Parametric study on the pile response under a lateral load - Construction of P-Y curves from the DPT test

Y. Sail,
University of Blida 1, Department of Civil Engineering, Algeria
yacinesail@yahoo.fr

A. Bouafia
University of Blida 1, Department of Civil Engineering, Algeria
ali.bouafia@univ-blida.dz

ABSTRACT: The P-Y curves is one of the most commonly used methods for the design of the pile foundation subjected to lateral loads. The objective of this paper is to present a practical method of direct construction of the P-Y curves on the basis on the Dynamic Penetration Test (DPT) data carried out in sandy soils. This method was derived from the interpretation of full-scale lateral loading tests on fully instrumented piles in sandy soils in France. A parametric study was then conducted in order to identify the effects of some geometric and geotechnical parameters on the pile response under lateral loading in loose sand soil. Different key parameters were investigated such as: the ground water level, the pile slenderness ratio and the number of blows quantifying the soil stiffness. Practical recommendations were at last outlined for the engineering practice.

Keywords: Pile, lateral loading, P-Y curves, parametric study, dynamic penetration test (DPT), loose sand.

1 INTRODUCTION

The response of single piles subjected to horizontal loading is a complex problem due to the nonlinearity of the soil/pile interaction and the multitude of mechanical and geometric parameters involved.

The P-Y curve, called also the non-linear subgrade reaction method is widely used for the analysis and design of laterally loaded piles. As shown in Figure 1, this curve depicts the relationship between lateral soil resistance (*P*) and lateral deflection (*Y*). This non linear curve is often characterized by an initial slope E_{ti}, called the lateral reaction modulus and a horizontal asymptote P_u, known as the lateral soil resistance.

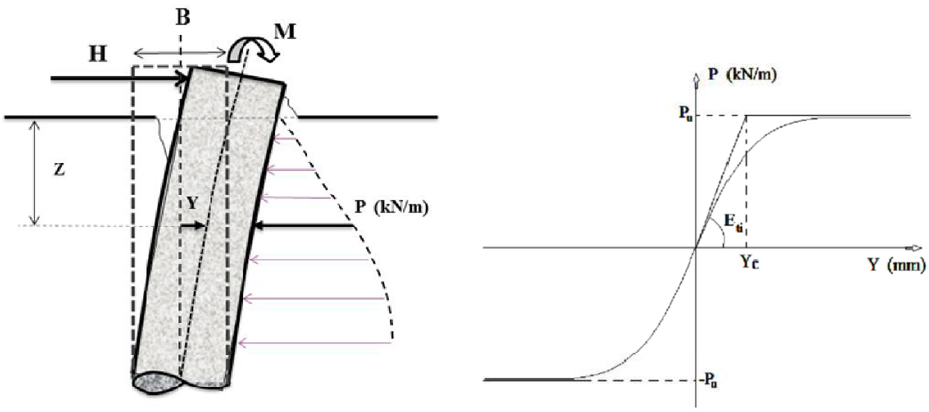

Figure 1. Schemes of forces balance and the P-Y curves (Laouedj & Bouafia 2022)

In the literature, several researchers have attempted to construct P-Y curves from in-situ tests such as the standard penetration test (SPT) (Bouafia 2022, Laouedj and Bouafia 2017), pressuremeter test (PMT) (Bouafia 2023, Bouafia 2007, Bouafia & Lachenani 2004, Baguelin 1982), cone penetration test (CPT) (Bouafia & Merouani, 1995; Bouafia 2017, Li et al. 2019, Guo et al. 2014), dilatometer test (DMT) (Robertson et al. 1989, Marchetti et al. 1991, Borden and Lawter 1989, Gabr et al. 1994), and cone penetration test with pore pressure measurement (CPTU) (Li et al. 2018). However, very few attempts have been made to construct P-Y curves from dynamic penetration test (DPT) parameters, despite it being one of the simplest, least expensive, fastest, and widely used in-situ tests in geotechnical projects (Sail et al., 2022).

