Laterally loaded single piles - Construction of P-Y curves from the cone penetration test

Pieux isolés sous charge latérale - Construction des courbes P-Y à partir de l'essai de pénétration statique

Ali Bouafia
University of Blida-1 Department of civil engineering P.O. Box 270 R.P Blida 09000 Algeria, ali.bouafia@univ-blida.dz

ABSTRACT: P-Y curves-based design offers a powerful tool of analysis of laterally loaded piles. However, there is no practical method available in the literature for constructing the P-Y curves on the basis of the cone penetration test (CPT). This paper aims at suggesting a practical method for the analysis of the load-deflection behaviour of a single pile based on the CPT data. This design method was derived from a detailed interpretation of several full-scale lateral loading tests on piles embedded in a variety of soil configurations. It was found the lateral pile/soil stiffness ratio is a key parameter influencing the P-Y curve parameters, namely the lateral reaction modulus and the lateral soil resistance.
The methodology of construction of the P-Y curve from the CPT data is presented and the validation of the proposed method by testing it in a small sized database of full-scale loading tests showed a very good predictive capability.

RÉSUMÉ : Le dimensionnement à la base des courbes P-Y offre un outil performant d'analyse des pieux sous charges latérales. Il n'existe par contre pas de méthode pratique de construction des courbes P-Y à partir de l'essai de pénétration statique (CPT). Cette communication a pour objectif de proposer une méthode pratique d'analyse du comportement en charge-déflexion d'un pieu isolé à partir des données de l'essai CPT. La méthode de calcul est issue d'une interprétation détaillée de plusieurs essais de chargement latéral de pieux instrumentés en vraie grandeur et installés dans une variété de sols. Il a été démontré que la rigidité relative pieu/sol est un paramètre clé influençant les paramètres de la courbe P-Y.
La méthodologie de construction de la courbe P-Y à partir du CPT est présentée, et la validation de la méthode proposée en la testant dans une petite base de données d'essais de pieux grandeur nature a montré une très bonne qualité prédictive.

KEYWORDS: P-Y curve, Pile, Full-scale test, Lateral loading, Cone penetration test, Deflection, Lateral reaction modulus.

1 INTRODUCTION

In many geotechnical codes like the AASHTO and the Eurocode 7, the design of pile foundations based on ultimate limit states as well as the serviceability limit states should account for the load-deflection behavior of the pile under lateral loads. However, the three dimensional pile/soil interaction make the analysis of such an aspect rather complex. The pile slenderness ratio and the pile/soil stiffness ratio are key factors governing the pile/soil system response. Moreover, realistic analysis of such an interaction should take into consideration the non-linear response of the surrounding soil as well as the non homogeneity of soil properties.

The concept of P-Y curves was introduced since the sixties and become a source of powerful methods of design of laterally loaded piles as well as flexible retaining walls. As illustrated by figure 1, the P-Y function describes a local relationship at a given depth along the pile between the lateral soil reaction P undertaken by a non linear spring at the pile/soil interface and the lateral pile displacement Y at the same depth. A typical P-Y curve has a non linear shape and is characterized by an initial slope denoted E_{ti} and called the lateral reaction modulus, and a horizontal asymptote P_u corresponding to the lateral soil resistance.

In spite of the large number of applications of the cone penetration test (CPT) in foundation engineering, it is rarely mentioned in the literature how to use the CPT test for analyzing the load-deflection behavior of piles.

Schmertmann (1978) recommended a rough approach to define an elastic plastic P-Y curve from the cone penetration resistance q_c. The lateral reaction modulus E_{ti} was given as function of q_c and the pile diameter B. The lateral soil resistance P_u is equal to 11% and 22% of q_cB for a loose sand and dense sand respectively.

Bouafia and Merouani (1995) showed the appropriate use of correlations between the pressuremeter test parameters and q_c to define P-Y curves leads to predict well the lateral response of single piles in medium dense sand.

