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Design and analysis of single piles under lateral loads in cohesionless soils based on the standard penetration test (SPT)

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Abstract. The Standard Penetration Test (SPT) is nowadays widely used in geotechnical projects to characterize cohesionless soils due to its simplicity and cost effectiveness. This test is appropriate to estimate the resistance and density of cohesionless soils and is largely practised in the Arabian Gulf region within the scope of foundation projects. Since this test was internationally standardized, it may be considered as a practical tool of soil characterization as well as of pile foundation design. This paper is aimed at presenting a practical method of constructing the P-Y curves on the basis of the SPT test derived from a thorough analysis of a worldwide database of pile loading tests in sandy soils. The two main parameters of the P-Y curve, namely the lateral subgrade reaction modulus and the lateral soil resistance, were correlated by a back-analysis procedure to the N_{spt}.

1 Introduction

The design of pile foundation submitted to lateral loads based on serviceability limit states as well as ultimate limit states requires the analysis of lateral load-deflection behaviour of a single pile. However, the response of a pile under lateral loads is rather a complex problem of soil/pile interaction due to the three-dimensional character of the lateral soil reaction, the diversity of the mechanical and geometrical parameters involved and the inherent nonlinearity of the soil behaviour. A pragmatic approach consists of analysing the pile deflections by calibrating the P-Y curves based on the experimental load-head deflections data obtained from full-scale lateral loading tests carried out within the scope of geotechnical projects.

The P-Y curve describes a local relationship at a given depth along the pile between the lateral soil reaction P undertaken by a spring at the pile/soil interface and the lateral pile deflection Y at the same depth. As shown in Figure 1, the 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 [1].

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In spite of the large number of applications of the Standard Penetration Test (SPT) in foundation engineering, there is seemingly no publication highlighting the contribution of SPT test to the definition of the parameters of P-Y curves.

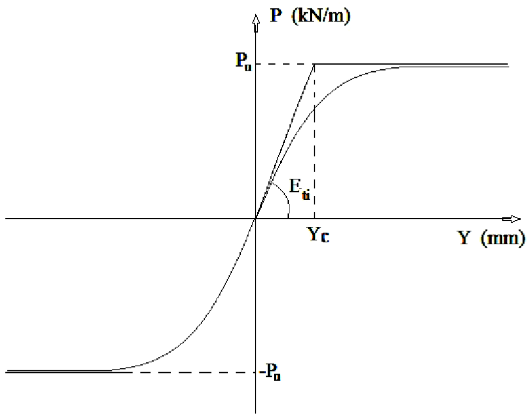

Fig. 1. Schematic shape of the P-Y curve [1].

This paper aims at presenting a practical method of construction of the P-Y curves for piles in sand on the basis of the SPT test, derived from a detailed interpretation of full-scale lateral loading tests on single piles carried out in sandy soils.

2 Methodology of analysis of the P-Y curves

As illustrated in figure 1, the P-Y curves were usually described as hyperbolic shaped functions, which show an inherent non-linear load-deflection response. In many research works, the experimental P-Y curves were fitted by the following hyperbolic function [2]:

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

At a given depth z, the P-Y curve parameters E_{ti} and P_u may be correlated to the N_{spt} and the pile characteristics, according to the following general equation:

$$f(E_{ti}, P_u, N_{spt}, D, B, E_pI_p, \sigma_{v0}) = 0 \tag{2}$$

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). By using the Vashy-Bukingham's theorem of dimensional analysis this equation is transformed into an equivalent equation described by (N-k) dimensionless parameters noted π, k being the number of fundamental units in equation (2). Since N=7 and k=3, the equivalent equation is written as follows:

$$g(\pi_1, \pi_2, \pi_3, \pi_4) = 0 \tag{3}$$

$\pi_1 = \frac{E_{ti}}{N_{spt}\sigma_{v0}}$ is noted hereafter K_E and called the modulus number,

$\pi_2 = \dfrac{P_u}{\sigma_{v0} B}$ is called the lateral resistance factor and noted by K_N,

$\pi_3 = \dfrac{D}{B}$ is the pile slenderness ratio,

$\pi_4 = \dfrac{E_p I_p}{\sigma_{v0} N_{spt} D^4}$ is the lateral pile/soil stiffness ratio noted hereafter by K_R.

