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Horizontal Loading Tests of Instrumented Tubular Piles Driven Into Clay — A Case History

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HORIZONTAL LOADING TESTS OF INSTRUMENTED TUBULAR PILES DRIVEN INTO CLAY - A CASE HISTORY

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ABSTRACT

Within the scope of an important experimental program of research on piles behaviour, the LCPC (Laboratoire Central des Ponts & Chaussées, France) carried out static lateral loads on two 915 mm diameter steel tubular piles in order to analyze the load-transfer P-Y curves. Each pile was driven up to 5 m deep into a brown clayey layer of thickness 6.50 m overlying a blue stiff marl. The instrumentation of each pile comprised 12 pairs of strain gauges for the measurement of bending moments along the pile and LVDTs for pile deflections. Process of double differentiation and double integration led to derive lateral soil reaction and pile deflection respectively and therefore to construct P-Y curves along the pile. Lateral reaction modulus as well as ultimate soil reaction were derived and compared to some usual methods in the literature of laterally loaded piles.

INTRODUCTION

These three decades have witnessed an increasing interest in the understanding of pile behavior under lateral loads. Although the diversity of theoretical approaches available since about half a century, experimental evidence from pile loading tests clearly shows the complexity of phenomenon as well as the multitude of parameters involved in such a soil/pile interaction.

Load-transfer theory or P-Y curves theory is widely used in pile design. Soil/pile interface is modeled by an infinity of non linear springs in which the soil reaction P at a given depth is undertaken by the spring for a lateral pile displacement Y. Full-scale tests on instrumented piles are often used to investigate the soil/pile response in the light of load-transfer theory. P-Y curves are derived from bending moment profiles measured by strain gauges along the pile.

The LCPC (Laboratoire Central des Ponts & Chaussées, France) has undertaken for many years an important research program on piles behavior by means of full-scale tests in quite homogeneous sites as well as of the centrifuge modeling. The present paper is aimed at presenting the results of interpretation of lateral load tests on twin short pipe piles driven into the clayey layer of Salledes. After a brief description of the piles and their instrumentation, the experimental site, one presents the main results obtained. The second part concerns with the construction and analysis of P-Y curves. Lateral reaction modulus and ultimate soil reaction were then derived. In the last part, these two parameters were compared with some usual methods of analysis of laterally loaded piles.

DESCRIPTION OF PILE/SOIL CONFIGURATION

Geotechnical context

The experimental site is located in Salledes in Clermont-Ferrand, about 450 km south east of Paris and belongs to the Stampien sedimentary deposit. Soil material is composed of a plastic layer of clay of salledes thick of 6.5 m in the vicinity of the test piles, overlying a blue soft to hard layer of marl. Ground surface is slightly sloppy with a slope angle of 8 to 10°. Prebored pressuremeter tests PMT and self-boring pressuremeter tests SBPMT were performed near each pile location. The ratio E_m/P_l where E_m and P_l are PMT modulus and limit pressure respectively varies between 7.5 to 22, which indicates an overconsolidated clay becoming normally consolidated versus depth. As indicated in figure 1, PMT characteristics within the first 5 meters vary with depth. Water level was recorded at 3.50 m deep with respect to the ground surface during pile loading tests, performed under a storming weather.

Piles and instrumentation

Two twin steel pipe piles were used for tests. As illustrated in figure 2, each pile served during tests as a reaction beam for the other one. Each pile is long of 6.14 m and driven up to an embedded length D of 5.0 m into the soil. Pile diameter B is of 0.915 m, the slenderness ratio D/B is 5.46, and the flexural stiffness $E_p.I_p$ is equal to 1074 MN.m^2. Distance between axes of piles is 1.46 m (1.6 times the diameter), which is judged sufficient to avoid the couple effect on pile response.