Anderson et al (2003) examined 7 case histories of laterally loaded piles by comparing standard P-Y curves whose required parameters were defined on the basis of classical correlations with q_c. This correlative approach may be useful whenever the CPT data are available but requires some engineering judgment due to the diversity of correlations.

According to Bouafia (2009), it is possible to correlate E_{ti} to the drained initial constraint modulus M_0 of unaged and uncemented predominantly silica sands and P_u to q_c, the modulus M_0 being itself empirically correlated to q_c.

The CPT test provides a resistance parameter, but according to many theoretical and experimental research works the soil stiffness of sandy soils may also be correlated to q_c (Baligh, 1985; Jamiolkovski, 1988).

The P-Y curve parameters E_{ti} and P_u may be correlated to the cone resistance q_c and the pile characteristics, according to the following general equation at a given depth:

$$f\,(q_c^*, E_pI_p, D, B, P_u, E_{ti}) = 0 \qquad (1)$$

E_pI_p, D and B are respectively the pile flexural stiffness, the pile embedded length and the pile diameter (or the dimension perpendicular to the lateral load direction).

Dimensional analysis of this equation according to the Buckingham's theorem leads to the dimensionless equation:

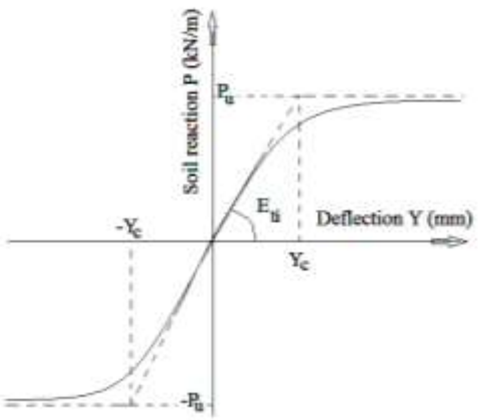

Figure 1. Typical P-Y curve along the pile

$$g\left(\frac{E_{ti}}{q_c^*}, \frac{P_u}{q_c^* B}, \frac{D}{B}, \frac{E_p I_p}{q_c^* D^4}\right) = 0 \qquad (2)$$

The first ratio is noted K_E and called the reaction modulus number such as:

$$E_{ti} = K_E.q_c^* \qquad (3)$$

The second ratio is noted K_c and called the lateral resistance factor:

$$P_u = K_c.q_c^*.B \qquad (4)$$

The third ratio is the pile slenderness ratio and the last one is noted K_R and called the lateral pile/soil stiffness ratio. Equation 2 implies that K_E and K_c are both functions of K_R and D/B.

The method of construction of the P-Y curves from the CPT test presented in this paper in based on the interpretation of several full-scale lateral loading tests on instrumented single piles carried out in a variety of soils worldwide. Detailed description of the experimental sites, the test piles and the interpretation of the experimental P-Y curves was given by Bouafia and Lachenani (2005).

A few full-scale tests on instrumented piles were reported in the literature with successful derivation of the 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).

This paper emphasizes on the formulation of K_E and K_c and the validation of the proposed P-Y curves by predicting the behavior of many test piles reported in the literature.

2 PARAMETERS OF THE P-Y CURVE

The experimental P-Y curves obtained for each test pile were fitted by the hyperbolic function as follows (Bouafia, 2014):

$$P(z) = \frac{y(z)}{\dfrac{1}{E_{ti}(z)} + \dfrac{|Y(z)|}{P_u(z)}} \qquad (5)$$

At a given depth z, the P-Y curve parameters are defined according to equations (3) and (4), and q_c^* is the net cone penetration resistance given by:

$$q_c^*(z) = q_c(z) - \sigma_{v0}'(z) \qquad (6)$$

To take into account the non homogeneity of the cone resistance versus the depth, an equivalent net cone resistance q_{ce}^* is defined as follows:

$$q_{ce}^* = \frac{1}{D_e}\int_0^{D_e} q_c^*.dz \qquad (7)$$

D_e is the effective embedded length of the pile, beyond which the pile segments do not deflect, defined as:

