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Analysis of P-Y curves for single piles from the cone penetration test

Analyse des courbes P-Y des pieux isolés à partir de l'essai de pénétration statique

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ABSTRACT

Design methods based on the load-transfer P-Y curves are currently considered as reliable approaches for the analysis of load-deflection behavior of pile foundations, taking into consideration the non homogeneity of soil properties as well as of the material non linearity in lateral pile/soil interaction.

Although the cone penetration test CPT is a routine in-situ test, it is rarely recommended in the literature how to define the P-Y curve parameters from the cone penetration resistance.

Thorough interpretation of full-scale lateral loading tests carried out in sandy soils led to the construction of experimental P-Y curves along the instrumented test piles.

The aim of the paper is to present a practical approach of construction of the P-Y curves in sand on the basis of the cone penetration resistance. It was shown the existence of fundamental power relationships between the P-Y curve parameters, the cone resistance and the lateral pile/soil stiffness. The prediction capability of the proposed method was demonstrated by comparing the predicted load-deflection curves to the ones obtained from full-scale piles or centrifuged models.

RÉSUMÉ

Les méthodes de calcul des pieux à la base des courbes P-Y de transfert de charges sont actuellement reconnues comme étant des approches fiables d'analyse du comportement en déflexion des pieux, prenant en considération la non homogénéité des propriétés du sol et la non linéarité matérielle du comportement à l'interface pieu/sol.

Bien que l'essai de pénétration statique CPT est un outil courant d'investigation géotechnique in-situ, il est rare de trouver dans la littérature des recommandations relatives à la définition des paramètres des courbes P-Y à partir de cet essai.

Une interprétation poussée des essais en vraie grandeur de chargement latéral de pieux isolés dans des sols sableux a permis de construire expérimentalement des courbes P-Y expérimentales le long des pieux d'essais.

L'objectif de cette communication est de présenter une approche pratique de construction des courbes P-Y dans le sable à la base de l'essai CPT. Il a été montré l'existence d'une relation fondamentale entre les paramètres de la courbe P-Y, la résistance pénétrométrique et la rigidité latérale pieu/sol. La qualité de prévision de la méthode proposée a été démontrée par comparaison des courbes de chargement prédites à celles obtenues expérimentalement à partir des essais sur pieux en vraie grandeur ou en centrifugeuse.

Keywords : Cone penetration test, Centrifuge, Deflection, Full-scale loading tests, Lateral loading, Pile, P-Y curve, Sand.

1 INTRODUCTION

During the last four decades an important contribution was made by the experimental research to undertstand the mechanisms of lateral-load deflection behaviour of pile foundations. Full-scale lateral loading tests are increasingly used within the scope of a research program or a pile foundations project. In the light of experimental observations it is nowadays recognized the lateral pile/soil response is a complex tridimensional soil/foundation problem.

The design methods based on P-Y curves assume the pile/soil interface is modelled by 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. The P-Y curve is non linear shaped and may be defined at each depth along the pile, which enables to account for the non-linear response of the surrounding soil as well as for the non homogeneity of soil properties and therefore offers more realistic analysis of the pile response.

Applications field of the cone penetration testing grows up with common use of this important in-situ test for the pile design. However, it is seldom mentioned in the litterature how to use the CPT test for analysing the load-deflection behaviour 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}, defined as the initial slope of the P-Y curve, was given as function of q_c and the pile diameter B. The limit lateral reaction P_u, refered to as the lateral soil resistance, is equal to 11% and 22% of q_cB for a loose sand and dense sand respectively.

Bouafia and Merouani (1995) showed the apropriate use of correlations between the pressuremeter test parameters and q_c to define P-Y curves leads to good prediction of 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 judgement due to the diversity of correlations.

This paper is aimed at presenting a practical method of defining the P-Y curves parameters, namely E_{ti} and P_u, for single piles in sandy soils from the cone resistance q_c.

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2 INTERPRETATION OF THE CPT TEST

A key parameter in the lateral pile/soil interaction is the pile/soil stiffness ratio K_r defined as:

$$K_r = \frac{E_p I_p}{E_c D^4} \quad (1)$$

Where E_pI_p and D are respectively the flexural stiffness and the embedded length of the pile, and E_c is a characteristic deformation modulus of the soil surrounding the pile.

The CPT test provides the cone penetration resistance q_c which is a resistance parameter, but according to many theoretical and experimental research works (Baligh 1985, Jamiolkovski 1988, Lunne et al. 1997) it is possible to correlate the soil stiffness of sandy soils to q_c.