This article presents, on one hand, the methodology for defining the parameters of P-Y curves for a single pile under lateral loads in sandy soils. On the other hand, it discusses a parametric study conducted on two categories of piles (semi-rigid and flexible), examining the effect of certain parameters on the pile head displacement, including the pile slenderness ratio, the groundwater level, and the pile/soil stiffness ratio.

2 METHODOLOGY TO CONSTRUCT P-Y CURVES

The experimental P-Y curve at a given depth z is described by the hyperbolic function given by equation (1).

$$P = \frac{Y}{\frac{1}{E_{ti}} + P_U} \tag{1}$$

The analysis and interpretation of full scale lateral loading tests on fully instrumented piles in sandy soils have enabled the derivation of simple and direct formulas for the two parameters E_{ti} and P_u. These two parameters were correlated to the soil characteristics represented by the number of blows N_d of the DPT test and the initial total vertical stress σ_{v0}, as well as to the pile characteristics represented by the diameter or frontal width of the pile B and the pile slenderness ratio D/B as follows (Sail et al., 2022):

$$E_{ti}(z) = \frac{23000 \times (N_d)^{0.6} \times \sigma_{v0}(z)}{\frac{D}{B}} \tag{2}$$

$$Pu(z) = 20 \times B \times \sigma_{v0}(z) \tag{3}$$

It should be noted that this method applies to the flexible and semi-rigid piles. The classification of piles can be determined based on the calculated values of K_R and L_0 by following the steps outlined below:

1- Divide the soil along the pile into N horizontal thin slides such that the lateral reaction modulus $E_{ti}(z)$ value can be assumed to vary linearly within any slide.
2- Consider the effective embedded length of the pile D_e, to be equal to the pile embedded length D.
3- Calculate the characteristic soil modulus E_{ti}^{c} along the embedded length of pile De, as follows:

$$E_{ti}^{c} = \frac{1}{D_e} \int_0^{D_e} E_{ti}(z) \cdot dz \tag{4}$$

The integration calculation can be approximated using the trapezoidal method summation on the E_{ti} values calculated from the equation (2).

4- Determine the elastic pile length L_0, which can be deduced by incorporating the pile flexural stiffness $E_p\, I_p$ as follows:

$$L_0 = \sqrt[4]{\frac{4\, E_p\, I_p}{E_{ti}^{c}}} \tag{5}$$

5- Calculate the lateral pile/soil stiffness ratio noted K_R as follows:

$$K_R = \frac{E_p\, I_p}{E_{ti}^{c} \times D^4} \tag{6}$$

6- Determine the effective embedded length D_e defined by:

$$D_e = \min\{D, 3L_0\} \tag{7}$$

The classification of piles can be deduced by verifying the following inequalities:

- If $D < 2L_0$, the pile is rigid and the method is not applicable.
- If $2L_0 < D < 3L_0$, the pile is semi-rigid.
- If $D > 3L_0$, the pile is flexible. In this case, an iterative calculation must be performed, by introducing the value of *De* at each iteration step until convergence is reached.

The analysis of the load-deflection response of a single pile under lateral loads is carried out using SPULL program developed in the university of Blida.

3 PARAMETRIC STUDY

3.1 Dimensional analysis of the problem

The problem can be described by the general equation *f* with 7 variables, namely: the lateral load H_0, the pile head deflection Y_0, the number of blows N_d of the *DPT* test, the pile embedded length *D*, the diameter or frontal width of the pile *B*, the pile flexural stiffness *Ep Ip* and the vertical overburden stress σ_{v0} according to the following general equation at a given depth:

$$f\left(H_0, Y_0, N_d, D, B, E_p\, I_p, \sigma_{v0}\right) = 0 \tag{8}$$

Dimensional analysis of the equation (1) according to the Buckingham's theorem leads to the dimensionless equation:

$$f\left(\frac{Y_0}{B}, \frac{H_0}{\gamma\, B\, D^2}, \frac{D}{B}, \frac{E_p\, I_p}{\gamma\, N_d\, D^5}\right) = 0 \tag{9}$$

The first term represents the output parameter known as the normalized displacement, while the three other terms are input parameters named respectively: the normalized lateral load, the pile slenderness ratio, and the lateral pile/stiffness ratio at the embedded length.