$$D_e = \min\{D, \pi L_0\} \qquad (8)$$

The elastic length (or the transfer length) L_0 is given by:

$$L_0 = \sqrt[4]{\frac{E_p.I_p}{K_E.q_{ce}^*}} \qquad (9)$$

The lateral pile/stiffness ratio may then be defined as follows:

$$K_R = \frac{E_p.I_p}{q_{ce}^*.D^4} \qquad (10)$$

It was found that the reaction modulus number K_E and the lateral resistance factor K_c remarkably vary as power functions of the pile/soil stiffness ratio K_R as follows:

$$K_E = aK_R^n \qquad (11)$$

$$K_c = bK_R^m \qquad (12)$$

Table 1 summarises the values of coefficients a, b, n and m. Due to the limited data regarding the behaviour of experimental piles in organic clays and in silty soils it was not possible to analyse K_E and K_c for such soils. Average values were nevertheless proposed in Table 1.

3 PROCEDURE OF CONSTRUCTION OF P-Y CURVES

Construction of the P-Y curves may be done by following the step-by-step procedure :

1. The profile of cone resistance is to be filtered by eliminating the peaks of resistance which sometimes do not reflect the real penetration resistance of the soil. The peaks should be simply replaced by linearly interpolated values.

2. Subdivide the soil along the pile into N horizontal slices thin enough so that the net cone resistance q_c^* may be considered varying linearly within any slice. The value of q_c^* at the mid-slice is then considered as representing all the slice.

3. Assume the pile is semi-rigid or rigid, which implies that $D_e = D$.

4. Compute the equivalent net cone resistance q_{ce}^* according to equation (7). For practical purposes, replace the integration formula by that of the summation of trapezes :

$$q_{ce}^{e*} = \frac{1}{D_e}\int_0^{D_e} q_c^*(z)dz \approx \frac{1}{D_e}\sum_{k=1}^{k=N} q_c^*(k)\Delta z(k) \qquad (13)$$

Table 1. Values of the coefficients a, b, n and m

Soil	D/B	K_R	a	n	b	m
Sand	D/B ≥ 10	≥ 0.02	0.10	- 1.10	1.40	0.83
		< 0.02	7.00	0.00	0.06	0.00
Clay	D/B ≥ 7.5	≥ 0.03	3.00	-0.33	7.70	1.38
		< 0.03	3.00	-0.33	0.06	0.00
Silt			10.80	0.00	0.10	0.00
Organic clay			25.30	0.00	0.04	0.00

5. Compute the lateral pile/soil stiffness ratio K_R according to the equation (10).

6. Compute the modulus number K_E by the equation (11).

7. Compute the transfer length L_0 by equation (9).

8. Compute the effective embedded length D_e of the pile based on equation (8). If $D > D_e$ (flexible pile), then repeat steps 4 to 8 along an iterative process until the convergence of K_R.

9. Compute the values of E_{ti} and P_u for each slice according to equations (3) and (4) respectively.

10. Construct the P-Y curve for each slice along the pile according to equation (5).

11. Use a software to analyze the load-deflection response of the pile on the basis of the constructed P-Y curves. SPULL (**S**ingle **P**ile **U**nder **L**ateral **L**oads) developed at the University of Blida is a freeware available upon request sent by E-mail to the author.

4 VALIDATION OF THE PROPOSED METHOD

In order to assess the predictive capability of the proposed method, the lateral load-deflection response of many case histories reported in the literature was predicted.

Table 2 summarizes the main features of a small sized database of 18 full-scale lateral loading tests of single piles carried out in 12 sites. For each test pile, the P-Y curves parameters were defined according to the methodology described above on the basis of the CPT data, and a load-deflection curve was simulated by a computation using SPULL.

It was found very good agreement for low levels of measured deflections defined as less than the reference deflections Y_0^R. Since all the experimental load-deflection curves clearly exhibited a hyperbolic shape like that illustrated in figure 1, they were then fitted by a hyperbolic function identical to that defined by equation 5. For a given pile test, the reference deflection Y_0^R corresponds to the ratio H_u/K_H, H_u and K_H being respectively the limit lateral load and the initial lateral stiffness obtained by the hyperbolic fitting.

