

P-Y Curves for Piles in Sand Based on the SPT Test–Parametric Study and Practical Recommendations



Abdesselem Laouedj and Ali Bouafia

Abstract ULS and SLS limit state design of pile foundations under lateral loads is often undertaken on the basis of the P-Y curves concept. Since more than half a century, the methods of P-Y curves have been subject of an extensive research work worldwide. Nowadays, the P-Y curves parameters, namely the reaction modulus and the soil lateral resistance, are derived by correlation with geotechnical parameters measured by laboratory test or in-situ tests like the cone penetration test. The contribution of the standard penetration test SPT to the direct construction of P-Y curves is however not demonstrated in the literature. The paper aims at presenting an original semi-empirical method of construction of the P-Y curves along the pile directly based on the N-value measured by the SPT. On the basis of a detailed parametric study it was highlighted some key factors affecting the pile load–deflection behavior.

Keywords Pile · Lateral load · P-Y curve · SPT test · Sand

1 Introduction

The load–deflection behavior analysis of a pile foundation based on the P-Y curves is a practical approach allowing powerful analysis of the forces and displacements of the pile under a horizontal load. These curves are constructed as prescribed by geotechnical standards such as the API and Eurocode 7, following empirical or semi-empirical correlation to the geotechnical parameters measured by the laboratory or in-situ tests (AFNOR [1], API [2]).

The P-Y curve describes a local constitutive law between the lateral soil reaction P undertaken by a spring at the pile/soil interface at a given depth along the pile, and the lateral pile deflection Y at this depth. As shown in Fig. 1, the P-Y curve

A. Laouedj
National Marine Science and Coastal Planning School University, Dély Ibrahim, Algeria

A. Bouafia (✉)
University Saâd Dahleb of Blida, Ouled Yaïch, Algeria
e-mail: ali.bouafia@univ-blida.dz

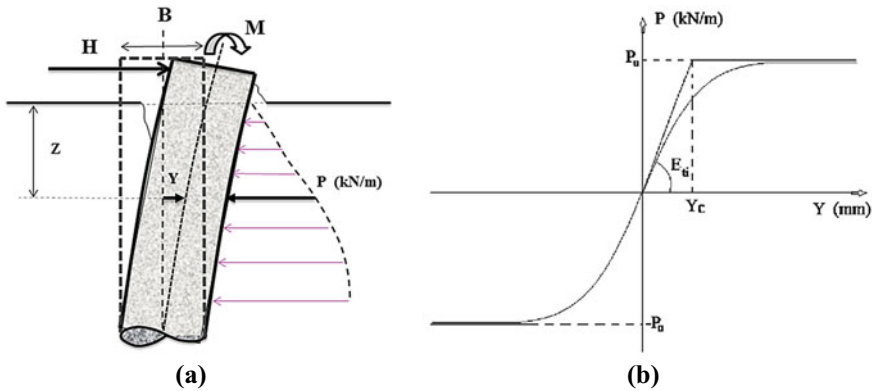


Fig. 1 Schemes of forces balance and the P-Y curves [3]

is non-linear shaped and characterized by an initial slope called the lateral reaction modulus denoted E_{ii} , and a horizontal asymptote P_u corresponding to the lateral soil resistance [3–5].

In spite of the large number of applications of the standard penetration test (SPT) in foundation engineering, it is rarely mentioned in the literature how to use directly the N-value measured by the SPT test to analyze the load–deflection behavior of piles.

This paper aims at presenting a practical method of direct construction of the P-Y curves for piles in sandy soil on the basis of the SPT test.