3.2 Features of the model

The model is made of a pipe with a diameter of 0.5m, a flexural stiffness which varies depending on K_R value and an embedded length that varies from 3.5 m to 10 m, as shown in Table 1 below. The lateral load *H* is applied at 1m above the ground surface. Ten loading stages have been applied at the head of the pile, namely: H=50kPa, 100kPa, 150kPa, 200 kPa, 250kPa, 300kPa, 350kPa, 400kPa, 450kPa, and 500kPa.

Table 1. Geometric characteristics of the pile.

Embedded length (D)	Diameter (B)	Slenderness ratio (D/B)	Flexural stiffness (E_p I_p)
3.5 m		7	
5 m	0.5 m	10	Varies depending on K_R
10 m		20	

Three groundwater level scenarios are examined, including: Dry sand without groundwater, sand with a water level at mid-length of the pile located at D/2, and submerged sand with a water table located at the ground surface.

The ground is composed of a loose sandy layer with a dry unit weight γ_d=13.91 kN/m^3, a submerged unit weight γ'=8.66 kN/m^3 and the N value measured by the DPT varies between 2.4 and 6. This variation in the number of blows, assumed to be linear along the pile's embedded length, was determined from correlations with the N_{SPT} as recommended in geotechnical literature.

3.3 Results and discussion

The SPULL software requires the introduction of the P-Y curves parameters as well as the boundary conditions. The P-Y curves parameters were computed based on the N_{DPT} values and the pile geometry according to the equations (2) and (3). The boundary conditions are determined based on the pile classification according to the methodology described above. For flexible and semi-rigid piles, the bottom of the pile can be considered at rest with zero displacement and rotation as boundary conditions. In the case of rigid pile, the tip pile can be considered as free with zero moment and shear force.

In this study, all results will be presented in the form of graphs showing the evolution of normalized displacement on the x-axis as a function of normalized lateral loading on the y-axis. Two categories of piles will be investigated in parallel, namely semi-rigid piles and flexible piles.

For semi-rigid piles, calculations are carried out by adopting the value of K_R = 1.00E-02. This K_R value, which remains constant for this category of piles, will be kept fixed based on the variation of other parameters, including the ground water level and the pile slenderness ratio. For flexible piles, calculations are conducted by adopting an initial value of K_R =1.00E-3 before iterations. For this category of piles, an iterative calculation must be performed until convergence is achieved. The final value of K_R obtained for flexible piles, considering variations in the ground water level and the pile slenderness ratio, ranges between 1.20E-03 and 1.33E-03.

3.3.1 Effect of the groundwater level

In this study, we investigated three cases of water table levels, with one located at ground level, another situated at mid-depth of the pile anchor, and a third positioned at the base of the pile. Figure 2 illustrates the impact of the water table level on the response of a pile under lateral loading in loose sand, with consideration for each pile category and slenderness ratio. It can be noticed that the influence of the water level is minimal, if not negligible, as indicated by the nearly identical curves observed for both semi-rigid and flexible piles, irrespective of the pile's slenderness ratio. For semi-rigid piles, the maximum displacement difference recorded during the last loading step is approximately 9.5% for a slenderness ratio *D/B* of 7, 7.2% for *D/B*=10, and 4.3% for *D/B*=20. For flexible piles, the maximum displacement difference is about 10% for *D/B*=7, 8.2% for *D/B*=10, and 6.1% for *D/B*=20.