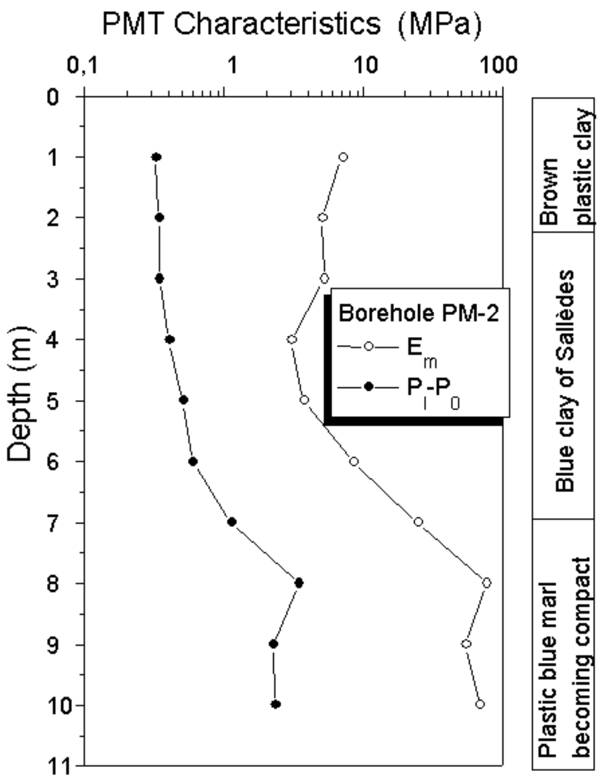

Fig. 1. Typical PMT characteristics of the site Salledes

Each pile was instrumented by 12 pairs of Vishay CEA strain gauges fixed along two diametrically opposite axes. Gauges distribution started 0.9 m from pile top with an increment of 0.25 m for the first 4 gauges and 0.50 m for the remaining ones. Moreover, 2 LVDTs were fixed at ground surface level to measure pile deflections at surface. Since the integration procedure of bending moments to obtain pile deflection necessitates two boundary conditions, pile top rotation was measured by means of 2 servo-accelerometers as well as of 2 leveling micrometer screws at 0.75 m and 0.88 m above ground surface respectively. Moreover, 3 temperature gauges were mounted at inner and outer sides of piles. According to figure 2, lateral loads were measured by a load cell incorporated between the hydraulic jack and a steel hinge fixed at the pile head.

Other devices

Lateral load is provided by two hydraulic jacks connected to a piston pump with double effect. Data acquisition system consisted of an acquisition central HBM-UPH 3200 monitored by an HP computer (Pouget, 1988).

ANALYSIS OF RESULTS

Initial programme of loading tests comprised a series of monotonic load increments of 50 kN of duration half an hour each, applied at a distance e=0.50m above the ground surface. Due to two troubles in performance of hydraulic jacks caused by loss of oil, the actual experimental programme was performed as illustrated in figure 3. In fact, three sequences of loading were carried out and some loads were maintained only for 15 minutes. It is to be noticed that a possible consolidation phenomenon may be exhibited by the frontal zones ahead the pile at shallow depths, and behind the pile near its tip. Pile deflections may therefore increase in time.

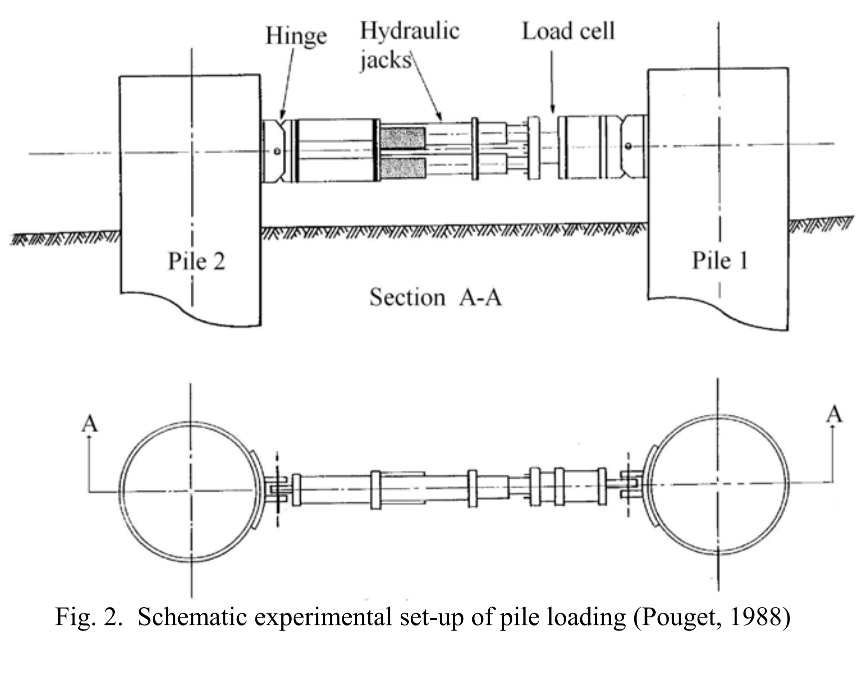

Fig. 2. Schematic experimental set-up of pile loading (Pouget, 1988)