The terms K_E and K_N should be independent since the first one corresponds to the small displacements of the pile, whereas the second one corresponds to the large displacements. Consequently, the equation (3) may by uncoupled to the two following equations:

$$K_E = \frac{E_{ti}}{N_{spt}\sigma_{v0}} = h(N_{spt}, K_R, \frac{D}{B}) \quad (4)$$

$$K_N = \frac{P_u}{\sigma_{v0} B} = j(N_{spt}, K_R, \frac{D}{B}) \quad (5)$$

Deriving the functions h and j allows a practical formulation of the P-Y curves parameters as follows:

$$E_{ti} = K_E N_{spt} \sigma_{v0} \quad (6)$$

$$P_u = K_N B \sigma_{v0} \quad (7)$$

The lateral pile/soil stiffness K_R described by the term π_4, will hereafter be calculated on the basis of a "Characteristic soil modulus" along the pile, noted E_c, as follows:

$$K_R = \frac{E_p I_p}{E_c D^4} \quad (8)$$

$E_c$is defined as the weighted average value of the product $(N_{spt}(z).\sigma_{v0}\,(z))$ along the effective length D_e:

$$E_c = \frac{1}{D_e} \int_0^{D_e} N_{spt}(z) \sigma_{v0}(z) dz \quad (9)$$

D_e is the effective embedded length of the pile, beyond which the pile segments do not deflect, and is computed as follows [2]:

$$D_e = min\ (D, \pi L_0) \quad (10)$$

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

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

E_{ti}^c is called "Characteristic subgrade reaction modulus" (or the average subgrade reaction modulus) of the equivalent homogeneous soil given by:

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

The back-analysis procedure was undertaken for each pile-loading test by seeking the values of K_E and K_N giving the best calibration of the experimental loading curve at the pile top. In other words, it is aimed at finding for each pile loading test, on the basis of the least squares technique, the couple (K_E, K_N) giving the best value of the regression coefficient R. The function h and j will be then derived by fitting respectively the values of K_E and K_N as functions of the variables D/B, K_R and N_{spt} appearing in equations (4) and (5).

The tool of the back-analysis was the P-Y curves-based software SPULL (**S**ingle **P**ile **U**nder **L**ateral **L**aods), developed at the University of Blida [21], [22]. During this process, sets of hyperbolic P-Y curves along the pile, described by the equation (1), were input and the output was the pile head deflection for a given lateral load, which provides a predicted load-deflection curve, as illustrated in figure 2, for a couple of parameters (K_E, K_N) and the corresponding regression coefficient R computed. The trial-and-error process continues until an excellent agreement is found between the experimental deflections and the predicted ones. Consequently, the coefficient R should be as close as possible to 100% with a threshold of acceptance fixed at a level of 95%.

3 Description of the database of pile loading tests

A lot of technical documents and reports describing full-scale lateral loading of piles are available in the pile foundations literature. References [3-20] were used to build a medium sized database of pile loading tests. 44 loading tests were carried out in 15 sites where the SPT test was carried out within the scope of the geotechnical investigation.

The test piles were made from reinforced or prestressed concrete, steel pipe, HP pile or composite materials, and installed into the soil according to many techniques: boring, driving, cast-in-drilled hole, and cast-in-steel shell.

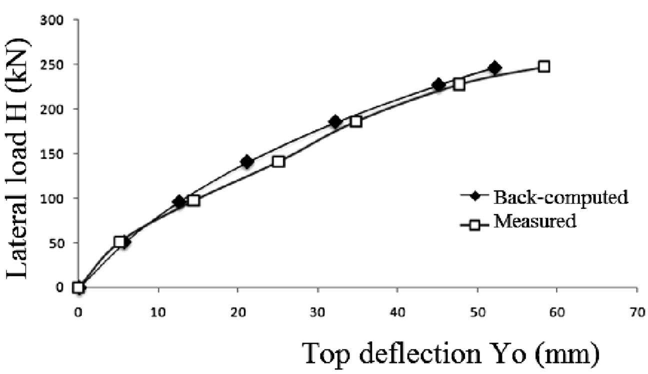

Fig. 2. Illustrative example of back-computation

The margin of slenderness ratio D/B and the pile/soil stiffness ratio K_R for the piles analysed are respectively: 10-60, and 10^{-4}-$2x10^{-1}$. It is to be noted that 70% of the test piles are characterised by K_R less than 10^{-2}, which usually corresponds to flexible piles. Figure 3 illustrates a typical experimental arrangement of a pile loading test.

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Lithology of the experimental sites is mainly composed of multi-layered deposits of silty and/or clayey sand whose N_{spt} profile is not homogeneous with depth. In some sites, a ground water table was found.

4 Presentation of the results

Back-computation of the experimental piles led to conclude that the slenderness ratio D/B has a negligible effect on both the parameters K_E and K_N. However, it was found all the piles analysed were flexibles ($D > \pi L_0$) which limits the proposed values of K_E and K_N to the flexible piles. Moreover, K_E and K_N depend on the position of the P-Y curve with respect to the ground water level. Table 1 summarizes the values of these parameters, which allows directly defining the P-Y curves on the basis of the equations (1), (6) and (7). In figure 4 are shown typical histograms of the modulus number and the factor of lateral resistance.