Physically, this observation can be explained by the fact that the water contained in loose sand contributes very little to support the horizontal load applied to the pile. Indeed, this behavior is characteristic of loose granular soils, distinguished by a high volume of pores between grains and high permeability. Consequently, it is the grains themselves that bear almost the entire applied load, resulting in an instantaneous deformation that remains unchanged regardless of the soil's moisture content. Therefore, the effect of the slenderness ratio and relative stiffness will be investigated only for the case of saturated soils.

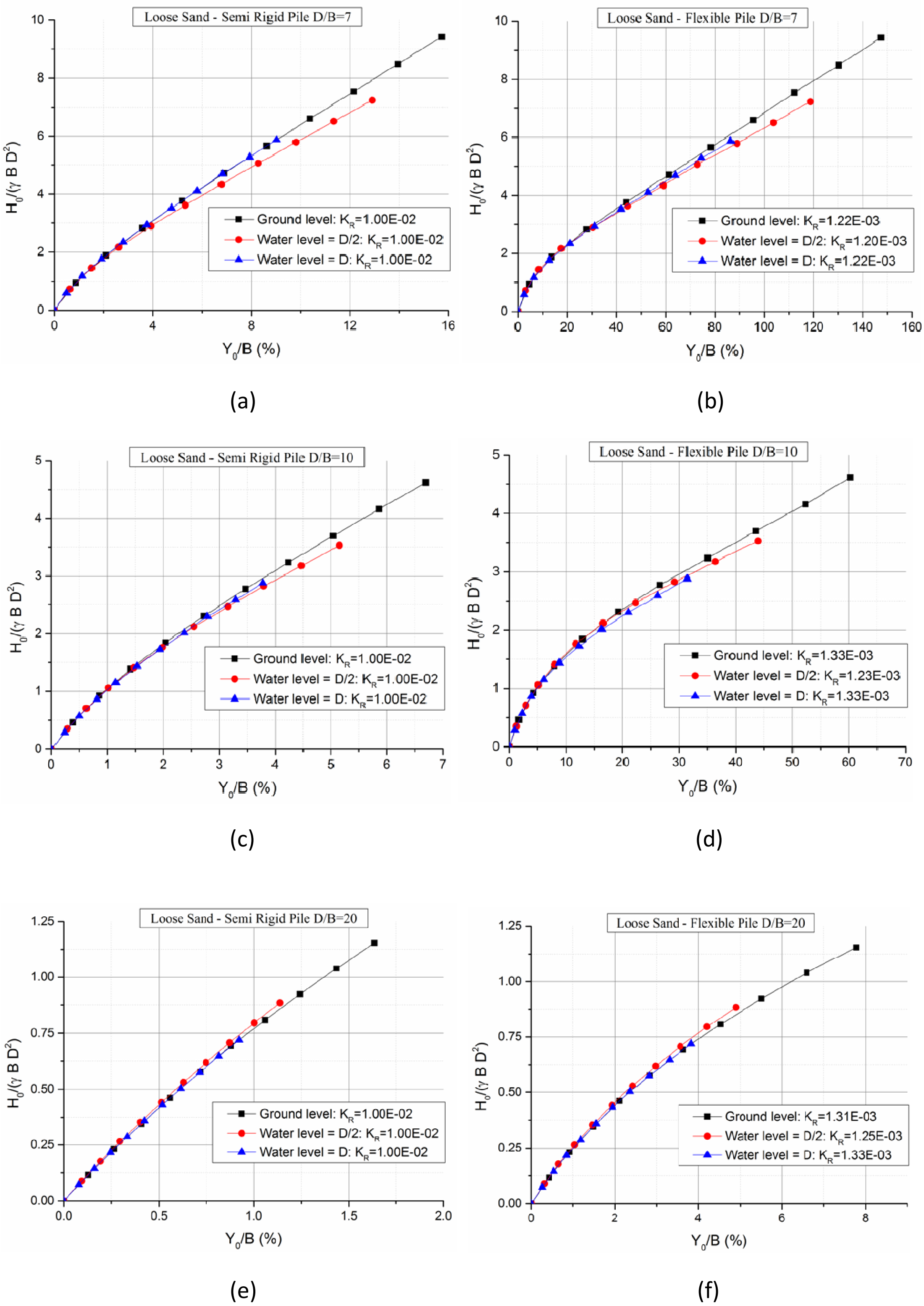

Figure 2. Effect of ground water level on the behavior of the pile in loose sand soil : (a) semi rigid pile with D/B = 7; (b) flexible pile with D/B = 7; (c) semi rigid pile with D/B = 10; (d) flexible pile with D/B = 10; (e) semi rigid pile with D/B = 20; (f) flexible pile with D/B = 20.

3.3.2 *Effect of the pile slenderness ratio*

The pile slenderness ratio is one of the main parameters to consider as it plays an important role in the bearing capacity and structural response of the piles. In this study, the effect of three pile slenderness ratios was investigated to understand the behavior of semi-rigid and flexible piles in saturated loose sand soil. As can be seen in Figure 3, for semi-rigid piles, the effect of the slenderness ratio is negligible for both *D/B* ratios of 7 and 10, as the deformation curves overlap (see Figure 3a). However, the *D/B* ratio of 20 stands out with a significantly greater deflection, showing a maximum difference of about +41.4% (see Figure 3b). Furthermore, the effect of the slenderness ratio is negligible for flexible piles regardless of the value of the slenderness ratio (see Figure 3c and 3d).