Figure 2 illustrates a direct comparison of the predicted pile deflections on the basis of the propose method of P-Y curves to the measured ones. Statistical analysis of the ratio predicted deflection to the measured one is illustrated by the histogram of the figure 3, describing a population of 85 values of this ratio, which was fitted by a normal Gauss's function and gave a mean value μ of 0.97 and σ equal to 0.145, which means this ratio may be characterized by a value equal to 1 and the proposed method has a very good predictive capability. This finding is encouraging seeing the multitude of uncertainties affecting the data analysis during the process of development of this method.

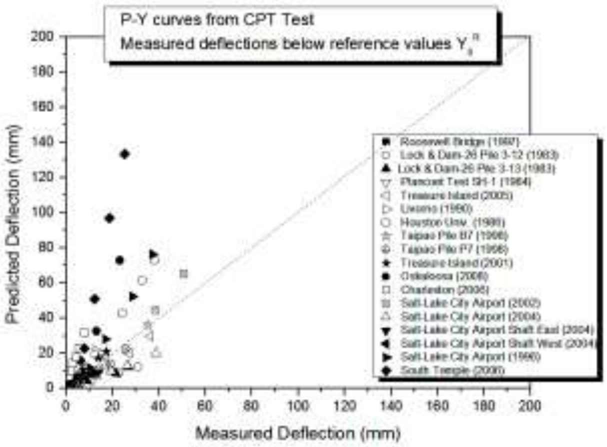

Figure 2. Comparison of predicted to measured pile deflections

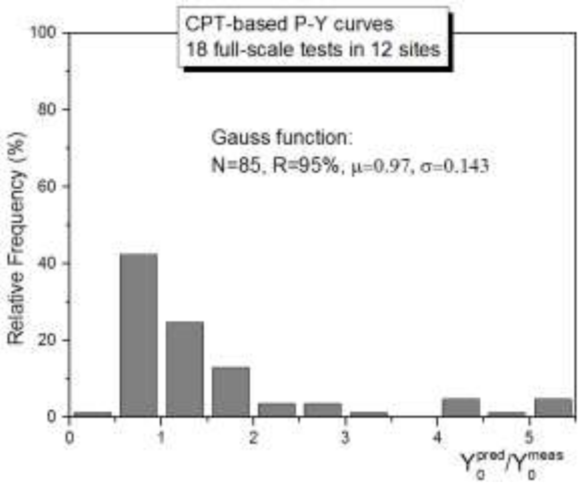

Figure 3. Histogram of analysis of the ratio Y_0^{pred}/Y_0^{meas}

5 CONCLUSIONS

The analysis of several full-scale lateral loading tests carried out on instrumented piles in a variety of soils led to the definition of hyperbolic P-Y curve whose parameters are correlated to the CPT data.

It was shown the lateral reaction modulus and the lateral soil resistance depend on the lateral pile/soil stiffness ratio and the net cone resistance measured during the CPT test.

A step-by-step procedure was suggested to define the parameters of P-Y curves for single pile under lateral loads in multi-layered soils.

The proposed method of construction of P-Y curves was validated by predicting the load-deflection response of single laterally loaded piles in a variety of soils. The comparison of the predicted pile deflections to the measured ones showed very good predictive capability of the proposed method.

6 REFERENCES

Anderson, J.B., Townsend, F.C.& Grajales, B. 2003. Case history evaluation of laterally loaded piles, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 129, No. 3, pp: 187-196.

Baligh, M.M. 1985. Strain path method, *Journal of Geotechnical Division*, ASCE, Vol. 111, No.9, pp: 1108-1136.

Bouafia, A. & Garnier, J. 1991. Experimental study of P-Y curves for piles in sand, *Proc. 1st Int. Conf. CENTRIFUGE'91*, Boulder, Colorado, 13-14 June 1991, pp 261-268, A A Balkema.