2 Parameters of the P-Y Curve

The experimental P-Y curve, at a given depth z , derived from the analysis of fully instrumented full-scale test piles by Laouedj and Bouafia [6] were fitted by the hyperbolic function given by Eq. (1), where the two parameters of the P-Y curve E_{ii} and P_u were correlated to the N_{spt} value and the pile characteristics.

$$P(z) = \frac{Y(z)}{\frac{1}{E_{ii}(z)} + \frac{|Y(z)|}{P_u(z)}} \tag{1}$$

The first parameter of the P-Y curve E_{ii} is called the initial lateral reaction modulus and expressed as follows:

$$E_{ii} = K_E N_{spt} \sigma_v' \tag{2}$$

The second parameter of the P-Y curve is called the lateral soil resistance and defined as follows:

Table 1 Values of the parameters K_E and K_N

Above water table	Below water table
$K_E = 207$	$K_E = 156$
$K_N = 21$	$K_N = 17$

$$P_u = K_N \sigma_v' B \tag{3}$$

The coefficients K_E and K_N are respectively called “the modulus number” and “the lateral resistance coefficient”. It was shown they may be directly correlated to the N_{spt} value. In Table 1 are summarized the values of K_E and K_N depending on the position of pile segment with respect to ground water table [6].

Laouedj and Bouafia [7] found out for all the test piles studied that the embedded length D was greater than 3 times the elastic length L_0 ($D > 3L_0$), which leads to classify their behaviour as of flexible piles, and consequently limits the results presented here to the category of flexible piles [7].

3 Parametric Study

3.1 Dimensional Analysis of the Problem

In studying the mechanics of piles under a horizontal force H_0 , the deflection at the grand surface Y_0 of the pile can then be determined. The P-Y curve parameters may be correlated to vertical overburden stress σ_{v0} and N_{spt} the properties of the soil around the geometric properties of the pile, namely the pile flexural stiffness $E_p I_p$, the embedded length D , and the diameter B (or the dimension perpendicular to the lateral load direction), according to the following general equation at a given depth z :

$$f(H_0, Y_0, E_p I_p, B, D, \sigma_{v0}(z), N_{spt}) = 0 \tag{4}$$

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

$$g\left(\frac{Y_0}{B}, \frac{H_0}{\sigma_{v0}(D)BD}, \frac{D}{B}, N_{spt}\right) = 0 \tag{5}$$

The first term is called the normalized displacement, the second is the normalized lateral load, and the third is the pile slenderness ratio. The parametric study presented hereafter focuses on the effect of the following parameters: the pile slenderness ratio, the groundwater level, and the sand density.

3.2 Features of the Model

In this parametric study, the load–deflection curve of a single pile embedded within a homogeneous deep sandy layer having different densities (loose, medium, or dense) was investigated. The model is a steel pipe pile with 0.5 m in diameter, a flexural stiffness of 50 MN.m² and an embedded length varying from 5 to 25 as summarized in Table 2. The lateral load H load is applied at 1 m above the ground surface.

The soil unit weight (submerged or dry) depending on the position of the water table was estimated by empirical correlations with the N_{spt} value as recommended in geotechnical literature.

Terzaghi [8] suggested to correlate the N_{spt} with the in-situ state of density of the sandy deposits as shown in Table 3, and the Table 4 summarizes the physical and mechanical characteristics of the sandy soil used in this parametric study.

Four possible groundwater levels are studied, namely: dry sand without water table, submerged sand (water table at ground level), sand with a water level at mid-length of pile, say D/2, and sand with a water level at a depth of D/4.

The P-Y curves for a given model of pile/soil system were generated and input in the software SPULL (Single Pile Under Lateral Load) developed at the University of Blida.

Table 2 The geometric characteristics of the pile

Embedded length (m)	Diameter	Slenderness ratio D/B	Flexural stiffness
D = 5.0	B = 0.5 m	10	E _p I _p = 50,000 kN.m ²
D = 10.0		20	
D = 25.0		50	

Table 3 Relation between N_{SPT} and density of the sand (after Terzaghi [8])

N value	Relative density
4–10	Loose
10–30	Medium
30–50	Dense

Table 4 The characteristics of the sandy soil model

N value	Dry unit weight (kN/m ³)	Submerged unit weight (kN/m ³)
N _{SPT} = 5	γ _d = 13.91	γ' = 8.66
N _{SPT} = 20	γ _d = 14.98	γ' = 9.33
N _{SPT} = 40	γ _d = 16.28	γ' = 10.13

3.3 Discussion of the Parametric Study Results

3.3.1 Effect of the Pile Slenderness Ratio

Load–deflection curves are illustrated in Fig. 2 which demonstrates the important effect of the pile slenderness ratio on the pile response. In Fig. 2a and b related to the cases of dry and saturated loose sand respectively, the difference of deflections for $D/B = 10$ and 20 is about 92.5%, and for $D/B = 10$ and 50, the difference of is about 99.7%. Consequently, the D/B ratio has considerable effect on the pile deflections. One can conclude that for a given lateral load, an increase in slenderness ratio results in an important increase of the pile deflection, whatever the density of the sand and its degree of saturation.

