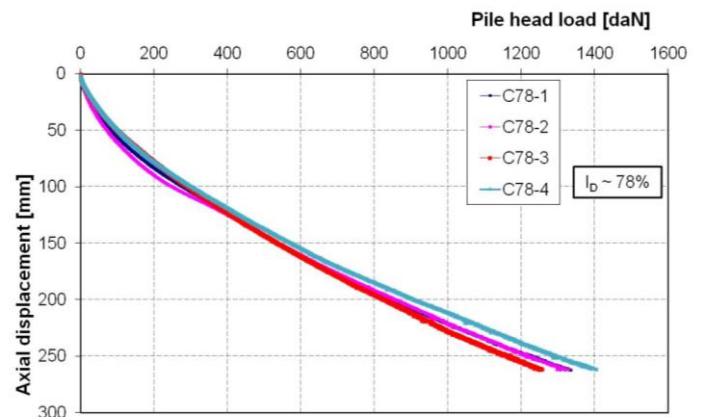


Figure 4. Repeatability of the pile head force.

5 MONOTONIC LOADING

The general behaviour of the pile under axial loading can be represented by the variation of the pile head resistance as a function of the displacement. Nevertheless, the measurement of the skin friction and the tip resistance offer more relevant information.

5.1 Compression loading

The load displacement response of the pile under monotonic loading is shown in Figure 5. Overall, the curve shows an irreversible process behavior which is more and more important as the pile head displacements increases. The curve reflects the general behavior observed during *in situ* tests and shows two

parts, a first part which looks like elastic behavior and a second part where the pile head force reached a maximum constant value. The curve does not show any peak and any degradation with increasing displacement.

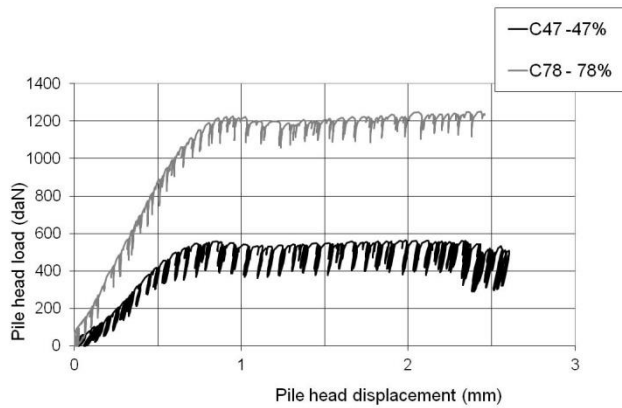


Figure 5. Load displacement response under monotonic loading (pile head).

In the case of the density ratio of 78%, the pile tip response behaves similarly to the pile head load displacement response but it seems to increase steadily (Figure 6). On the contrary, the global shaft friction plot shows a peak at a pile displacement of 0.85 mm followed by a loss of resistance as the pile head displacement increases. It can be noticed that the full shaft friction is mobilized before the tip resistance. Up to a pile head displacement of 0.7 mm (i.e. 0.035 B), the load displacement curve is linear and does not show any peak.

As far as the load distribution along the pile is concerned, the local skin friction shows a peak which is increasingly significant as the section is deeper (Figure 7). This peak is very large for sections T1 and T2 and diminishes as we approach the ground surface (section T5). This decrease of the peak can be attributed to the decrease of the confining pressure near the surface.

Besides, the value of the skin friction for the sections T1 and T2 were very large (Figure 7) compared with the values given by the French standards (AFNOR NF P 94-262, 2012). These elevated values of the skin friction in the vicinity of the pile tip have also been observed by Le Kouby et al. (2013) who suggested that it was due to the influence of the soil mass involved in the failure mechanisms at the pile tip. This influence was up to a height of six diameters above the pile tip for a jacked pile (120 mm here). In the current case, sections T1 and T2 are at a distance of about 118 mm (20+2X48 mm) from the pile tip.

5.2 Tension loading

On Figure 8, the load distribution for monotonic tension loading are plotted with depth for the two

densities. The effect of density shows that the tension bearing capacity increases with the density. Besides, it can be observed that the load at the pile tip is different from zero. It might be due to the residual stresses at the tip after unloading of the pile.