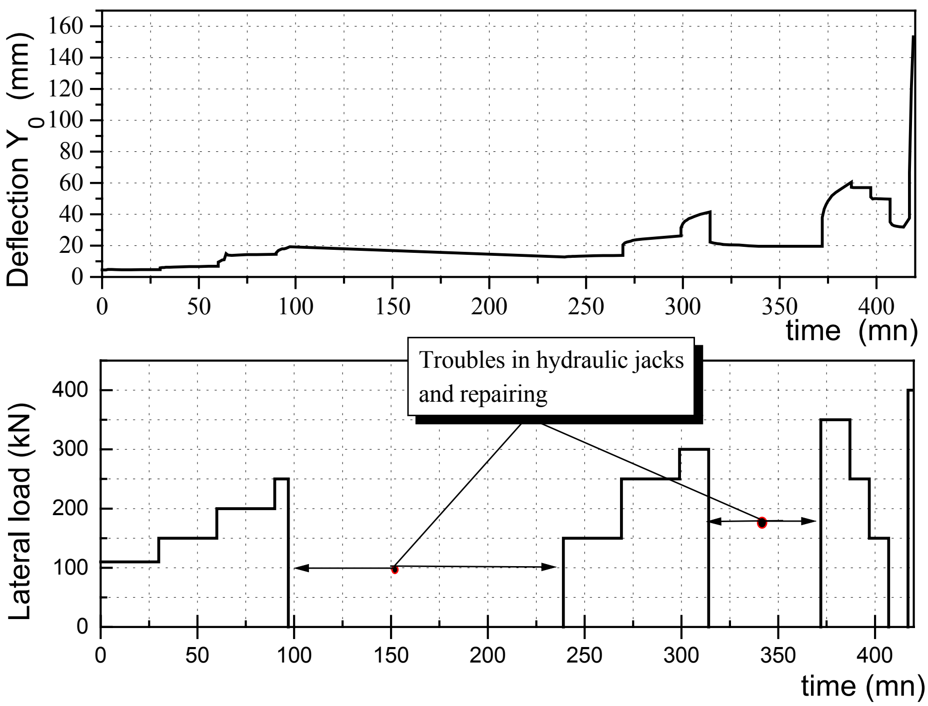

Fig. 3. Load-deflection evolution in loading tests

Results presented hereafter correspond to pile 1. Graphical method suggested by Asaoka (1978) for analysing 1D consolidation settlement evolution in time was used to estimate final pile deflection of pile 1 for a given load increment. Deflection–time curve for a given load was discretised into time increments of 1 minute. A recurrent series of deflections was then built and the final deflection corresponds to the intersection of this series with the bisectrix line. It was found that final deflection for the loads 110, 150, 200 and 250 kN correponds to measured deflection of 30 minutes. However, for loads 300 and 350 kN, final deflections were extrapolated according to this method. Figures 4 and 5 illustrate the application of this graphical procedure.

According to figure 6, load-deflection curve is hyperbolic shaped with remarkable trend to an asymptotic value for large lateral deflections. Hyperbolic curve fitting was performed according to the following formula:

$$\frac{Y_0}{H}=\frac{1}{\lambda}+\frac{Y_0}{Hu} \qquad (1)$$

where λ is the initial slope of H-Y_0 curve and H_u is the limit horizontal load or horizontal bearing capacity. λ and H_u were found equal to 29.8 kN/mm and 398 kN respectively, with regression coefficient of 99.8%. It can be noticed that the maximum lateral load corresponded to H_u. Furthermore, it can be seen from figure 6, that a deflection of about 10% of pile diameter is necessary to reach 90% of H_u, which is much greater than the usual recommended values of deflections corresponding to lateral failure. For example, in the French code Fascicule-62 the PMT-based method prescribes a threshold value of 1.7 to 2.5% of B depending on the depth (M.E.L.T, 1993).

Bending moments were found slightly depending on time. Figure 7 shows regular shapes of bending moments characterised by one curvature and a trend to negligible values at pile tip, which is usually expected for short and rigid piles behaving freely at tip. Maximum bending moment is located at 0.4 the embedded length whatever the load.