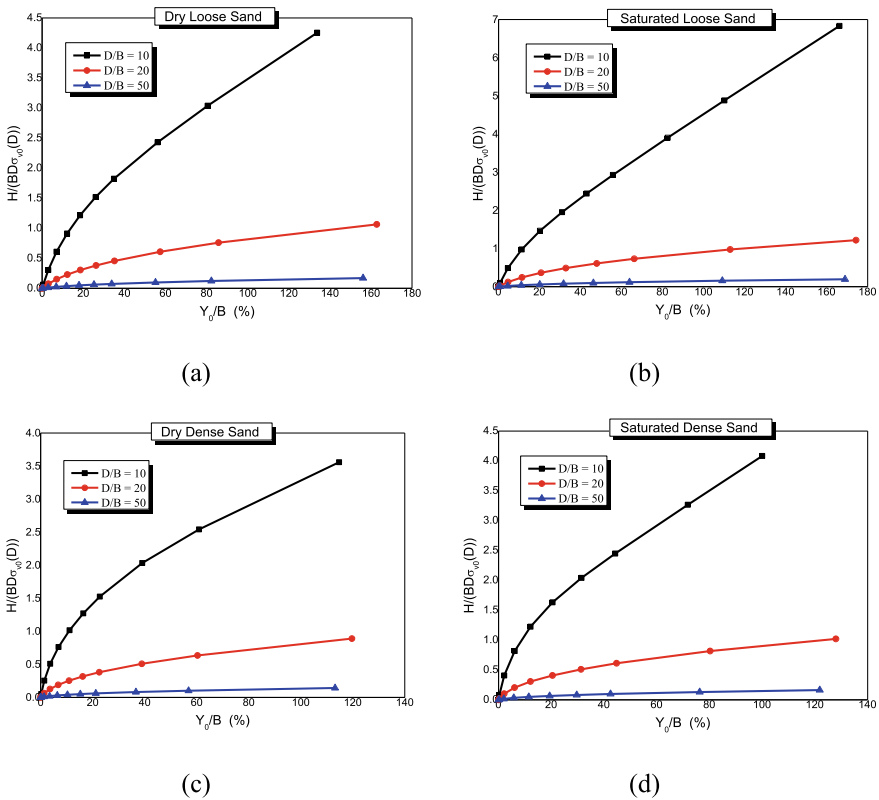


Fig. 2 The effect of pile slenderness on the behavior of the soil/pile system in sand: **a** pile in dry loose sand; **b** pile in saturated loose sand; **c** pile in dry dense sand; **d** pile in saturated dense sand

3.3.2 Effect of the Sand Density

Density is a key parameter governing the behavior of any sandy soil. This study includes three level of density: loose, medium and dense sand are illustrated in Fig. 3.

The influence of the density is correlated with N_{SPT} and its effect is studied with different parameters listed in Table 4. The lateral soil resistance is one of the most important factors that directly influences the pile response under lateral load. In Fig. 3a and b, the effect of the sand density on the pile deflection is shown for a pile slenderness ratio varying from 10 to 50. The other two figures Fig. 3c and d illustrate the same sand density and same slenderness ratio for a saturated sand.

At the same normalized of the pile top deflection, the normalized lateral load of medium and dense sand is quite equal, and the normalized deflection in a loose sand is larger by 14% than those in dense sand with a pile slenderness ratio of 10. For the