Based on an extensive analysis of calibration chamber tests, Eslaamizaad and Robertson (1996) suggested to correlate the drained initial constraint modulus M_0 to q_c for unaged and uncemented predominantly silica sands with different stress histories, as follows:

$$M_0 = K_M \sigma_{ref} \left(\frac{\sigma_{v0}'}{\sigma_{ref}} \right)^n \quad (2)$$

K_M is a dimensionless modulus number which can be determined using figure 1 as function of normalised cone resistance (q_c/σ_{ref}) and the overconlidation ratio (OCR). σ_{ref} is the atmospheric pressure (same units as σ_{v0}', M_0 and q_c) and **n** is a stress exponent equal to 0.200 and 0.128 for normally consolidated sands and overconsolidated sands respectively. OCR may be determined as suggested by Mayne (1991) by combining the two following equations giving OCR and the coefficient K_0 of earth pressures at-rest:

$$OCR = 5.04 (K_0)^{1.54} \quad (3)$$

$$K_0 = \frac{\frac{\sigma_{ref}}{\sigma_{v0}'} \left(\frac{q_c}{\sigma_{ref}} \right)^{1.6}}{145 \exp \sqrt{\frac{\frac{q_c}{\sigma_{ref}}}{12.2 (OCR)^{0.18} \left(\frac{\sigma_{v0}'}{\sigma_{ref}} \right)^{0.5}}}} \quad (4)$$

According to this empirical approach derived from the experimental data of calibration chambers, it is possible to evaluate the sand stiffness quantified by the initial constraint modulus, and to define a characteristic constraint modulus M_0^e as an average value taking into account the non homogeneity of soil along the pile as follows:

$$M_0^e = \frac{1}{D} \int_0^D M_0(z) dz \quad (5)$$

It is possible to evaluate K_r in equation 1 by defining the characteristic soil modulus E_c as being M_0^e. CPT data may hence provide an evaluation of the soil stiffness and the lateral soil resistance as well.

3 PRESENTATION OF FULL-SCALE TESTS IN SAND

The Laboratoire Central des Ponts & Chaussées (France) carried out many full-scale lateral loads on instrumented piles.

The experimental sandy sites S_1 and S_2 are located in Châtenay-Sur-Seine (Paris) and Le-Rheu (Rennes) respectively. Table 1 summarises the main characteristics of the soil/pile configurations studied here. Symbol between brackets are those of the USCS soil classification system.

Test piles are steel pipes instrumented by strain gauges distributed by pairs along two diametrically opposite axes.

Detailed geotechnical data and charcteristics of the piles may be found in Bouafia (2007).

4 INTERPRETATION OF RESULTS

Bending moments profile were determined from the axial deformations measured by strain gauges. Two successive differentiations and two successive integrations of the bending moment led to determine P and Y respectively and to construct therefore the P-Y curve at a given depth along the pile.

The experimental P-Y curves were fitted by the following hyperbolic function:

$$P = \frac{y}{\frac{1}{E_{ti}} + \frac{|Y|}{P_u}} \quad (6)$$

At a given depth, the following correlations were analysed:

$$E_{ti} = K_E M_0 \quad (7)$$

$$P_u = K_c q_c^* B \quad (8)$$

q_c* is the net cone penetration resistance:

$$q_c^*(z) = q_c(z) - \sigma_{v0}'(z) \quad (9)$$

It was found that the reaction modulus number K_E and the coefficient of lateral resistance K_c remarkably vary as power functions of the pile/soil stiffness ratio K_r for piles whose slenderness D/B is greater or equal to 10 as follows:

$$K_E = \frac{0.2}{\sqrt[3]{K_r}} \quad (10)$$

$$K_c = 1.85 \sqrt{K_r} \quad (11)$$

The proposed CPT-based P-Y curves method was assessed by predicting the lateral response of full-scale as well as in centrifuge test piles in sandy soils. For each pile, K_r, K_E, K_c and hence E_{ti} and P_u were evaluated from CPT data. P-Y curves built according to equations 6 to 11 were input into SPULL programme (Single Pile Under Lateral Loads) developped in the university of Blida.

A driven prestressed concrete pile was loaded in Hampton river site (Virginia), which is composed of saturated sandy silty soil (Pando et al. 2003). As shown in figure 2, the load-deflection curve is quite well predicted.

