P-Y curves from the prebored pressuremeter test for laterally loaded single piles

Courbes P-Y à partir de l'essai pressiométrique préforé pour les pieux isolés sous charge latérale

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ABSTRACT: The paper aims at presenting a practical method of constructing the P-Y curves for the analysis of the lateral load-deflection behaviour of single piles on the basis of the prebored pressuremeter test data. This method was derived from the interpretation of several full-scale lateral loading tests on fully instrumented piles in a variety of soils. After presenting the methodology of construction of the P-Y curve, the paper focuses on the validation of the proposed method, the comparison with the existing approaches and on the discussion of the concept of the critical deflection and the effect of the lateral pile/soil stiffness ratio on the P-Y curve parameters.

RÉSUMÉ : La communication a pour objectifs de présenter une méthode pratique de construction des courbes P-Y pour l'analyse du comportement en déflection des pieux isolés à la base des données de l'essai pressiométrique préforé. Cette méthode a été développée suite à l'interprétation de plusieurs essais de chargement latéral en vraie grandeur de pieux instrumentés dans une variété de sols. Après une présentation de la méthodologie de construction des courbes P-Y, la communication focalise sur la validation de la méthode proposée, la comparaison avec les méthodes existantes, ainsi que sur l'interprétation du concept du déplacement latéral critique et de l'effet de la rigidité latérale relative pieu/sol sur les paramètres de la courbe P-Y.

KEYWORDS: P-Y curve, Pile, Lateral load, Deflection, Pressuremeter test, Loading test, Full-scale.

1 INTRODUCTION.

During more than half a century the design methods of piles under lateral loads based on the P-Y curves concept demonstrated their capability to accurately predict the lateral pile response. The simple physical model of a spring at the pile/soil interface allows taking into consideration the non linearity of the pile/soil interaction as well as the non homogeneity of the soil properties along the pile.

As shown in figure 1, the P-Y curve is characterised by an initial slope denoted E_{ti} called the lateral reaction modulus, and a horizontal asymptote P_u corresponding to the lateral soil resistance.

The pressuremeter test PMT provides an experimental stress-strain curve describing the lateral expansion of the soil borehole under horizontal axisymmetric loads. Some methods of construction of P-Y curves assume some similarity in terms of stress and displacement fields between the lateral response of the pile and that of the PMT borehole (Baguelin et al, 1978), and relate the P-Y curve parameters E_{ti} and P_u to the ones of the PMT test, namely E_M and P_l which are respectively the Ménard deformation modulus and the PMT limit pressure, according to the following general equation at a given depth:

$$f(P_l^*, E_M, E_pI_p, D, B, P_u, E_{ti}) = 0 \tag{1}$$

P_l^*, E_pI_p, D and B are respectively the net PMT limit pressure, 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:

$$g\left(\frac{E_{ti}}{E_M}, \frac{P_u}{P_l^* B}, \frac{D}{B}, \frac{E_pI_p}{E_M D^4}\right) = 0 \tag{2}$$

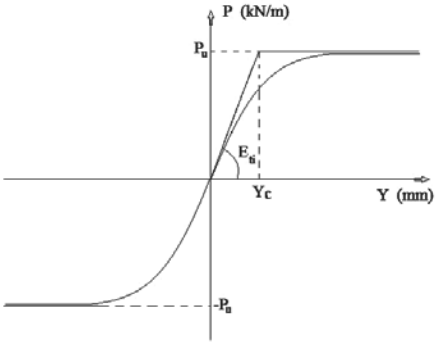

Figure 1. Schematic shape of the P-Y curve

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

$$E_{ti}=K_E.E_M \tag{3}$$

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

$$P_u=K_p.P_l^*.B \tag{4}$$

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 shows that K_E and K_p are both functions of K_R and D/B.

Because of the three-dimensional aspect of the lateral pile/soil interaction and the multitude of the key parameters involved in such an interaction, a rigorous determination of K_E and K_p is rather complex. Alternatively, full-scale lateral loading tests on instrumented piles were carried out for more than half a century to investigate this topic. P-Y curves are usually 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 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).