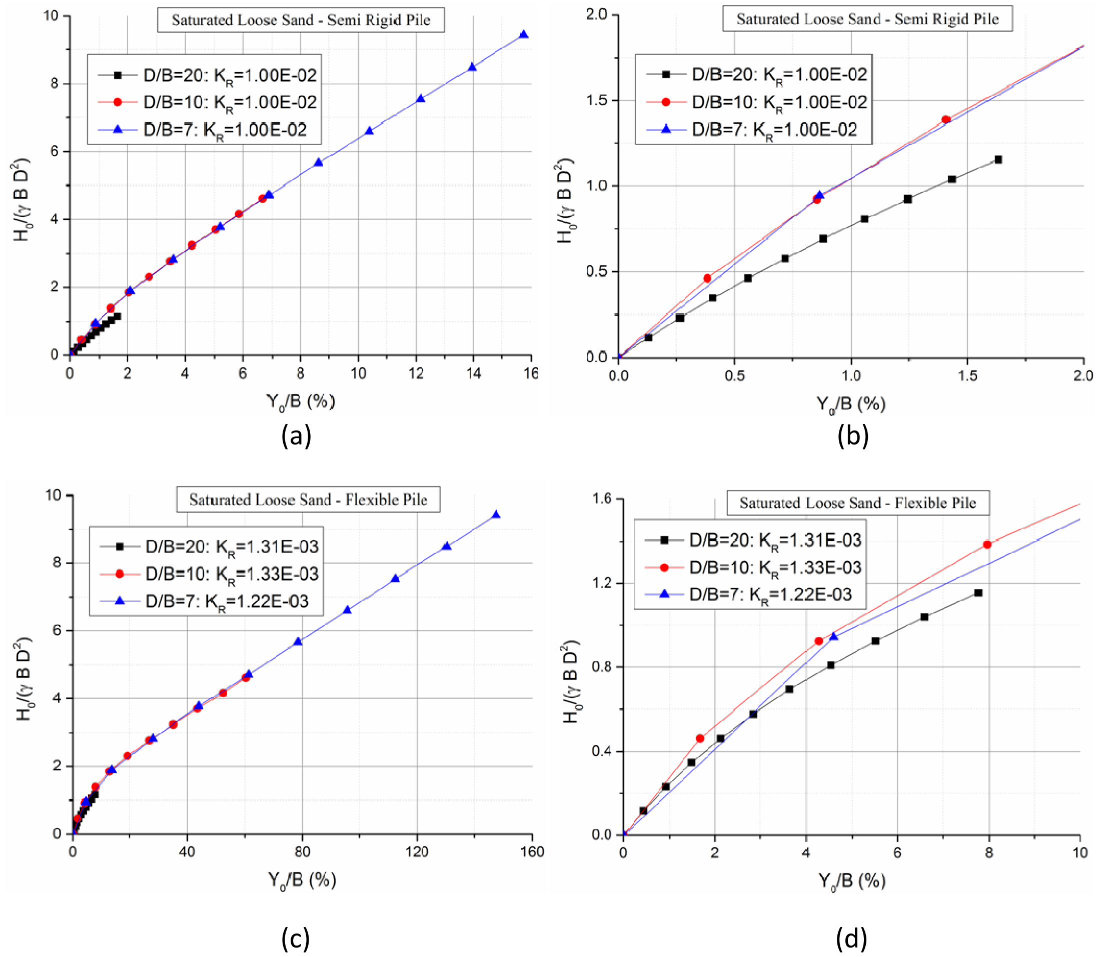

Figure 3. Effect of pile slenderness ratio on the behavior of the pile in saturated loose sand soil: (a) semi-rigid pile; (b) semi-rigid pile (enlarged figure); (c) flexible pile; (d) flexible pile (enlarged figure).

3.3.3 *Effect of the lateral pile/soil stiffness ratio*

The K_R parameter is an important factor which physically represents the ratio between the stiffness of the pile and the stiffness of the soil. In this study, we investigated the effect of three values of lateral pile/soil stiffness ratio on the behavior of semi-rigid and flexible piles in saturated loose sand soil. As can be seen in Figure 4, the value of K_R seems to have a significant effect on the pile response, regardless of the pile category and slenderness ratio. For a given loading, the pile displacement is disproportionate to the value of K_R, and this observation holds true for both semi-rigid and flexible piles, across all three pile slenderness ratios. For semi-rigid piles, the maximum displacement difference between K_{R1} and K_{R2} recorded during the last loading step is about 16.5% for a slenderness ratio D/B of 7, 15.5% for *D/B*=10, and 11.7% for *D/B*=20. For K_{R1} and K_{R3}, the maximum difference is approximately 33.1% for a *D/B*=7, 31.5% for a *D/B*=10, and 23.9% for *D/B*=20. For flexible piles, the maximum displacement difference between K_{R1} and K_{R2} is approximately 11.5% for *D/B*=7, 15.2% for *D/B*=10, and 12.8% for *D/B*=20. For K_{R1} and K_{R3}, the maximum difference is about 23.6% for a *D/B*=7, 32% for a *D/B*=10, and 25.7% for *D/B*=20.

We conclude that a decrease of 20 to 25 percent in the value of K_R for semi-rigid piles, and 7.5 to 20 percent for flexible piles, leads to doubling the pile deflection, confirming the highly significant effect of the K_R parameter on the response of piles under lateral loading.