Table 1. Main characteristics of the soil/pile configurations

Site	Soil description	q_c* (MPa)	Pile	D/B	E_pI_p (MN.m^2)	K_r (x10^2)	E_c (MPa)	q_{ce}* (MPa)	Pile installation
			T_5	14.2	0.059	2.15	9.80	2.30	jacked
S_1	medium dense sand (SP)	1-12	T_{10}	15.0	0.869	0.67	23.8	6.13	jacked
			T_{15}	15.3	4.332	0.52	28.1	7.30	jacked
S_2	dense sand (SP)	5-15	P_1	10.0	56.37	0.12	78.3	8.10	bored
			P_2	5.50	743.6	1.52	78.1	7.75	bored

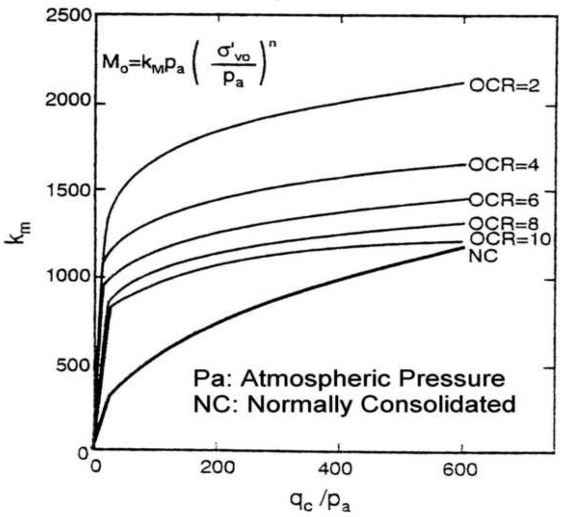

Figure 1. Chart of modulus number K_M (Lunne at al. 1997)

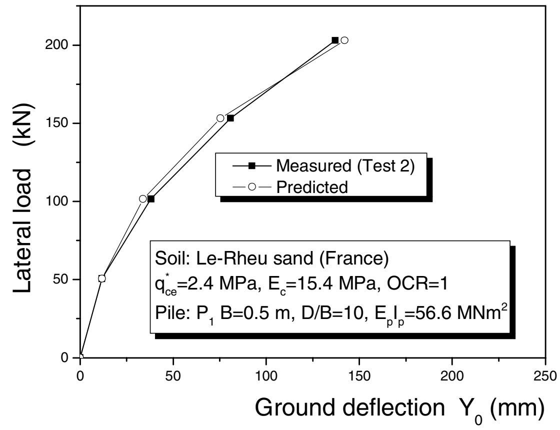

Figure 3. Comparison of load-deflection curves of centrifuge tests

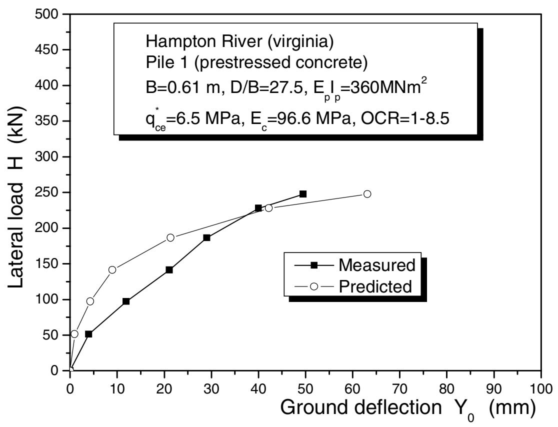

Figure 2. Comparison of load-deflection curves of full-scale tests

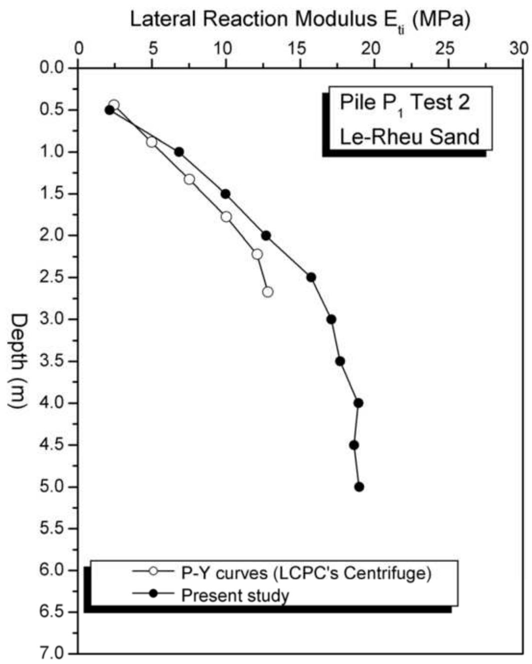

Figure 4. Comparison of the lateral reaction moduli

Since two decades, many lateral loading tests on centrifuged models of single piles were undertaken in LCPC centrifuge (France) within the scope of an important research programme. The reduction scales of piles were 1/18 to 1/40 (Bouafia 1990).