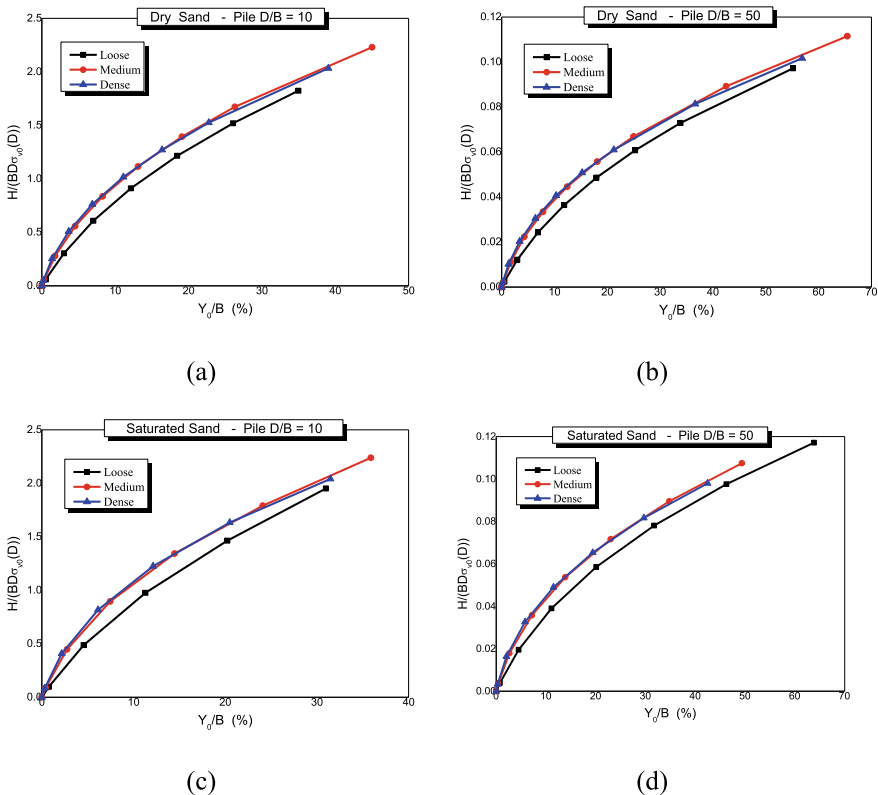


Fig. 3 The effect of sand density on the behavior of the soil/pile system: **a** pile of $D/B = 10$ in dry sand; **b** pile of $D/B = 50$ in dry sand; **c** pile of $D/B = 10$ in saturated sand; **d** pile of $D/B = 50$ in saturated sand

slenderness ratio of the pile equal to 50 in loose sand, the deflection is larger 17% than those in medium or dense sand.

In the saturated sand, for a slenderness ratio of 10, the comparison of the normalized deflection due to the same normalized lateral load gives an excess of 11% in loose sand compared to medium or dense sand, and with a slenderness ratio of 50, an excess of 14.5% is noticed for the same comparison.

It can be concluded that the sand density plays a major role in the behavior of piles under lateral loading. It can also be seen from these figures that the single pile in medium or dense sand shows practically the same displacements, regardless of the pile slenderness ratio and the saturation degree of the sand. The reduction in displacements is therefore observed only when passing from loose sand to a medium-dense sand. When the density of the sand increases, the displacement of the pile decreases, regardless of the degree of saturation of the sand and the slenderness ratio of the pile.

3.3.3 Effect of the Groundwater Level

In this study, the performance of a laterally loaded single pile embedded in a sandy soil with different ground water levels is presented. Four water table cases we simulated. Accurate ground water level information is then needed for the estimation of the soil density as well as the parameters K_N and K_E as shown in Table 1.

From Fig. 4 it can be seen that the effect of groundwater position on the pile top deflection. The lateral soil resistances along the pile in medium and dense sands are larger than those in loose sand. Whatever the slenderness ratio of the pile and the density of sand, the relative differences in pile top deflection are within 10%, the load–deflection curves being practically merged, regardless of the level of the water table. In other words, for low levels of lateral load, the position of the water table has practically negligible influence on the pile deflections as long as they are less than 10% of B.

4 Conclusion

A detailed parametric study was undertaken in order to investigate the effects of the pile slenderness ratio, the sand density, and the position of the groundwater. The main results from this study are summarized as follows:

1. The pile top deflection decreases with the increase of the pile slenderness ratio (D/B), which is then an unfavorable effect on the stability of the pile/soil system.
2. The increase in sand density leads to a decrease in the pile top deflection. It can be concluded that the sand density plays a favorable key role in the design of laterally loaded piles.

