Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-1955

Analysis of P-Y curves for single piles from the prebored pressuremeter test

Analyse des courbes P-Y des pieux isolés à partir de l'essai pressiométrique normal

A. Bouafia & A. Lachenani
University of Blida, Department of civil engineering, P.O.Box: 270, R.P. Blida 09000 Algeria
e-mail: bouafia1@yahoo.fr

ABSTRACT
The proposed paper is aimed at presenting the results of an extensive analysis of sixteen full-scale horizontal piles loading tests in a diversity of soil conditions (2 sandy sites, 3 clayey sites and 1 silty site). It was shown the existence of fundamental relationships between the P-Y curve parameters, the measured PMT parameters and the lateral pile/soil stiffness K_r. Comparison between the experimental load-deflection behaviour of test piles and the predicted ones according to these relationships showed very good agreement in sandy soils as well as in clayey soils.

RÉSUMÉ
L'article a pour objectif de présenter les résultats de l'analyse de seize essais de chargement horizontal de pieux en vraie grandeur, menés dans une diversité de sols (2 sites sableux, 3 sites argileux et 1 site limoneux). Il a été montré l'existence d'une relation fondamentale entre les paramètres de la courbe P-Y, les paramètres mesurés de l'essai pressiométrique PMT et la rigidité latérale sol/pieu K_r. La comparaison entre le comportement expérimental des pieux d'essai et celui prédit à partir de ces relations a montré une bonne concordance aussi bien dans les sols sableux que dans les sols argileux.

1 INTRODUCTION

Full-scale tests on instrumented piles are often used to investigate the pile/soil response in the light of the load-transfer theory. P-Y curves are derived from bending moment profiles measured by strain gauges along the pile. However, a few full-scale tests on instrumented piles were reported in the literature with successful derivation of P-Y curves from double differentiation and integration of the bending moment profile.

The main difficulty in deriving these curves is due to the high sensitivity of the lateral soil reaction P to the experimental conditions as well as to the method of fitting and differentiation of the bending moments (Bouafia and Garnier 1991).

The proposed paper is aimed at presenting the results of an extensive interpretation of 16 full-scale horizontal piles loading carried out in 6 quite homogeneous soils in France. These tests were undertaken by the LCPC (Laboratoire Central des Ponts & Chaussées) for about 4 decades within the scope of an important research programme on the load-deflection behaviour of piles (Baguelin et al, 1990).

2 PRESENTATION OF THE EXPERIMENTAL SITES

Lateral loading tests were undertaken in 2 sandy soils (sites S_1 and S_2), 3 clayey soils (sites S_3, S_4 and S_5) and in 1 silty soil (site S_6). Table 1 summarises the main characteristics of the soil/pile configurations studied here. E_m, P_l and P_{le}^* are respectively the pressuremeter modulus, the limit pressure measured in PMT test and the net equivalent limit pressure. Symbols between brackets are those of the USCS soil classification system.

Table 1. Main characteristics of the soil/pile configurations

Site	Soil description	E_m/P_l	Pile	Date	Test	D/B	E_pI_p ($MN.m^2$)	K_r ($x10^2$)	E_c (MPa)	P_{le}^* (kPa)	Pile installation
			T_5	1987	T_5	14.2	0.059	6.20	3.40	448	jacked
S_1	medium dense sand (SP)	7-12	T_{10}	1987	T_{10}	15.3	0.869	2.32	6.80	700	jacked
			T_{15}	1987	T_{15}	15.3	4.332	1.44	10.8	760	jacked
S_2	dense sand (SP)	9	P_1	1988	P_1	10.0	56.37	0.41	21.7	1626	bored
			P_2	1988	P_2	5.50	743.6	5.47	21.7	1690	bored
			D	1964	3	5.80	60	4.24	9.40	800	jacked
			D	1964	4	7.50	60	1.40	10.4	800	jacked
			B	1964	5	6.20	26	6.17	8.50	800	jacked
S_3	plastic saturated clay (CH)	7-20	B	1964	6	11.8	26	0.35	11.1	800	jacked
			B	1964	7	9.65	26	0.87	10.1	800	jacked
			A	1965	9	8.10	16	1.13	9.40	800	jacked
			A	1964	10	10.8	16	3.22	10.6	800	jacked
			B	1964	11	11.4	26	0.41	10.8	800	jacked
S_4	plastic clay (CL-CH)	7.5-22	A_m	1984	12	5.50	1074	32.3	5.30	295	jacked
S_5	organic clay (OH)	4-20		1973	13	27.4	900	1.34	3.90	240	bored
S_6	saturated stiff silt (Ml-CL)	16-28	B	1967	14	8.15	26	1.00	17.1	625	jacked