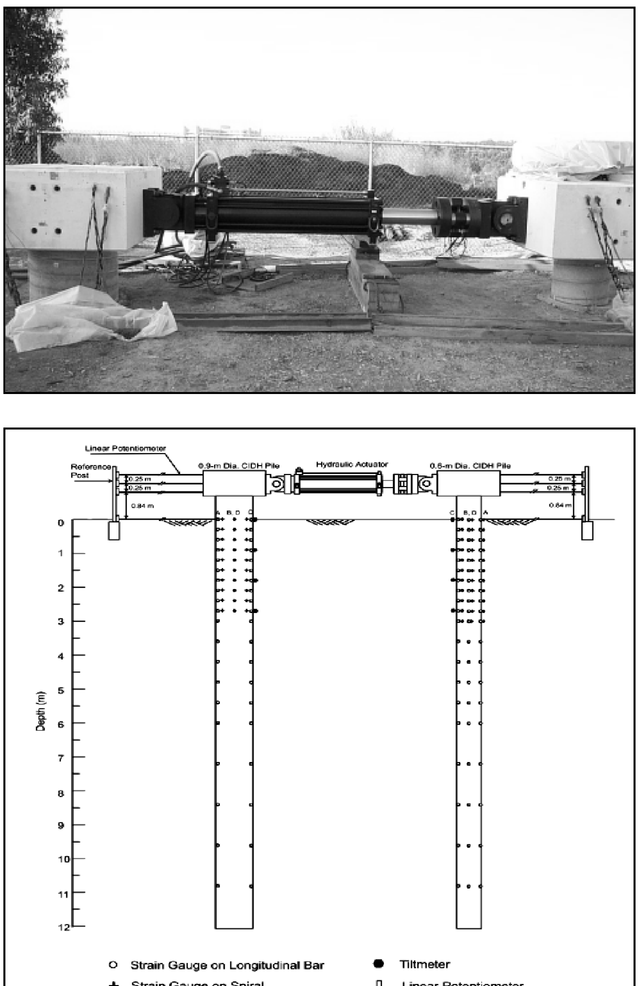

Fig. 3. Typical lateral load test set-up and locations of instruments [3].

According to table 1, submerged layers of sand exhibit lesser values of K_E and K_N than those above the water table.

Table 1. Values of the parameters K_E and K_N

	Flexible piles ($D > \pi L_0$)	
Above water table	K_E=318.0	K_N=25.3
Below water table	K_E=171.4	K_N=16.0

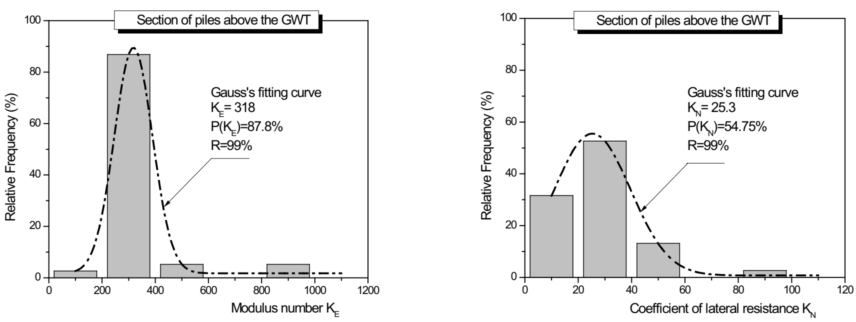

Fig. 4. Typical histograms of the parameters K_E and K_N

In all the geotechnical design using the SPT test (bearing capacity of shallow foundations and piles, liquefaction analysis, etc) a normalized value N_{spt}^1 is used rather than the gross measured N_{spt} value. According to ASTM standard, the coefficient of normalization C_N is given by [23]:

$$N_{spt}^1(z) = N_{spt}(z)C_N = N_{spt}(z)\sqrt{\frac{\sigma_{ref}}{\sigma_{v0}(z)}} \quad (13)$$

σ_{ref} is a stress reference conventionally equal to 100 kPa, and the coefficient C_N should be limited to the margin 0.5-2. It is suggested to reformulate the equation (6) in order to take into consideration N_{spt}^1 rather than N_{spt} as follows:

$$E_{ti}(z) = K_E N_{spt}^1(z)\sqrt{\frac{\sigma_{v0}^3(z)}{\sigma_{ref}}} \quad (14)$$

5 Conclusions

This paper presents a new practical method of defining the parameters of P-Y curves for single piles under lateral loading in sand on the basis of the Standard Penetration Test (SPT) derived from a thorough analysis of a worldwide database of pile loading tests in sandy soils, which presents a contribution to the use of the SPT in the design of laterally loaded piles.

The two parameters of the P-Y curve, namely the subgrade reaction modulus and the lateral soil resistance were correlated to the N_{spt} depending on the position of the curve with respect to the ground water table as well as on the pile/soil stiffness ratio.

Further works will focus on the predictive capability of such a method of construction of P-Y curves by undertaking a validation process and analysing many case studies of pile loading tests.

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