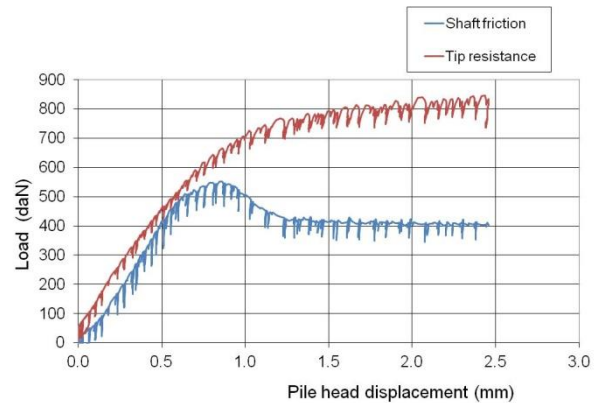


Figure 6. C78-2 : shaft friction and tip resistance for compression monotonic pile load test.

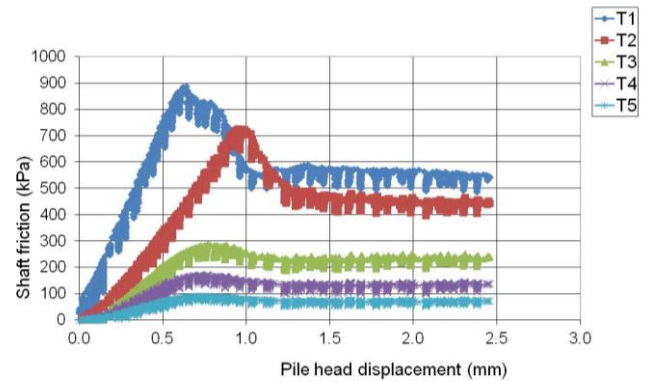


Figure 7. C24 - 78 % : Shaft friction for the five pile - segment (T5, T4, T3, T2, T1).

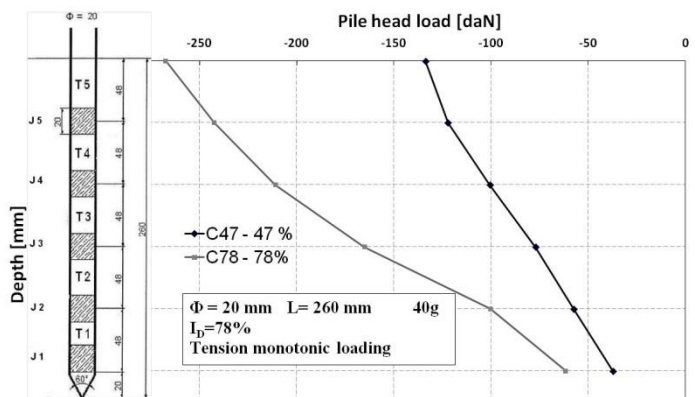


Figure 8. Tension tests – load distribution for two densities.

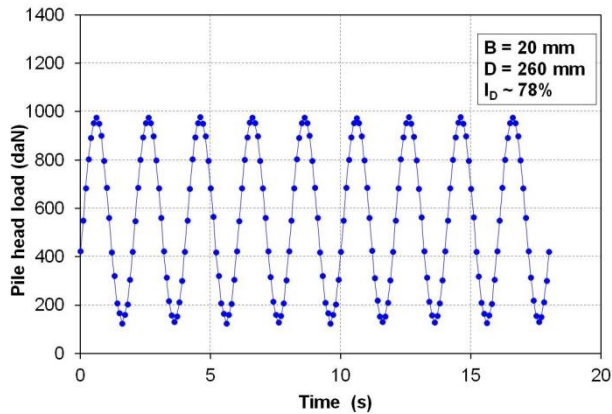
6 CYCLIC LOADING

The experimental program, presented in table 1, includes both tension and compressive cyclic loading, applied on four different piles (C78-1 to C78-4). The cyclic loading, which is a 0.5 Hz sine, is a load-

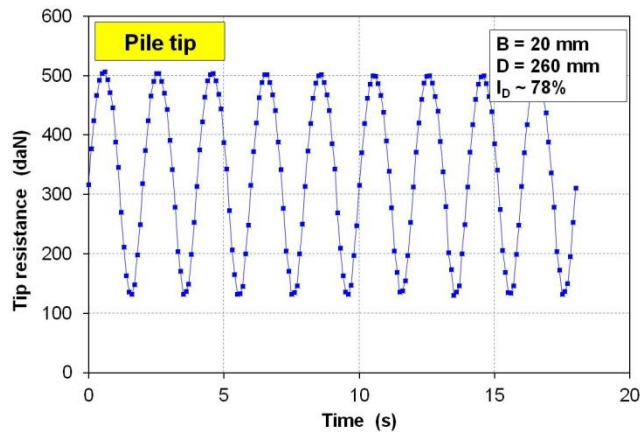
controlled test (Prototype value of frequency = 0.0125 Hz).