3 PRESENTATION OF THE TEST PILES

All the piles are steel pipes or Larssen caissons instrumented by pairs of strain gauges distributed along two diametrically opposite axes. Piles of site S_2 were filled in with bentonite-cement grout. Pile of site S_5 was filled in with concrete along a height of 2 m from the pile base. In table 1 D, B and E_pI_p are respectively the embedded length, the diameter or breadth and the flexural stiffness of the test pile. K_r and E_c, as they will be defined hereafter, are respectively the lateral pile/soil stiffness and the characteristic pressuremeter modulus.

4 METHODOLOGY OF INTERPRETATION OF RESULTS

Measurement of the axial deformation by strain gauges along the pile allows the determination of bending moments curve for a given load at the pile top. Two successive integrations of this curve lead to easily determine lateral displacement Y along the pile. Moreover, two successive differentiations of this curve allow the determination of horizontal soil reaction P and then to define P-Y curve at any depth.

Since the soil reaction geometrically represents the curvature of bending moment distribution, it is therefore very sensitive to any fluctuation of bending moment at a given depth and strongly depends on the choice of the fitting curve of bending moment. Quintic spline functions or polynomial functions were used to fit the bending moment distribution. The fitting function was chosen according to the criterion of static equilibrium of the test pile under lateral reaction profile P(z) and the loads on the pile top within a given tolerance (Bouafia, 2002a). This criterion was subsequently adopted in other studies in LCPC (Bouafia and Lachenani, 2004).

5 INTERPRETATION OF THE RESULTS

Figure 1 illustrates typical P-Y curves obtained according to this methodology. It can be seen that P-Y curves at different depths are non linear shaped with an increase in soil stiffness with depth. It is to be noticed that deflections and soil reaction change in sign at almost the same depth, say 7 diameters, which is in accordance with Winkler's hypothesis regarding the soil reaction modulus. Furthermore, it can be seen that beyond a deflection of about 3% of B, limit lateral reaction is reached with exhibition of asymptotic values in the P-Y curves along the pile.

The procedure of construction of P-Y curves was validated by back-computation of all the test piles. P-Y curves were introduced in the P-Y curves based computer program SPULL (Single Pile Under Lateral Loads) developed in the university of Blida. Computed deflections were found in very good agreement with the experimental results. It is therefore possible to accurately describe the lateral load-deflection behaviour of such test piles by means of these experimental P-Y curves.

6 ANALYSIS OF P-Y CURVES

Hyperbolic formulation is often used to describe the elastic plastic constitutive laws of soils as well as the P-Y curves. Experimental P-Y curves were fitted by the following hyperbolic function:

$$P=\frac{Y}{\frac{1}{E_{ti}}+\frac{Y}{P_u}} \tag{1}$$

E_{ti} is the initial tangent lateral reaction modulus and P_u is the limit lateral soil reaction.

It should be emphasized that the influence of the lateral pile/soil stiffness on the P-Y curve was not accounted for by the current P-Y methods. Most of these methods simply correlate the parameters of P-Y curve to those measured in PMT test (Gambin, 1979). The lateral pile/stiffness may be defined as follows:

$$K_r=\frac{E_p.I_p}{E_c.D_e^4} \tag{2}$$

E_c is the characteristic pressuremeter modulus defined by equation 3 as an average value of the PMT modulus along the pile and D_e is the effective embedded length of the pile.

$$E_c=\frac{1}{D}\int_0^D E_m.dz \tag{3}$$

It was found that the average values of the ratio ψ defined as:

$$\psi=\frac{E_{ti}}{E_m} \tag{4}$$

vary as a power of K_r as illustrated in figures 2 and 3 for sandy soils and clayey soils respectively. It is to be noticed in figure 2 that pile P_2 whose slenderness ratio D/B is equal to 5.5 should be considered rather as a pier. The proposed correlations are valid only for piles with D/B greater than 10 and 5 in sandy and clayey soils respectively (Bouafia,2002). It is possible to write:

$$E_{ti}(z) = E_m(z).\psi= E_m(z).a.K_r^b \tag{5}$$

Moreover, ultimate lateral reaction P_u was correlated to the net limit pressure P_l^* by defining the ratio:

$$\xi=\frac{P_u}{P_l^*.B} \tag{6}$$

It can be seen from figures 4 and 5 that in sandy and clayey soils ξ varies as a power of K_r such as:

$$\xi= c + d.K_r^e \tag{7}$$

Table 2 summarises the values of coefficients a through e of the ratios ψ and ξ. Due to the limited data regarding the behaviour of experimental piles in organic clays and in silty soils it was not possible to analyse the ratios ψ and ξ for such soils. Nevertheless, the average values were mentioned in table 2.