The method of construction of the P-Y curves presented in this paper in based on the interpretation of several full-scale lateral loading tests on fully instrumented piles carried out in a variety of quite homogeneous soils in France. A detailed description of the experimental sites, the test piles and the interpretation of the experimental P-Y curves was given by Bouafia (2005) and Bouafia and Lachenani (2005). The paper rather focuses on the formulation of K_E and K_p, the validation of the proposed P-Y curves by predicting the behaviour of test piles reported in the literature and the discussion of the concept of the critical pile deflection.

2 FORMULATION OF THE P-Y CURVE

The P-Y curve at a given depth is described by a usual hyperbolic formulation as follows (Reese, 1971; Garassino, 1976; Georgiadis et al, 1992):

$$P = \frac{y}{\dfrac{1}{E_{ti}} + \dfrac{|Y|}{P_u}} \tag{5}$$

The parameters E_{ti} and P_u may be computed according to equations (3) and (4) respectively.

The modulus number and the lateral resistance factor were found varying as a power with the pile/soil stiffness ratio K_R, such as (Bouafia, 2007):

$$K_E = aK_R^n \tag{6}$$

$$K_p = b + cK_R^m \tag{7}$$

Table 1 summarises the values of coefficients a, b, c, 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_p for such soils. Average values were nevertheless proposed in Table 1.

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 methods of construction of P-Y curves which simply correlate the parameters of the P-Y curve to those of the PMT test (Gambin, 1979).

The lateral pile/stiffness may be defined as follows:

$$K_R = \frac{E_p.I_p}{E_c.D_e^4} \tag{8}$$

E_c is the characteristic PMT modulus defined as the average value of the PMT moduli such as:

$$E_c = \frac{1}{D_e}\int_0^{D_e} E_M.dz \tag{9}$$

D is the embedded length of the pile and D_e is the effective embedded length of the pile, beyond which the pile segments do not deflect. It is computed as:

$$D_e = \min\{D, \pi L_0\} \tag{10}$$

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

$$L_0 = \sqrt[4]{\frac{E_p I_p}{E_{ti}^c}} \tag{11}$$

E_{ti}^c is the characteristic lateral reaction modulus of the equivalent homogeneous soil (or the average lateral reaction modulus) given by:

$$E_{ti}^c = \frac{1}{D_e}\int_0^{D_e} E_{ti}(z)dz \tag{12}$$

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

Soil	D/B	K_R	a	n	b	c	m
Sand	D/B ≥ 10	≥ 0.01	0.33	- 0.5	0.0	3.0	0.5
		< 0.01	3.40	0.0	0.0	0.31	0.0
Clay	D/B ≥ 5		1.85	- 0.2	0.3	1.0	1.0
Silt			5.50	0.0	2.30	0.0	0.0
Organic clay			3.70	0.0	0.14	0.0	0.0

3 METHODOLOGY OF CONSTRUCTION OF THE P-Y CURVE

The following step-by-step procedure helps using the method to define the P-Y curves parameters:

1. Subdivide the soil along the pile into N horizontal slices enough thin so that the PMT data (E_m, P_l) may be considered varying linearly within any slice. The value of any of these parameters at the mid-slice is then considered as representative within the slice.

2. If the soil is composed of n layers around the pile, compute the average PMT modulus E_M^i for each layer i supposed thick of h_i as follows:

$$E_M^i = \frac{1}{h_i}\int_0^{h_i} E_M.dz \tag{13}$$

3. Assume D_e=D that is to say the pile is assumed to be semi-rigid or rigid.

4. Compute the characteristic soil modulus E_c by equation 9. For practical purposes, replace the integration formula by that of the summation of trapezes:

$$E_c = \frac{1}{D_e}\int_0^{D_e} E_M(z)dz = \frac{\sum_{i=1}^{i=n} E_M^i h_i}{D_e} \tag{14}$$