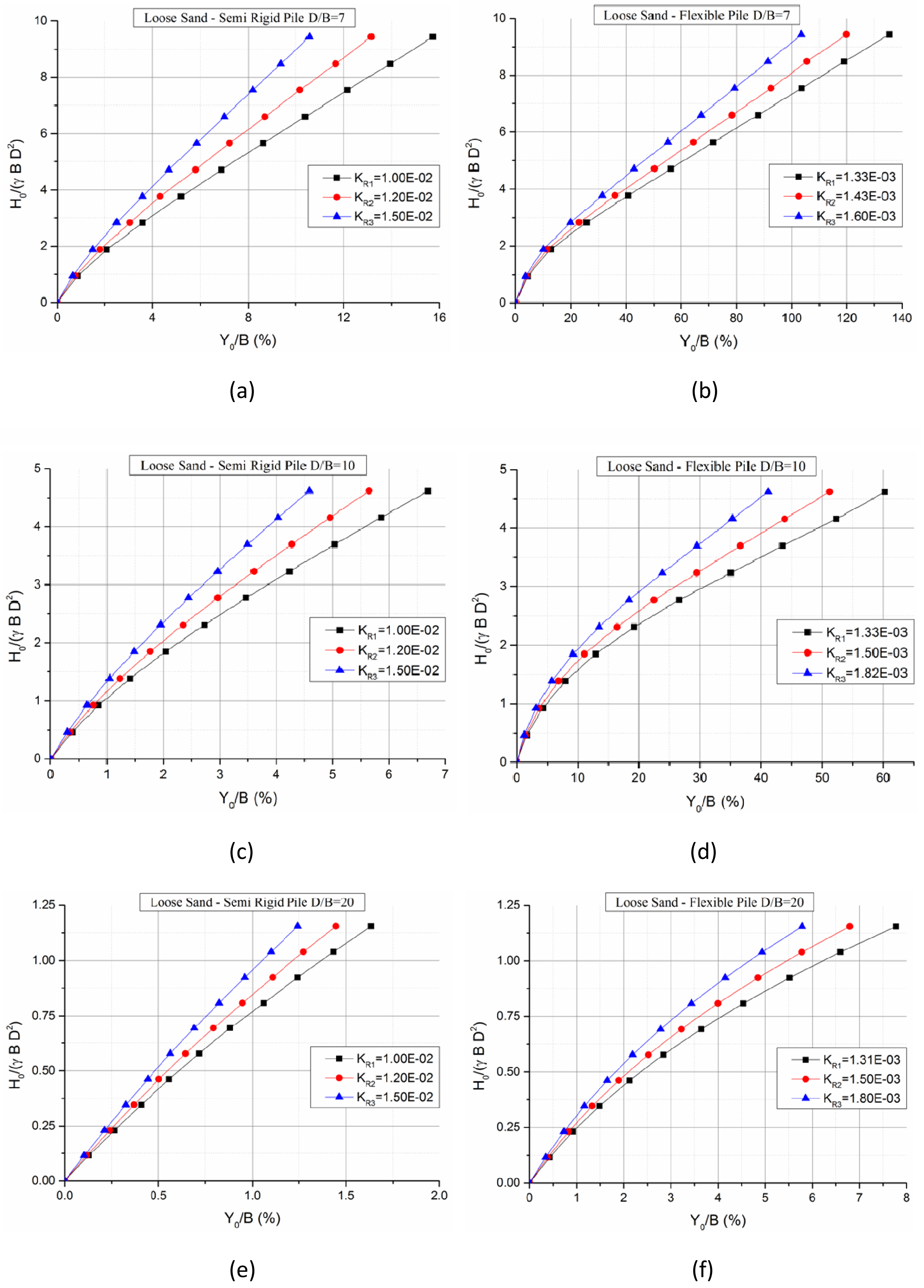

Figure 4. Effect of lateral pile/soil stiffness ratio on the behavior of the pile in saturated loose sand soil : (a) semi rigid pile with *D/B* = 7; (b) flexible pile with *D/B* = 7; (c) semi rigid pile with *D/B* = 10; (d) flexible pile with *D/B* = 10; (e) semi rigid pile with *D/B* = 20; (f) flexible pile with *D/B* = 20.

3.4 *Conclusion*

This paper presents a practical method for the construction of P-Y curves from Dynamic Penetration Test (DPT) data in sandy soils. The parametric study conducted on two categories of piles, semi-rigid and flexible, revealed the following findings in loose sands:

1. The water table level has a very weak effect regardless of the pile category and slenderness.
2. The slenderness ratio of the pile has a negligible effect on flexible piles and on semi-rigid piles with slenderness ratios of D/B=7 and D/B=10. However, a significant effect was observed for a slenderness ratio of D/B=20, showing a noticeable increase in deflection at the pile head for semi-rigid piles.
3. Conversely, the lateral soil/pile stiffness ratio has a highly significant effect for both pile categories, regardless of the pile slenderness. For a given loading, the pile head displacement increases with a decrease in the value of K_R.