Equation 7 shows that the limit lateral reaction around a rigid pile is greater than the one around a flexible pile. Moreover, It increases with the pile flexural stiffness and decreases with the embedded length of the pile. Equations 5 and 7 lead to simple formulae in case of a solid circular pile. For example in a homogeneous sandy soil, combining equations 2, 5 and 7 leads to:

Table 2. Values of coefficients of equations 5 and 7

Soil	a	b	c	d	e
sand	0.28	-0.55	0.0	3.00	0.5
clay	1.84	-0.20	0.3	1.00	1.0
silt	5.55	0.00	0.0	2.30	0.0
organic clay	3.70	0.00	0.0	0.14	0.0

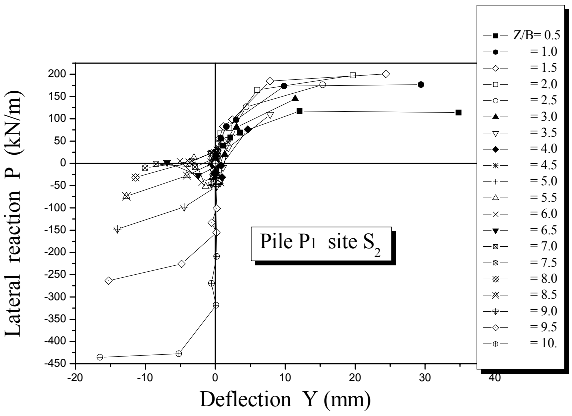

Figure 1. Typical experimental P-Y curves

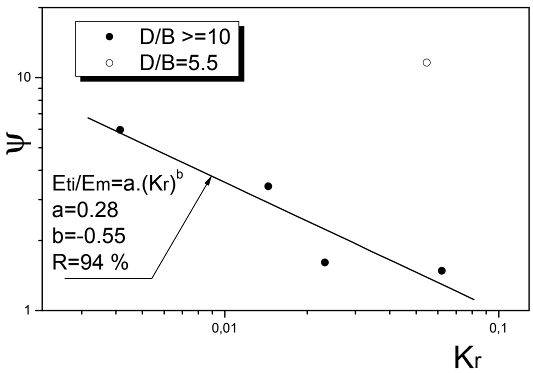

Figure 2. Variation of the ratio ψ in sandy soils

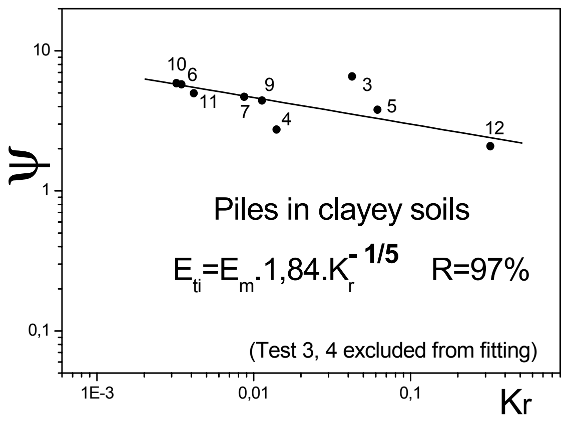

Figure 3. Variation of the ratio ψ in clayey soils

$$\frac{E_{ti}}{E_m} \approx \frac{5}{4} (D/B)^2 \frac{1}{\sqrt{K}} \tag{8}$$

$$\frac{P_u}{P_l^* B} = \frac{2}{3} \frac{\sqrt{K}}{(D/B)^2} \tag{9}$$

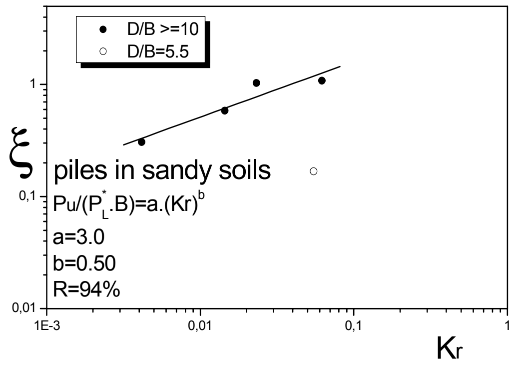

Figure 4. Variation of the ratio ξ in sandy soils

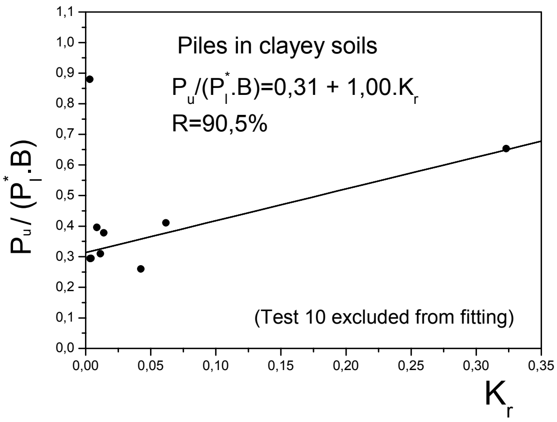

Figure 5. Variation of the ratio ξ in clayey soils

where:

$$K = E_p/E_m \tag{10}$$

is the pile/soil compressibility.

Equations 8 and 9 show the important influence of the pile/soil compressibility and the pile slenderness on the parameters of P-Y curve.

Test piles were computed on the basis of the proposed method of construction of P-Y curves. For each pile, pile/soil stiffness K_r was evaluated, the hyperbolic P-Y curves according to equations 5 and 7 were constructed and input in the programme SPULL to predict the load-deflection curve. As shown in figures 6 and 7, very good agreement was found between the observed deflections and the ones predicted.