5. Compute the lateral pile/soil stiffness ratio K_R according to the equation (8).

6. Compute the modulus number K_E^i of each layer i (i=1, n) on the basis of equation (6) and table 1.

7. Compute the average lateral reaction modulus E_{ti}^i of the layer i at the mid-segments of the pile:

$$E_{ti}^{i} = \frac{1}{h_i}\int E_{ti}(z)dz = \frac{K_E^i}{h_i}\int E_M(z)dz = K_E^i E_M^i \qquad (15)$$

8. Compute E_{ti}^{c} according to equation 12 as follows:

$$E_{ti}^{c} = \frac{1}{D_e}\int_0^{D_e} E_{ti}(z)dz = \frac{\sum_{i=1}^{i=n} K_E^i E_M^i h_i}{D_e} \qquad (16)$$

9. Compute the transfer length L_0 by equation 11.

10. Compute the effective embedded length D_e of the pile based on equation 10. If L_0 leads to $D>D_e$ (flexible pile), repeat steps 4 to 10 along an iterative process until the convergence of K_R.

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

12. Use a PC software to analyze the load-deflection response of the pile on the basis of the P-Y curves so built. SPULL (Single Pile Under Lateral Loads) developed at the University of Blida is a freeware available upon request sent by E-mail to the author.

4 VALIDATION OF THE METHOD

Lateral load-deflection response of some case studies reported in the literature was predicted. Piles are identified as mentioned in their references.

Five full-scale lateral loading tests in sandy soils were studied according to the proposed method.

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.

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 2 shows remarkable fluctuation of the 35 points of comparison around the ratio predicted to measured ground 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 experimental site located in Plancoët (Côtes-du-Nord, France) is a bi-layered soil composed of a clay (CL) thick of 4 m overlying a layer of sand (SM) thick of 4 m. The test pile is a driven rectangular pipe with 0.284 m of width and an embedded length of 6.5 m.

As shown in figure 3, very good agreement is noticed between the measured pile ground deflections and the ones predicted by the proposed method. The P-Y curves of Ménard and Gambin led to very pessimistic prediction (Hadjadji et al, 2002). The P-Y curves of the French code Fascicule-62 however overpredicted at small deflections and then underpredicted at larger deflections (Hadjadji et al, 2002).

Moreover, two other multi-layered experimental sites were studied.

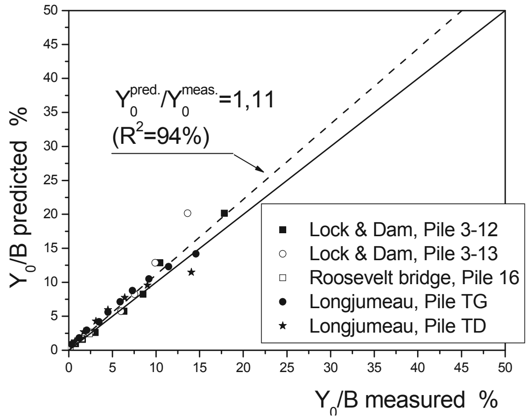

Figure 2. Comparison of predicted and measured deflections in sand

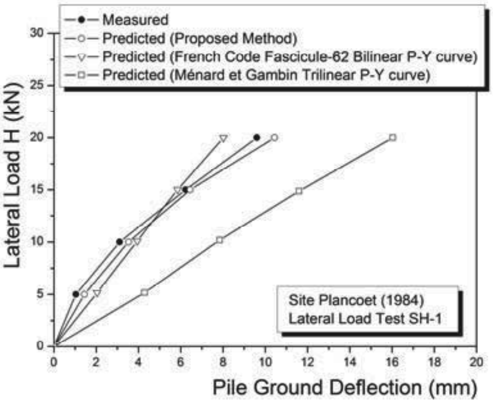

Figure 3. Comparison of predicted and measured deflections in bilayered soil

The first one is located in Vallée de Voulzie (Provins, France) and composed of 14 m de silt overlying 2.5 m of gravelly sand and then a layer of soft chalk becoming hard in depth. The test pile is a vibratory driven pipe having an outside diameter of 0.93 m and an embedded length of 23 m.

