Experimental analysis of large lateral displacement of piles in centrifuge 1.12

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EXPERIMENTAL ANALYSIS OF LARGE LATERAL DISPLACEMENTS OF PILES IN CENTRIFUGE

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ABSTRACT

Reduced scale model tests in centrifuge have been carried out for measurement of the ultimate horizontal load of a pile driven in dense sand. The construction of the load-transfer P-Y curves has allowed to analyse the response of the soil to the large displacements of the pile. The comparison between experimental results and those predicted by the current methods has shown the insufficiency of the theoretical approaches.

KEYWORDS

Pile, Sand, Model, Centrifuge, P-Y curves, Horizontal load, Prediction.
INTRODUCTION

During the last two decades, an important progress has been done in the research works on the behavior of the laterally loaded piles. This phenomenon is a complex soil/structure interaction, and it depends on several parameters notably: the geometrical properties of the pile (slenderness, shape of the section, diameter, stiffness,...), the geotechnical characteristics of the soil (density, over-consolidation degree,...) and the pile installation method (driving, boring,...).

There are various ways to study this problem, notably:
- the theoretical approaches where the difficulty is how to model the interaction between the pile and the soil and how to take into account of the physical parameters affecting the phenomenon. The current design methods such as those of the elasticity or the subgrade reaction theory are based on a simplistic assumptions concerning the modelling of the pile response (Bouafia 1990, Bouafia and Garnier 1991).
- the full-scale tests which are limited by the costs, the time of the experimentation and the quasi impossibility to carry out the parametric studies about this problem.
- the tests on small scale models in centrifuge which have known a great success and have allowed the geotechnical researchers to explore a large domain difficult to access by the other traditional approaches.

In soil mechanics, the mass forces are preponderant and the non-linear behavior of the soil is essentially governed by the stresses level. According to the similarity conditions, in order to keep stresses and strains between the model and the prototype when the dimensions are reduced in the scale 1/N, it is necessary to increase the mass forces scale inversely, that is N. This condition can be accomplished by placing the model in a centrifuge.

This paper presents an experimental study of the behavior of a centrifuged model of a driven pile in dense sand submitted to a large lateral displacements. The tests are carried out on the centrifuge of the LCPC (central laboratory of the roads and the bridges) in France.

DESCRIPTION OF THE EXPERIMENTAL DEVICES

The centrifuge

The LCPC centrifuge at Nantes is a powerful tool of the experimental geotechnical research. It allows to take a model weighing 2000 kg at a centrifugal acceleration of 100 times that of terrestrial gravity (Garnier 1990).

The model of pile

The model is a circular steel pipe, simulating at the scale 1/25 a prototype pile, noted P3, having a diameter B=0.5 m, a flexural stiffness $E_{pl} = 628 \text{ MN.m}^2$, a slenderness $D/B$ varying from 6.25 to 10 and submitted to a lateral force applied at $c=2.25$ m above the ground surface.

The pipe is instrumented by 11 pairs of the strain gauges fixed on the external surface of the model along a two diameterally opposite axes. The measured strain of the gauge allows to obtain the bending moment along the pile.

The model is calibrated in the laboratory as a cantilever beam. This test has shown a good response of the gauges within 9% of those computed from the beam theory.

The soil

The soil is a red quartzic sand, clean and poorly graded, taken from the experimental site LF. RHEU (France). After the USCS classification this is a sand SP. The maximum and minimum dry unit weight determined after the ASTM standards are 16.8 and 13.4 kN/m$^3$ respectively. The sand is pluviated in a container using an automatic hopper. The advantage of this technique is to obtain a good homogeneity and repetitive characteristics for various tests.

The dry unit weight of the sand in these tests is 16.5 kN/m$^3$, corresponding to a very dense sand with a relative density of 95%. The internal friction angle determined from direct shear box test on reconstituted samples by pluviation is 42° for the same dry unit weight of the tests in centrifuge.

Other experimental setups

The lateral loading is continuously applied by a hydraulic jack. A load cell is incorporated at the front of the jack by an aluminium cylindrical support.

The displacements of the pile top are measured by two LVDT having a large stroke and taken by pivoting supports in order to follow the top pile rotation. The figure 1 shows the general scheme of the experimental model.

![Fig. 1 View of the testing arrangement](image-url)
The pile is driven at the natural gravity into the sand by a manual driving device which is composed of a hammer of 1.03 kg, falling from a 1.02 m of height by slipping without friction along a rod.

The driving curves are similar for the different cases of the pile embedment length studied here. This shows that the driving procedure of the pile models is reproducible.

The experimental programme

The aim of these tests is to study the behaviour of a stiff single pile with 4 slenderness ratios D/B: 10, 8.75, 7.5 and 6.25. The horizontal loading is leaded to reach a displacements level of about 4 diameters which is much larger than this predicted by the traditional theories for the limit equilibrium of the soil around the pile.

ANALYSIS OF THE EXPERIMENTAL RESULTS

The following results are related to the pile prototype.

Load-deflection curves

Figure 2 shows the curves of the horizontal load versus the top displacement. It seems clearly that these curves are not characterised by a horizontal asymptote for the large displacements as prescribed by the theory. Then, the soil failure shall be defined either by a presence of a horizontal asymptote but for a threshold displacement level much larger than the traditional values or by a hardening behaviour.

\[ H_u = H_u \tanh \left( \frac{k Y_H}{H_u B} \right) \]  

(1)

where k is the slope of the curve for the small relative displacements Y_H/B. A further comparison is made between the value of H_u so determined and this predicted by the different current methods used in practice.