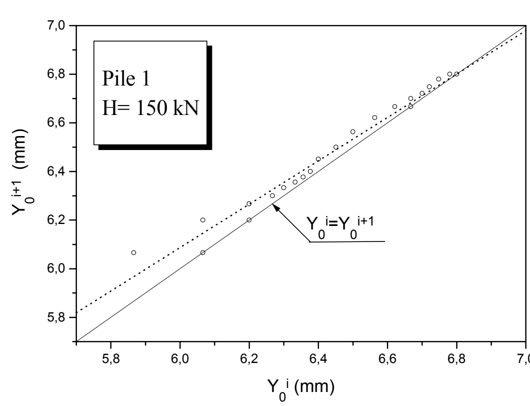

Fig. 4. Evolution of pile deflection for a load of 150 kN

P-Y CURVES ANALYSIS

Methodology

Recent developments in numerical analysis in goetechnical engineering made possible the analysis of laterally loaded piles taking account of non linear response of soil/pile interface as well as the non homogeneity of soil properties. P-Y curves describe a simple relationship between soil reaction P and pile deflection Y at a given depth. Several experimental works were carried out worldwide since more than half a century to analyse P-Y curves.

Usual procedure of determination of P-Y curves consists of fitting bending moment curve, then double differentiating and double integrating the fitting curve to obtain P and Y respectively. Soil reaction is much more difficult to derive since it strongly depends on the curvature of bending moment curve as well as on the fitting function (Bouafia and Garnier, 1991; King, 1994). Choice of the fitting function is governed in this study by a criterion of forces balance along the pile (Bouafia 1990, Bouafia and Bouguerra 1995). Deflections determination necessitates 2 boundary conditions, which are usually the deflection and rotation measured at pile top during the loading test.

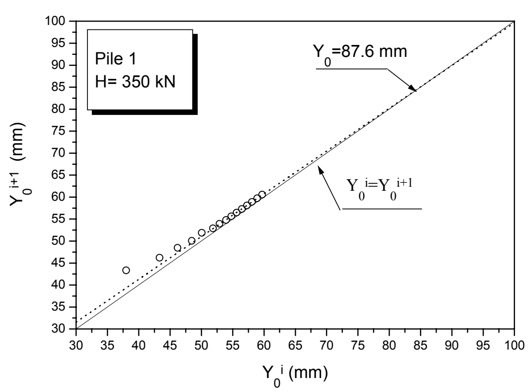

Fig. 5. Evolution of deflection for a load of 350 kN.

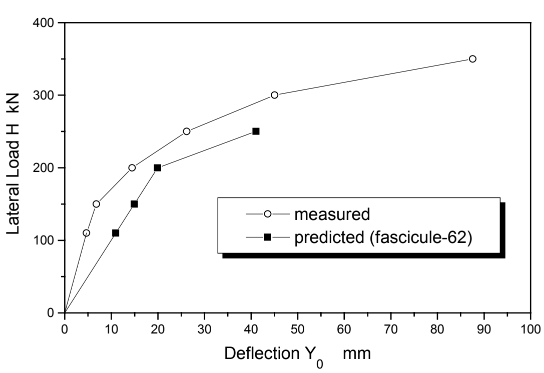

Fig. 6. Load-deflection curve of pile 1.

Deflection profiles were found not passing by zero as expected for short and rigid overturning piles, which might be due to some incompatibility between measurements of deflection and rotation
at pile top used as boundary conditions. Nevertheless, experimental evidence shows the difficulty to accurately derive P-Y curves in the vicinity and beyond the centre of rotation (point of zero deflection) (Bouafia, 2002; Bouafia and Lachenani, 2003). P-Y curves analysis is hereafter presented for shallower depths. According to figure 8, P-Y curves are a non linear shaped even for small magnitudes of deflections. Moreover, they tend to a horizontal asymptote for large displacements.

Hyperbolic fitting of such curves with a function similar to that described by equation 1 allowed to derive initial slope which is the lateral reaction modulus noted E_{ti} as well as the horizontal asymptote which is the ultimate soil reaction P_u.

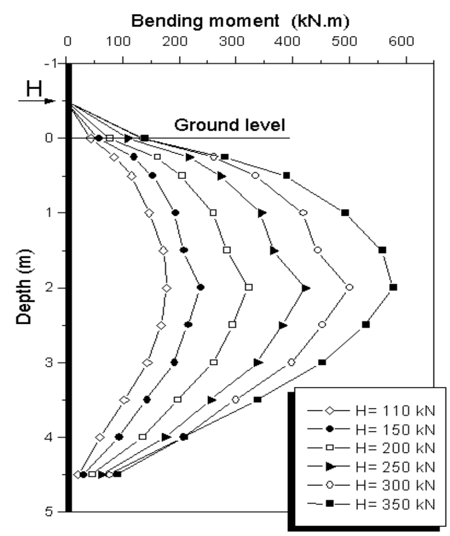

Fig. 7. Bending moment profiles of pile 1.