The second site is located in Livry-Gargan (France) and composed of clayey sand thick of 4 m, followed by a layer of marl thick of 10 m then a deep layer of chalk. The test pile is a bored pipe having an outside diameter of 0.7 m and an embedded length of 20 m (Moussard and kersale, 2011).

As illustrated by figure 4, the pile ground deflections were accurately predicted by the proposed method. The results of predictions are encouraging seeing the multitude of approximations made during the process of definition of the method.

5 ANALYSIS OF THE FEATURES OF THE METHOD

5.1. The modulus number

Equation 6 may be reformulated in case of a solid circular pile embedded in a homogeneous soil. For example, in sandy soils, combining equations 6 and 8 leads to:

$$K_E = \frac{3}{2}(D/B)^2 \frac{1}{\sqrt{K}} \qquad (17)$$

where $K = E_p/E_c$ is the pile/soil compressibility. This equation shows that the modulus number increases with the pile slenderness ratio and decreases with the pile/soil compressibility.

5.2. The lateral resistance factor

Equation 7 shows that the lateral soil resistance around a rigid pile is greater than the one around a flexible pile and it increases with the pile flexural stiffness and decreases with the embedded length of the pile. For example, in case of a homogeneous sandy soil, combining equations 7 and 8 gives:

$$K_p = \frac{2}{3}\frac{\sqrt{K}}{\left(\frac{D}{B}\right)^2} \tag{18}$$

In contrast with K_E, K_p decreases however with the pile slenderness ratio and increases with the pile/soil compressibility.

5.3. Concept of the critical deflection

As illustrated by figure 1, the critical deflection Y_c corresponds to the intercept of the initial linear portion with a slope equal to E_{ti}, and the horizontal asymptote corresponding to the lateral resistance P_u. Y_c is therefore defined as the threshold of large lateral deflections of the pile section and of full mobilisation of the lateral soil resistance according to the elastic plastic scheme of the P–Y curve. Based on Equations (6) and (7), the ratio Y_c/B may be expressed by the following function of K_R and the PMT parameters measured in sand:

$$\frac{Y_c}{B} = 9K_R\frac{p_L{}^*}{E_M} \tag{19}$$

and in clay by:

$$\frac{Y_c}{B} = \frac{(0.3+K_R)}{1.84}\frac{p_L{}^*}{E_M} \tag{20}$$

It is to be noted from equation 5 that the critical deflection Y_c corresponds to half the limit lateral reaction in the hyperpoblic formulation, say to a factor of safety of 2, and to all the limit lateral reaction in the elastic plastic formulation.

Equations (19) and (20) provide simple and useful tool to estimate the threshold of large lateral load-deflection behaviour.

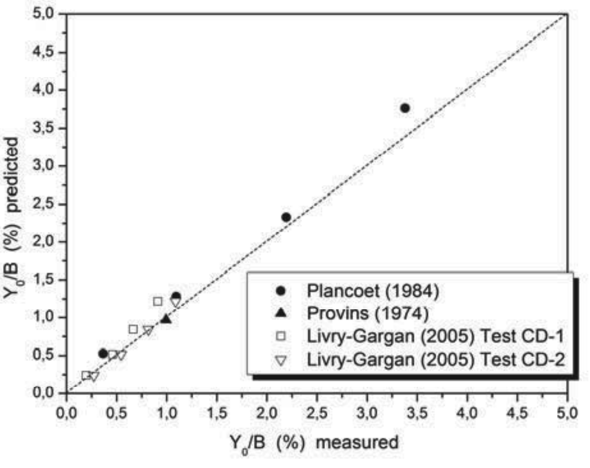

Figure 4. Comparison of predicted and measured deflections in multi-layered soil

CONCLUSION

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 with the PMT data.

It was shown the lateral soil reaction modulus and the lateral soil resistance were correlated to the lateral pile/soil stiffness ratio and the parameters measured during the PMT test (PMT modulus and soil limit pressure).

A step-by-step methodology was presented to define the parameters of P-Y curves for single pile under lateral loading in multi-layered soils.

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

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