6.1 Load distribution along the pile

Figures 9 (a) and (b) show respectively the cyclic load applied at the pile head and the corresponding response at the pile tip. These results show that the load applied at the pile head is fully transmitted into the pile-soil system and that the instrumentation of the pile allows the observation of the mechanical response of the pile-soil system during cyclic loading.



(a) - Cyclic loading measured at the pile head



(b) – Response of the pile tip to cyclic loading (J1)

Figure 9. Force versus time in dense sand.

The case of tension loading (test C78-3 : $V_m = 0,3 V_{ut}$ and $V_c = 0,1 V_{ut}$) is typical. 200 cycles have been applied. Figure 10 shows the distribution of load along the pile for $N = 1$ and $N = 200$ at the maximum load ($V_{max} = V_m + V_c$). The pile response at the first pile section (T5) shows similar results for $N = 1$ and $N = 200$. Regarding the pile sections T4, T3 and T2, the mobilized shaft friction seems to increase from section T4 to section T1 between $N = 1$ and $N = 200$ probably due to the densification at the pile-soil interface with cumulative displacement that can reach 25% of the pile diameter (Table 2). The tip resistance, on the contrary, is smaller at $N = 200$ than at $N = 1$ probably due to the loading / unloading phases at the pile tip that loosens the stresses around the tip. Nevertheless, in this case, the values at the

tip represent a low percentage of the total load applied.

The increasing mobilization of the shaft friction with the number of cycles (from $N = 1$ to $N = 200$) can lead to the shaft resistance degradation as the pile displacement increases.

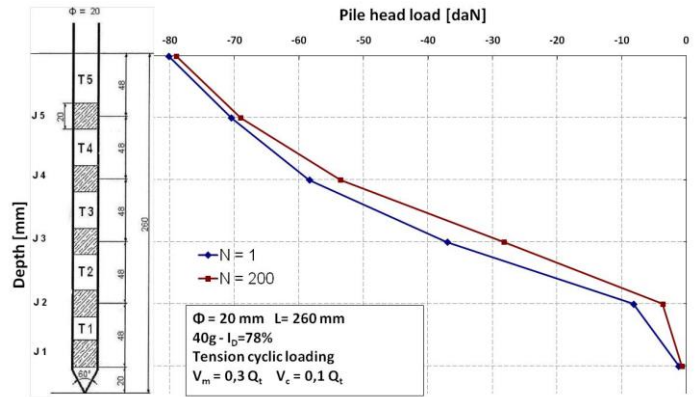


Figure 10. Evolution of distribution of load along the pile for tension loading test from $N = 1$ to $N = 200$.

6.2 Cumulative displacement

Several formulas and models have been proposed to evaluate the cumulative displacement during cyclic load sequences. Diyaljee and Raymond (1982) and O’Riordan et al. (2003) proposed formulas that rely on the rate of loading (X) and the Number of cycles (N). The paper only proposes the models by Diyaljee and Raymond (1982) that has been used by Al-Douri and Poulos (1995) for Carbonate sands. The proposed equation for the calculation of the cumulative settlement (S_p) is as follows :

$S_p/D = A \cdot \exp(nX) \cdot N^m$ With
 N : number of cycles, D : pile diameter
 X : level of loading (maximum loading) as the ratio between V_{max}/V_{ut}
 m, n et A : empirical parameters

For N cycles : $\ln(S_p/D) = \ln(A) + m \ln(N) + nA$
 N fixed, A is a constant

- To determine n :
When the curve $\ln(S_p/d) = f(X)$ is plotted, n is the slope.

- To determine m :
 X is fixed, $\ln(S_p) = m \ln(N)$ is plotted and m is the slope of the curve.

From m and n , A can be calculated. Table 2 shows the values of X , S_p that have been used to determine the parameters m , n and A .