Lateral reaction modulus

Profile of E_{ti} illustrated in figure 9 slightly vary with depth and can be characterised within the upper half the pile by an average value of 17.3 MPa and a coefficient of variation C_v of 12%.

According to Menard's PMT-based theory, soil reaction modulus is evaluated as follows:

$$Eti = \frac{18.Em.B}{(4.B_O.(2.65x\frac{B}{Bo})^{\alpha}+3.B.\alpha)} \qquad (2)$$

According to figure 9, values computed by equation 2 are about half the experimental ones and therefore lead to overpredict the pile deflections. Moreover, in the light of classical Winkler's theory, deflections of a free tipped short rigid pile embedded in a homogeneous medium are computed as follows:

$$Y_0 = \frac{2.H}{Eti}(2+3\frac{e}{D}) \qquad (3)$$

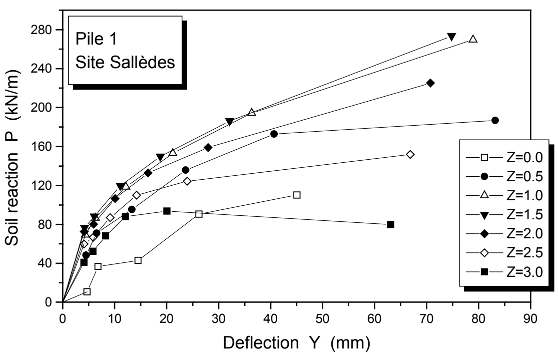

Fig. 8. P-Y curves of pile 1.

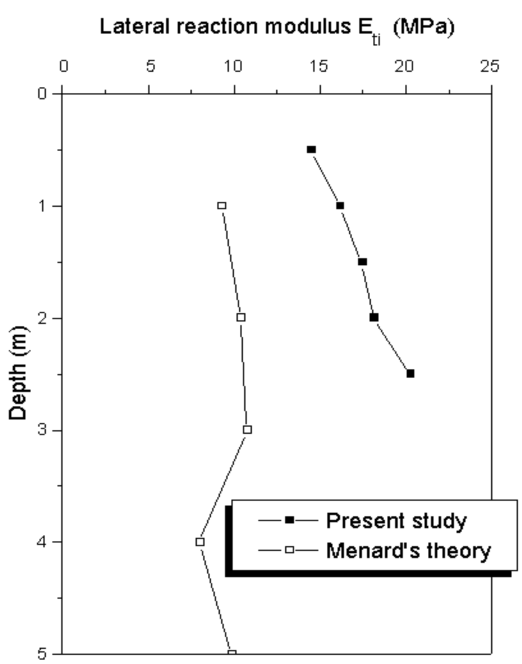

Figure 9. profiles of lateral reaction modulus

Because of the inherent non linearity of load-deflection curve, the ratio H/Y_0 was computed instead of Y_0 by equation 3, and compared to the initial slope λ of H-Y_0 curve. H/Y_0 was found equal to 18.8 kN/mm, which is 37% less than λ= 29.8 kN/mm.

Elastic theory of Poulos (1980) was also applied with estimation of the soil modulus E_s by correlation with E_m:

$$E_s = E_m/\alpha \qquad (4)$$

α is a rheological factor varying between 0.5 and 1, introduced by Menard to account for the soil structure (Baguelin et al, 1978). E_s estimated as an average value is equal to 7.1 MPa. Ratio H/Y_0 given by Poulos (1980) was found equal to 12.3 kN/mm, which is about half the experimental value of λ.

Ultimate soil reaction

Asymptotic values obtained by hyperbolic fitting of P-Y curves were drawn versus depth in figure 10. It is to be noticed the regular decrease of P_u with depth to a likely zero pressure point, which indicates a change in sign of soil pressures against the pile.
This scheme is to be compared with some classical theories of lateral soil resistance. Menard (1962) proposed a profile of P_u on the basis of P_l with gradual variation versus depth within a critical depth equal to 2 diameters below ground surface. Beyond this depth, P_u remains constant and change in sign beyond a depth Z_r.

Static equilibrium of pile under lateral load at pile top and ultimate soil reaction profile led to compute an ultimate load H_u equal to 500 kN with an excess of 25 % with respect to the ultimate lateral load determined form load-deflection curve.