Bending moments

Figure 3 shows typical curves of the bending moment along the pile. They are characterised by a change in curvature in about 7 diameters of depth, then indicating a change of the sign of the lateral soil reaction, and the zero moment value at the tip corresponding to a free pile base.

Determination of the P-Y curves

The pile/soil interface is usually modelled by an infinite number of springs characterised by a load-transfer curves, called P-Y curves and defining the soil reaction P at a given depth versus the corresponding displacement Y of the pile. Due to the simplicity of the pile behaviour modelling, the P-Y curves has known a large application field.

The curves are developed here from the measured moment versus depth relations. The displacement Y(Z) is obtained by double integration. The soil reaction P(Z) is obtained by double differentiation of the moment curve M(Z) and depends mainly of the fitting method.

The quintic spline functions are used to fit the moment curve with the use of a parameter of adjustment. The choice of this parameter is governed by the static equilibrium of the
pile under the lateral reaction profile \( P(Z) \) and the forces on its top (Bouafia and Bouguerra 1995).

Typical P-Y curves are presented in the figure 4. They are non-linear and show an increase in the soil stiffness with depth. From these curves, it is not obvious that the large displacements of the pile correspond to a horizontal asymptote in the P-Y curves as used in the subgrade reaction theory to define the failure of the soil.

These curves are introduced in the computer program PILATE (Pile under Lateral Loads) which is a non-linear subgrade reaction method to back-calculate the pile response. As shown in figure 5, the computed top deflections are in good agreement with those measured.

It is possible to conclude that these centrifuge tests together with the method of construction of the P-Y curves provide valid these curves for the interpretation of pile / soil interaction at the large displacements (Bouafia and Bouguerra 1996).

The secant subgrade reaction modulus \( E_s \) is the ratio of the reaction \( P \) to the displacement \( Y \) at a given depth for a given top loading. In considering the values of \( E_s \) for the ultimate load as defined previously by adjustment, it seems that the \( E_s \) profile as shown in figure 6 is linear and depends little of the slenderness \( D/B \) and the relative load eccentricity \( c/D \). It is possible to conclude that the concept of the linear subgrade reaction profile for the granular media, as recommended by the literature for the small deflections, is also valid for the large displacements of the pile (Bouafia and Merouani 1995).

**ANALYSIS OF SOME CURRENT DESIGN METHODS**

There are many approaches for the evaluation of the ultimate lateral load on the pile in cohesionless soils. Based in general on an ultimate soil reaction profile \( P_u (Z) \).

Table I summarises some of these methods with the principal assumptions. A detailed analysis of these approaches is given by Bouafia (1990).

Figure 7 allows a direct comparison between the ultimate profiles for a pile slenderness of 10. It shows that the experimental values are greater in the upper half of the pile. In the lower part, the values are comparable. Near the centre of rotation, except the Menard method, the theoretical values are very important in spite of a very small displacements in this zone.

The ultimate lateral load is computed from the static equilibrium of the pile under the profile of the soil reaction and the forces in the top. As shown in figure 8, the measured ultimate load is greater than this predicted by the various design methods. The discrepancy increases with the slenderness of the pile.

Except the Menard method, the others consider the mechanism of failure of the soil either by an edge or by the

Fig 4. Typical P-Y curves for different depths

![Fig 4. Typical P-Y curves for different depths](image)

Fig 5. Comparison between computed and measured top deflection for D/B = 8.75

![Fig 5. Comparison between computed and measured top deflection for D/B = 8.75](image)

Fig 6. Profile of the \( E_s \) modulus for \( H_u \)

![Fig 6. Profile of the \( E_s \) modulus for \( H_u \)](image)
Table 1 Summary of some current approaches

<table>
<thead>
<tr>
<th>Author</th>
<th>Principle and assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blum (1932)</td>
<td>failure by edge</td>
</tr>
<tr>
<td>Hansen (1961)</td>
<td>failure by edge in surface and horizontal flow in depth</td>
</tr>
<tr>
<td>Reese (1974)</td>
<td>idem</td>
</tr>
<tr>
<td>Verdecyn (1967)</td>
<td>limit active and passive earth pressures</td>
</tr>
<tr>
<td>Broms (1964)</td>
<td>cylindrical expansion cavity</td>
</tr>
<tr>
<td>Dembicki (1977)</td>
<td>amplified active earth pressure profile</td>
</tr>
<tr>
<td>Petrasovits (1972)</td>
<td>idem</td>
</tr>
<tr>
<td>Pender (1988)</td>
<td>idem</td>
</tr>
<tr>
<td>Meyerhof (1981)</td>
<td>idem</td>
</tr>
</tbody>
</table>

Fig 8 Comparison between predicted and measured ultimate horizontal load

Except this method which requires the measurement of the limit pressure, the other methods are based on the density and the internal friction angle of the sand. These two parameters are the most difficult to obtain for this soil.

CONCLUSIONS

An experimental study has been carried out on a centrifuged instrumented model of a rigid pile driven in dense sand and submitted to a large horizontal displacement. The load-transfer P-Y curves are determined. It has been shown that the theoretical ultimate profiles of the soil reaction are not realistic. The ultimate lateral load predicted by the current design methods is less than measured for very large displacements.

The study of another configuration of the soil/pile systems by this experimental method will allow to describe the pile behaviour by more realistic mechanisms.

REFERENCES