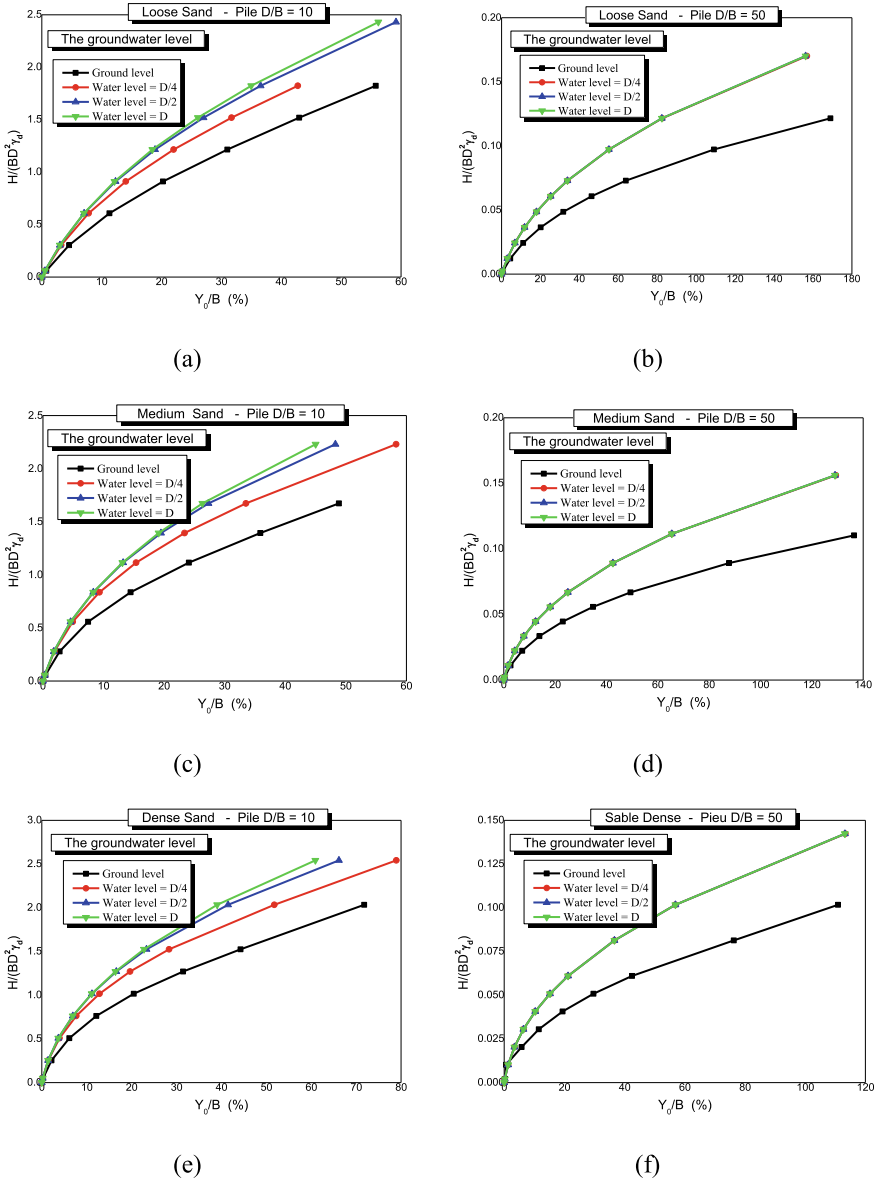


Fig. 4 The effect of groundwater level on the behavior of the soil/pile system: **a** pile with $D/B = 10$ in loose sand; **b** pile with $D/B = 50$ in loose sand; **c** pile with $D/B = 10$ in medium sand; **d** pile with $D/B = 50$ in medium sand; **e** pile with $D/B = 10$ in dense sand; **f** pile with $D/B = 50$ in dense sand

3. The increase in the level of the water table with respect to the ground level in sandy soil has negligible influence on the pile top deflection under small level of lateral loads. For deflections greater than 10% of B, the effect of the existence of the groundwater generates an amplification of deflections with a rise of the ground water level to the soil surface.

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