P_u profile proposed by Broms (1964) starts as from 1.5 diameters below ground surface and is composed of two uniform parts opposite in sign. Ultimate soil reaction is equal to 9.C_u.B, where C_u is the undrained shear strength. Discontinuity of pressures at the sign change point is not realistic since in the zone of centre of rotation, deflections are small and resulting soil reaction should not reach the ultimate values (Bouafia, 1999).

Undrained shear strength was estimated from P_l by using the following equation describing cylindrical cavity expansion in purely cohesive soil:

$$\beta = 1 + \ln(\frac{E_m.\beta}{\alpha.(P_l - P_0)}) \qquad (5)$$

where β is the ratio $(P_l-P_0)/C_u$. Values of C_u were found ranging between 70 and 125 kPa. Ultimate lateral load according to Broms was computed for an average value of C_u and found equal to 673 kN with an excess of 68% with respect to experimental value.

At last, the PMT-based method prescribed by the French code Fascicule-62 were used to predict the whole load-deflection

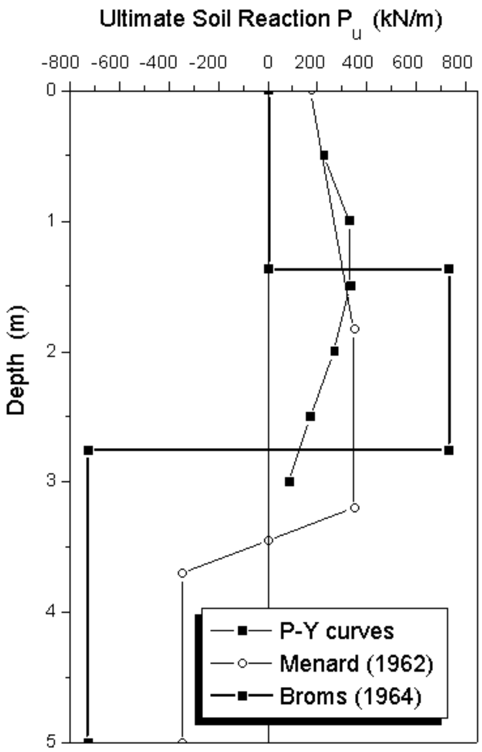

Fig. 10. Profiles of ultimate soil reaction.

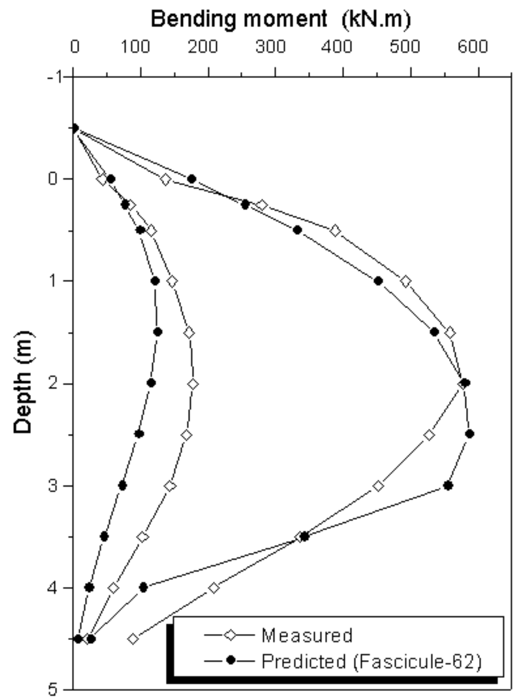

Figure 11. Predicted and measured bending moments.

behaviour of the test pile.

P-Y curve of fascicule 62 is blinear and composed of an initial portion with a slope E_{ti} given by equation 2 and a horizontal straight line corresponding to an ultimate value equal to (P_l-P_0).B (M.E.L.T, 1993). P-Y curves were generated and input in the programme PILATE (PILate under LATEral loads) developed by the LCPC. As shown in figure 11, bending moments are well predicted whereas in figure 6 deflections are overpredicted.

CONCLUSIONS

Full-scale lateral loading tests were performed on two twin steel pipe piles driven into a clayey layer in the site Salledes. The instrumentation of piles allowed to analyse the load-deflection behaviour in the light of P-Y curves theory.

Interpretation of bending moment profiles by a procedure of fitting and double differentiation and double integration led to derive soil reaction P and pile deflection Y. P-Y curves are characterised by a lateral reaction modulus slightly depending on depth. Moreover, these curves show asymptotic values corresponding to the ultimate soil reaction.

At last, non exhaustive comparative study was undertaken which led to analyse the quality of prediction of some commonly used methods of pile design.

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