Moreover, lateral load-deflection response of some case studies reported in the literature was predicted. Due to limited space allowed to the paper, it will be focused hereafter on full-scale tests in sand. Table 3 summarises the main geotechnical and physical characteristics of soil/pile configurations used in this regard. Piles are identified as mentioned in the references.

The Lock & Dam 26 site is composed of alluvial deposits (poorly graded sand) 3 m thick and overlying glacial deposits (medium to coarse sand with gravel) 17 m thick. The bedrock is a hard limestone from the Mississipian age. Lateral load tests were performed on two identical HP-14x73 piles socketed in the limestone bedrock, jacked apart, and the lateral displacements of each pile were measured.

The Longjuemau site is located near Paris and composed of a tertiary silty fine sand, rather uniformly graded. Piles TG and TD are driven and loaded as in the above site.

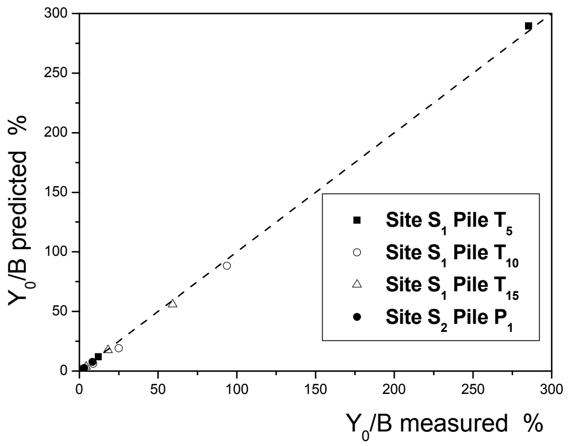

Figure 6. Comparison of predicted and measured deflections in sand

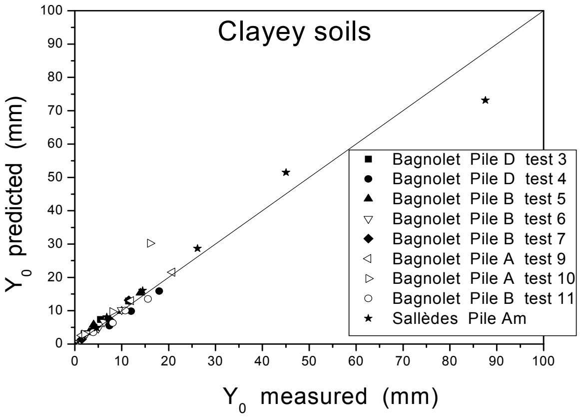

Figure 7. Comparison of predicted and measured deflection in clay

The Roosevelt bridge site is composed of loose layer of sand thick of 4 m, overlying a thick layer of very dense partially cemented sand. The site was submerged by water up to 2 m above the ground level. Square prestressed concrete pile was driven and tested up to cracking under a load of 200 kN and concrete failure occurred under a load of 320 kN.