On Figure 11, the S_p/D % plots allow us to determine n value and on Figure 12, the procedure is shown to determine m value and more especially its range of values. The values obtained are : $n = 9.15$; $m = 0.97-1.1$ and $A = 1.98 \cdot 10^{-5}$. Al Douri and Poulos (1995) obtained $n = 3$; $m = 0,35$ and $A = 4 \cdot 10^{-3}$ in carbonated sands.

Table 2. Quantification of permanent displacements for tension cyclic test (C78-3).

X	S_p/D (N=10)	S_p/D (N=50)	S_p/D (N=100)	S_p/D (N=150)	S_p/D (N=200)
0.1	0.07%	0.32%	0.60%	0.79%	0.91%
0.2	0.10%	0.35%	0.65%	0.88%	1.15%
0.3	0.32%	1.23%	2.27%	3.17%	4.01%
0.4	0.51%	3.08%	8.00%	16.07%	25.33%

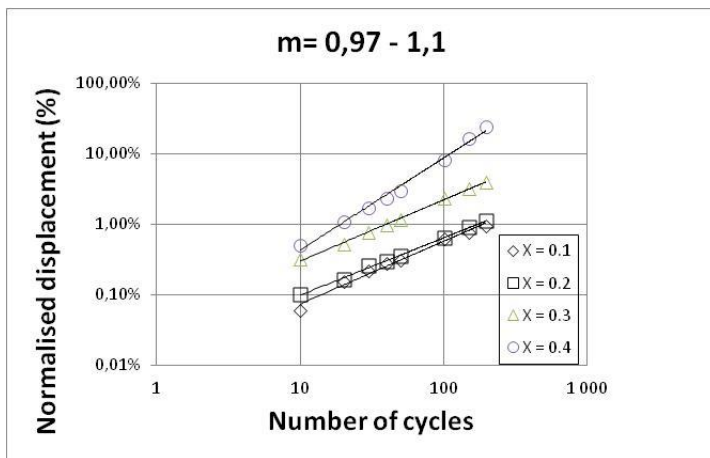


Figure 11. Evolution of normalized displacement as a function of the number of cycles (Tension test – 78%) - $n = 9,15$.

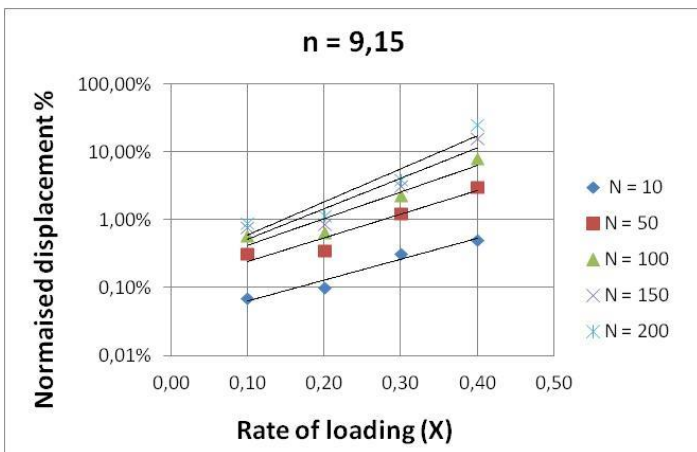


Figure 12. Evolution of normalized displacement as a function of the rate of loading (Tension test – 78%) - $m = 0,97 - 1,1$.

7 CONCLUSIONS

An instrumented model pile (of diameter $D = 20$ mm and maximum embedment $D = 260$ mm) has been developed to study the pile behaviour under ax-

ial loading in a centrifuge. The pile was installed in flight by jacking.

The compressive and tension monotonic loadings have shown typical pile responses: the maximum skin friction was mobilized before the pile tip resistance because of a progressive mobilization of both skin friction and tip resistance. Tension cyclic test was analyzed and showed an increasing shaft friction mobilization with the number of cycles that could lead to cyclic degradation.

The Dyaljee and Raymond model was tested in order to determine the empirical parameters of their formulas that can give the pile cumulative displacement for given cyclic level of loading and number of cycles. However, this procedure showed some limitations as it only takes into account the maximum cyclic load (V_{max}) and not the cyclic load (V_c). It could represent an issue if the minimum load is close to zero leading to more cumulative displacement.

The pile instrumentation seems to be effective and can provide good results.

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