Table 2. Main characteristics of the soil/pile configurations

Site	Location	Soil description within the effective length D_e	Date	B (m)	D/B	E_pI_p (MNm^2)	D_e (m)	K_R ($x10^{-2}$)	q_{ce}* (MPa)	Pile installation	Reference
S_1	Roosevelt bridge (USA)	Deep layer of sand	1997	0.760	18.4	893.8	7.80	0.22	10.70	Driven	Ruesta & Townsend (1997)
S_2	Mississipi river (USA)	Deep layer of sand	1988	0.356	57.3	61.0	4.10	0.003	10.16	Driven	Briaud (1989)
S_3	NGES Treasure Island (USA)	Sand (SP-SM)	2005	0.324	35.5	30.0	4.30	0.042	4.080	Driven	Rollins et al (2005)
S_4	Treasure Island (USA)	Sand (SP-SM)	2001	0.600	23.1	291.8	8.30	0.27	2.860	Bored	Weaver et al (2004)
S_5	Plancoet (France)	Bi-layered: Clay (CL)/ Sand (SM)	1984	0.284	22.9	30.0	5.50	1.500	1.151	Driven	Hadjaji et al (2002)
S_6	Livorno (Italy)	Clay (CH)	1990	0.500	114	148.4	4.70	0.002	0.810	Driven	Marchetti et al (1991)
S_7	Houston (USA)	Bi-layered: Sand / Clay	1986	0.273	44.7	14.0	3.20	0.012	1.685	Driven	Brown et al (1988)
S_8	Taipao (Taiwan)	Multi-layered: Sand (SM)/ Silt (ML)/ Sand (SM)	1998	1.500	22.7	6800	15.2	0.092	5.570	Bored	Huang et al (2001)
				0.800	40.0	790.0	10.5	0.027	2.800	Driven	
S_9	Oskalosa (USA)	Bi-layered: Silt (ML)/Clay (CL)	2008	0.254	39.0	18.3	4.10	0.19	1.013	Driven	Suleiman et al (2010)
S_{10}	Charlston (USA)	Multi-layered: Sand (SP)/ Clay (CH)/ Sand (SM-SP)/ Marl (CH-MH)	2006	2.590	18.1	100748	30.3	0.67	3.640	Bored	Rollins et al (2006a)
S_{11}	Salt Lake City (USA)	Multi-layered: Clay (CL)/ Silt (ML)/ Clay (CL)/Sand (SM)	2002	0.324	35.5	30.0	3.74	0.05	3.450	Driven	Rollins et al (2010)
		Multi-layered: Sand (SW)/ Silt (ML)/ Clay (CL)	2004	0.324	40.1	30.0	3.53	0.01	7.147	Driven	Rollins et al (2010)
			2004	1.220	14.0	3310	13.4	0.97	4.295	Bored	Taylor (2006)
			2004	1.22	17.5	3310	13.3	0.37	4.278	Bored	
		Multi-layered: Silt (ML)/ Clay (CL)/ Silt (ML)/ Sand (SP)	1996	0.324	22.8	30.7	3.84	0.23	4.413	Driven	Rollins et al (1998)
S_{12}	South Temple Overpass (USA)	Multi-layered: Clay (CH)/ Sand (SM)/ Silt (ML)	2006	0.324	36.7	30.0	4.20	0.11	1.385	Driven	Rollins et al (2006b)

Bouafia, A. & Merouani, Z. 1995. Analysis of horizontally loaded pile behavior from cone penetration tests in centrifuge, *Proc. Int. Symp. on Cone Penetration Testing*, 4-5 October 1995, Linkoping, Sweden, Vol. 2, pp: 407-413.

Bouafia, A and Lachenani A .2005. Analysis of P-Y Curves for Single Piles from the Prebored Pressuremeter, Proc. 16th ICSMGE, September 12-16, 2005, Osaka, Japan, pp : 1955-1958.