Figure 8 shows remarkable fluctuation of the 35 points of comparison around the ratio predicted to measured deflection of 1.11. Moreover, $Y_0^{pred.}/Y_0^{meas.}$ has a mean value of 1.22 and a coefficient of variation of 21%.

The results of predictions are encouraging seeing the multitude of approximations made during the process of definition of this method. Detailed comparative study with other P-Y curves based methods is being published elsewhere.

Table 3. Summary of the pile/soil configurations in full-scale tests

Site	Pile	D/B	E_c	K_r
Lock & Dam-26	3-12	57.3	20.6	$1.9x10^{-3}$
Lock & Dam-26	3-13	57.3	20.6	$1.9x10^{-3}$
Longjumeau	TG	10.0	6.65	$3.3x10^{-2}$
Longjumeau	TD	10.0	5.33	$4.1x10^{-2}$
Roosevelt bridge	16	18.4	61.3	$1.1x10^{-2}$

CONCLUSION

The analysis of 16 full-scale horizontal piles loading tests carried out in 6 sites in France with a diversity of soil conditions

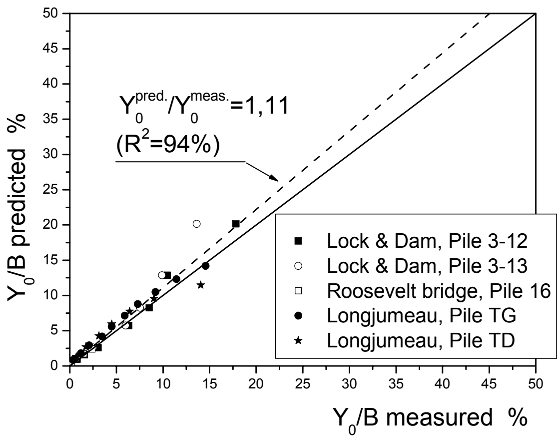

Figure 8. Comparison of predicted and measured deflections

showed the existence of fundamental relationships between the P-Y curves parameters, namely the lateral soil reaction modulus and the lateral soil resistance, the PMT parameters and the lateral pile/soil stiffness K_r. The important influence of the slenderness ratio and the pile/soil compressibility on the P-Y curve was demonstrated.

Based on these relationships, hyperbolic functions were proposed to describe P-Y curves for single piles. Validation process was undertaken by computing other case studies reported in the literature. Comparison of the predicted deflections to the ones measured showed the good prediction capability of the proposed pile/soil stiffness dependant P-Y curves method.

ACKNOWLEDGEMENTS

The study reported herein is supported by the Algerian ministry of higher education and research MESRS within the scope of the project MISOPISS (Modélisation de l'Interaction SOl-Pieu et Sol-Soutènement) under the code J0901/04/02/2004. The authors are grateful to Jacques Roudier, General Manager of the LCPC for authorizing them to access to the experimental data of full-scale lateral loading tests of piles carried out by the LCPC.

REFERENCES

Baguelin, F., Frank, R., Jézéquel, J.F. 1990. The Ménard pressuremeter test and the behaviour of laterally loaded piles in sand, *Proceedings of ISP3, the 3rd International Symposium on Pressuremeters*, Oxford University, 2-6 April 1990, pp 381-391.

Bouafia, A., Garnier, J. 1991. Experimental study of P-Y curves for piles in sand, *Proceedings of the International conference CENTRIFUGE'91*, Boulder, Colorado, 13-14 Juin 1991, pp 261-268, A A Balkema.

Bouafia. A. 2002. Interpretation of full-scale horizontal pile loading tests in sand - Analysis of P-Y curves, *Proceedings of the 9th International Conference on Piling and Deep Foundations DFI 2002*, Nice, France, 3-5 June 2002, pp: 609-615, ISBN 2 85978 358 X, Presses de l'Ecole Nationale des Ponts & Chaussées, Paris.

Bouafia, A. 2002a. Response of a flexible pile under lateral loads in dense sand in centrifuge, *Proceedings of ICPMG'02 International Conference on Physical Modelling in Geotechnics*, St-John's, Newfoundland, Canada July 10-12 2002, edited by Canadian Geotechnical Society.

Bouafia A., Lachenani, A. 2004. Courbes P-Y des pieux isolés dans le sable–Détermination à partir de l'essai pressiométrique, (in French), *Revue Française de Géotechnique RFG* N° 108, pp: 5-15, 3e trimester 2004, editions Presse de l'ENPC, Paris.

Gambin, M. 1979. Calculation of foundations subjected to horizontal forces using pressuremeter data, *Sols-Soils* N° 30/31, pp 17-59.