Sandy soils were characterised by CPT tests carried out by miniature cones during centrifugation. As shown in figure 3, an excellent agreement was found between the predicted deflections and the measured ones of the prototype pile P_1.

Moreover, Figure 4 illustrating a direct comparison of the profiles of lateral reaction moduli of the above test in centrifuge shows a good prediction by the proposed method, at least at the upper half of the pile length in which the mechanism of soil reaction is mainly mobilized.

At last, in figure 5 were compared the predicted ground deflections to the measured ones for a variety of prototype piles embedded in homogeneous sands. The experimental deflections reached for these tests 27% of B.

Very good agreement is to be noticed with remarkable fluctuation of the 38 points of comparison around a ratio predicted to measured of 0.95. The results of predictions are encouraging seeing the multitude of approximations made during the process of definition of this method.

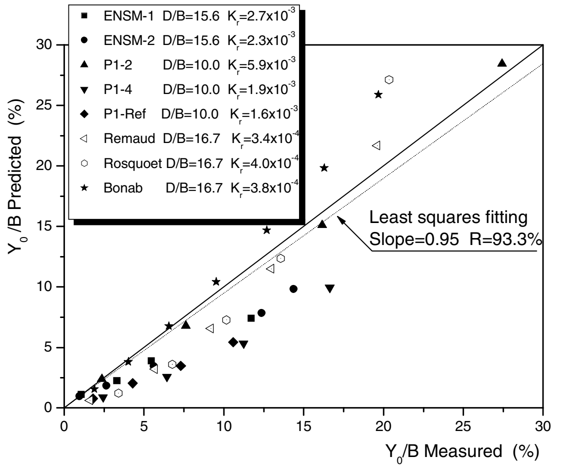

Figure 5. Comparison of ground deflction of prototype piles

5 INFLUENCE OF PILE/SOIL STIFFNESS ON P-Y CURVE

Equation 11 shows that for a given sandy soil the lateral resistance increases with the pile flexural stiffness and decreases with the embedded length of the pile. The lateral resistance mobilized by a short rigid pile is greater than that around a flexible pile.

According to equation 10, lateral reaction modulus decreases with K_r and increases with the slenderness ratio. In other words, the lateral reaction modulus of a short rigid pile is less than that of a long flexible pile.

Equations 7 through 11 lead to simple formulae in case of a solid circular pile. For example in a homogeneous sandy soil, combining equations 7 to 11 leads to:

$$\frac{E_{ti}}{M_0} = 0.55(D/B)^{4/3}\frac{1}{\sqrt[3]{K}} \qquad (12)$$

$$\frac{P_u}{q_c^* B} = 0.40\frac{\sqrt{K}}{(D/B)^2} \qquad (13)$$

where:

$$K = E_p/M_0 \qquad (14)$$

is the pile/soil compressibility.

Equations 12 and 13 show the important influence of the pile/soil compressibility and the pile slenderness on the parameters of P-Y curve.

6 CONCLUSIONS

The analysis of full-scale horizontal piles loading tests carried out in two experimental sites in France led to the analysis of P-Y curves in correlation with the CPT data.

Based on the empirical correlations between the cone resistance and the initial constraint modulus for uncemented unaged and predominantly silica sands, the soil stiffness was defined. For piles whose slenderness is equal or greater than 10, it was shown the existence of fundamental relationships between the P-Y curves parameters, namely the lateral soil reaction modulus and the lateral soil resistance, the cone penetration resistance and the lateral pile/soil stiffness ratio.

The paper presents a practical method of defining the parameters of P-Y curves for single piles under lateral loading in sand. Hyperbolic functions were proposed to describe P-Y curves for single piles.

The proposed method was assessed by predicting the load-deflection response of a small sized database of piles and centrifuged models. Comparison of the predicted deflections to the measured ones showed the good prediction capability of the proposed pile/soil stiffness dependant P-Y curves method.

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