Bouafia, A. 2009. Analysis of P-Y Curves for Single Piles from the Cone Penetration test, *Proc. 17th ICSMGE*, October 2-9, 2009, Alexandria, Egypt.

Bouafia. A (2014) *P-Y curves from the CPT test for laterally loaded single piles in sand, Proc. 3rd Int. Symp. Cone Penetration testing*, May 12-14 2014, Las-Vegas, Nevada, 7 p.

Briaud J.L, Moore B.H, Mitchell G.B.(1989) Analysis of pile load tests at Lock and Dam 26, *Proceedings of the Congress Foundation engineering- current principles and practices*, Evanston, June 25-29, 1989, Evanston, Illinois, Vol. 2, pp: 925-942.

Brown, D; Morisson, C; Reese, L. 1988. Lateral load behavior in sand, *Journal of Geotech. & Geoenvir. Eng*, Vol. 114, No.11, pp: 1261-1276.

Hadjadji T., Frank R. and Degny E. 2002. Analyse du comportement expérimental de pieux sous chargements horizontaux (in French), Rapport de recherche No. GT-74, mai 2002, 303 p.

Huang, A; Hsueh, C; O'Neill, M; Chern, S; Chen, C. 2001. Effects on construction on laterally loaded piles, *Journal of Geotech. & Geoenvir. Eng*, Vol. 127, No.5, pp: 385-397.

Jamiolkovski, M. 1988. Research applied to geotechnical engineering, James Forrest Lecture, *Proceedings ICE*, Part 1, pp: 571-604.

Marchetti, S; Totani, G; Calabrese, M; Monaco, P. 1991. P-Y curves from DMT data for piles driven in clay, Proc. 4th Intl. DFI Conf., Stresa, 7-12 April 1991, pp: 263-272.

Rollins, K; Peterson, K; Weaver, T. 1998. Lateral load behaviour of full-scale pile group in clay, *Journal of Geotech. & Geoenvir. Eng*, Vol. 124, No.6, pp: 468-478.

Rollins, K; Gerber,T; Lane,D; Ashford,A. 2005. Lateral resistance of a full-scale pile group in liquefied sand, *Journal of Geotech. & Geoenvir. Eng*, Vol. 131, No.1, pp: 115-125.

Rollins, K; Hales, J; Ashford, S; Camp, W. 2006a. P-Y curves for large diameter shafts in liquefied sand from blast liquefaction test, *Proc. ASCE Conf. Seismic preformance and simulation of pile foundations*, pp: 11-23.

Rollins, K; Olsen, R; Egbert, J; Jensen, D; Olsen, K; Garette, B. 2006b. Pile spacing effects on lateral pile group behvioursts, *Journal of Geotech. & Geoenvir. Eng*, Vol. 132, No.10, pp: 1262-1271.

Rollins, K; Snyder, J; Walsh, J. 2010. Increased lateral resistance of pile group in clay using compacted fill, *Proc. GeoFlorida Conf.*, GSP 199, pp: 1602-1611.

Ruesta P f., Townsend F C. 1997. Evaluation of laterally loaded pile group at Roosevelt bridge, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 123, N° 12, pp: 1153-1161.

Schmertmann, J.H. 1978. *Guidelines for CPT- Performance and design*, Report FHWA-TS-78-209, Florida Department of Transportation.

Suleiman, M; Voorte, V; Sritharan, S. 2010. Behavior and performance of UHPC H-Piles subjected to vertical and horizontal piles, *Journal of Geotech. & Geoenvir. Eng*, Vol. 136, No.10, pp: 1403-1411.

Taylor, A. 2006. Full-Scale lateral load test of a 1.2 m diameter drilled shaft in sand, M.Sc Dissertation of Brigham Young University.

Weaver, T; Ashford, S; Rollins, K. 2004. Performance and analysis of a laterally loaded pile in stone column improved ground, *Proc. 13th Conf. On earthquake Eng.*, Vancouver, 1-6 august, paper ID. 1822.