These results highlight the importance of considering the K_R parameter in the design and analysis of piles subjected to lateral loads, as it represents the most influential parameter governing the pile response.

4 REFERENCES

- Baguelin, F. (1982). Rules for the Structural Design of Foundations Based on the Self-Boring Pressuremeter Test. Symposium on the Pressuremeter and its Marine Applications, Paris.
- Borden, R.H., Lawter, R.S. (1989). Load-Deflection Response of piles in Sand: Performance Prediction Using the DMT. Transportation Research Record No 1235, pp79-88.
- Bouafia, A. (2022). Contribution of the standard penetration test SPT to the design of pile foundations in sand– Practical recommendations. Journal of Engineering Research. DOI : 10.36909/jer.18763
- Bouafia, A., (2023). New P-Y curve formulation for laterally loaded single piles based on the pre-bored pressuremeter. Arab J Geosci 16, 684 (2023). https://doi.org/10.1007/s12517-023-11804-4
- Bouafia, A., & Lachenani, A (2004). Courbes P-Y des pieux isolés dans le sable – Détermination à partir de l'essai pressiométrique (in French). Rev. Fr. Geotech. 108 pp. 5–15.
- Laouedj, A. & Bouafia, A. (2022). P-Y curves for piles in sand based on the SPT test– Parametric study and practical recommendations. 5th International Conference on New Developments in Soil Mechanics and Geotechnical Engineering. Near East University, Northern Cyprus , NICOSIA.
- 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. (2017). Laterally loaded single piles - construction of P-Y curves from the cone penetration test. Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering ICSMGE, Seoul, Korea.

Bouafia, A., (2007). Single piles under horizontal loads in sand: Determination of P-Y curves from the prebored pressuremeter test. Geotechnical and Geological Engineering 25, 283-301.
- Gabr, M.A., Lunne, T., Powell, J.J. (1994). P-y Analysis of Laterally Loaded Piles in Clay Using DMT. Journal of Geotechnical Engineering, Vol 120, Issue 5, pp 816-837.
- Guo, F., Lehane, B.M., Ju, J. (2014). Experimentally derived CPT-based p-y curves for soft clay. The 3rd International Symposium on Penetration Testing CPT14, Las Vegas, Nevada, Vol 1, pp 1021-1028.
- Laouedj, A., & Bouafia, A. (2017). Pieux isolés sous charges latérales-construction des courbes P-Y à partir de l'essai SPT . Rev. Française de . Geotech., 152, 4.
- Li, H., Liu, S., Tong, L., Wang, K., Ha, S. (2018). Estimating p-y Curves for Clays by CPTU Method: Framework and Empirical Study. International Journal of Geomechanics, Vol 18, Issue 12, 10p.
- Li, H., Liu, S., Tong, L. (2019). Evaluation of lateral response of single piles to adjacent excavation using data from cone penetration tests. Canadian Geotechnical Journal, Vol 56, No 2, pp 236-248.
- Marchetti, S., Totani, G., Calabrese, M., Monaco, P. (1991). P-y Curves from DMT data for piles driven in clay. Proc. 4th Internat. Conf. DFI-Deep Foundation Institute USA on Piling and Deep Foundations, Stresa Italy, Vol.1, pp 263-272.
- Robertson, P.K., Davies, M.P., Campanella, R.G. (1989). Design of Laterally Loaded Driven Piles Using the Flat Dilatometer. Geotechnical Testing Journal, Vol 12, No 1, pp 30-38.
- Sail, Y., Bouafia, A., Zennou, I. & Khiri, A. (2022). Laterally loaded single piles – construction of the P–Y reaction curves from the DPT test in sandy soils, International Journal of Geotechnical Engineering, 16:7, 838-849,DOI:10.1080/19386362.2021.1933314.