Civil Engineering
Engengharia Civil

Contribution to the forecast of horizontal displacements in continuous flight auger piles in granular soil profile

http://dx.doi.org/10.1590/0370-44672021750056

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Abstract

This article presents a series of propositions for the prediction of horizontal displacements for continuous flight auger piles in granular soil profiles through modifying the parameters A_y and B_y from the method proposed by Matlock and Reese (1961). Empirical proposals were also presented for calculating the horizontal soil reaction coefficient (n_h) for granular soils. Data from ten horizontal static load tests, conducted in the city of Paulino Neves (State of Maranhão, Brazil) were used to develop and validate the propositions. The data regarding results of nine static load tests (PCH 1 to PCH 9) were used to develop the propositions, whereas results for PCH 10 and other data from other studies (Cases A and B) were used in the validation step. Modifying the parameters used in Matlock and Reese's method resulted in convergent and coherent predictions for all the propositions assessed in this study. In addition, predictions made for piles used in the validation phase yielded results very congruent with experimental displacements.

Keywords: Prediction, Horizontal displacements, Continuous flight auger piles.

1. Introduction

The prediction of horizontal displacements in piles is a topic that has been addressed in diverse ways by several authors. The most recent works have focused on numerical modeling (Abagnara, 2009; Faro, 2014; Abreu, 2014; Ballarin, 2016; Santos *et al*., 2016) that allows for more elaborate predictions. However, these tools usually demand more complex analyses and are performed at high computational costs.

The analytical methods (Miche, 1930; Hetenyi, 1946; Matlock and Reese, 1961) are simpler and have been used in studies like Guo and Lee (2011), who concluded that the equation proposed by Hetenyi (1964) is comparable to numerical approaches if Winkler's parameters are estimated using the load transfer factor described in his study. Del Pino Jr. (2003) and Albuquerque *et al*. (2019) obtained values for the horizontal coefficient of the soil using retro analysis, according to the method suggested by Matlock and Reese (1961). Zammataro (2007) showed that excluding the equation term that considers the distance between ground level and load application axis can influence the coefficient of horizontal soil reaction. Phanikanth *et al*. (2010) obtained new coefficients A_y and B_y for the equation proposed by Matlock and Reese (1960), whereas Silva (2017) verified that, for the piles assessed in his work, the method suggested by Hetenyi (1964) resulted in more accurate predictions for the horizontal displacements than those proposed by Miche (1930) and Matlock and Reese (1961).

However, it is worth mentioning that results of the analytical analyses might be discordant with experimental values, both due to its more simplistic nature and for the fact that they can be influenced by variables that do not contemplate the particularities of each situation or analyzed scenario.

In order to estimate horizontal displacements (y_o), Matlock and Reese (1961) proposed the following expression, which encompasses the dimensionless constants A_y and B_y and variables H (horizontal load), M (moment applied to pile head), T (relative pile-soil stiffness), E (deformation modulus), and I (moment of inertia):

$$y_0 = A_y \frac{HT^3}{EI} + B_y \frac{MT^2}{EI} \quad (1)$$

This study presents a contribution to the prediction of horizontal displacements in piles, through modifying the parameters used in the method proposed by Matlock and Reese (1961), using the experimental results from horizontal static load tests as a reference, aiming at obtaining more convergent predictions.

To this end, the coefficients A_y and B_y and the relative pile-soil stiffness parameter (T) from the equation proposed by Matlock and Reese (1961) were modified. Correlations were also proposed to obtain nh from the SPT N-values of sandy soils.

2. Materials e methods

In this study, horizontal static load tests were performed on ten continuous flight auger piles (workload of 30 kN), installed in the town of Paulino Neves, State of Maranhão, Brazil. The ten piles had 600 mm of diameter and their lengths varied from 16.96 to 28.08 m, as detailed in Table 1.

Table 1 – Lengths (L) of tested piles.

Pile	PCH 1	PCH 2	PCH 3	PCH 4	PCH 5	PCH 6	PCH 7	PCH 8	PCH 9	PCH 10
L (m)	19.04	16.96	28.08	19.12	21.12	27.04	25.12	27.04	22.08	26.08

One percussion drilling (SP) was conducted where each pile was executed. Figure 1 shows the results for drilling SP 02, conducted in the vicinity of PCH 2, exhibiting subsurface layers, water level, and SPT N-values along soil depth. Figure 2 shows the SPT N-values varying along the depth for all performed percussion drillings (SP 01 to SP 10).

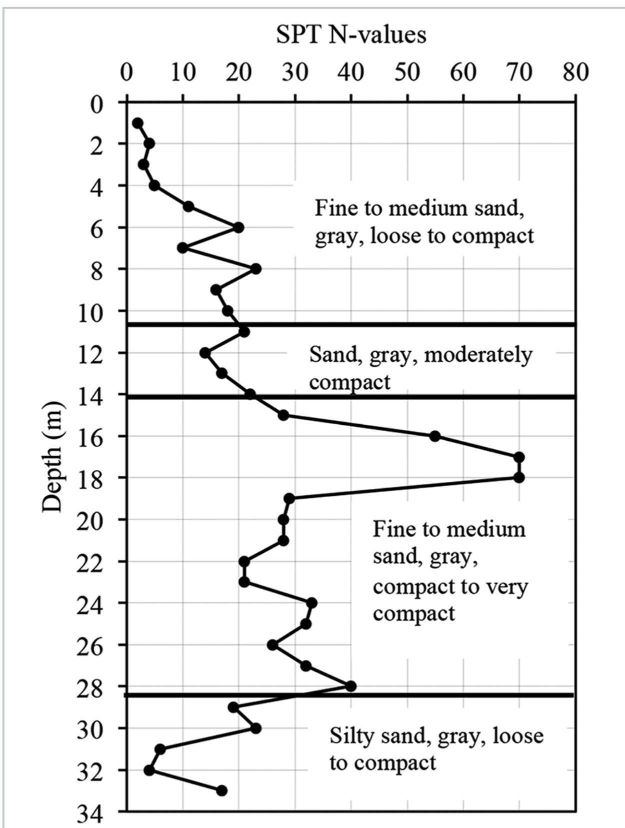

Figure 1 – Results for percussion drilling SP 02 (PCH 2).

As can be seen in Figure 1, the first layer was 2.35-m-thick, with fine-to-medium, gray sand, loose, with an average SPT N-value of 3. A water level was found at 0.35 m below ground level. The second layer was 9.47-m-thick (between the depths of 2.35 m and 11.82 m), with fine, gray silty-sand, loose to compact, with an average SPT N-value of 14. The third layer was a clayey-sand, gray in color, moderately compact to compact, from 11.82 m to 14.20 m below ground level, and average SPT N-value of 19. The fourth layer was a fine-to-medium sand, gray in color, compact to very compact, from 14.20 m to 28.10 m below ground level, and average SPT N-value of 36. Finally, the last layer was a gray silty-sand, loose to compact, from 28.10 m to 33.0 m below ground level, and average SPT N-value of 14.

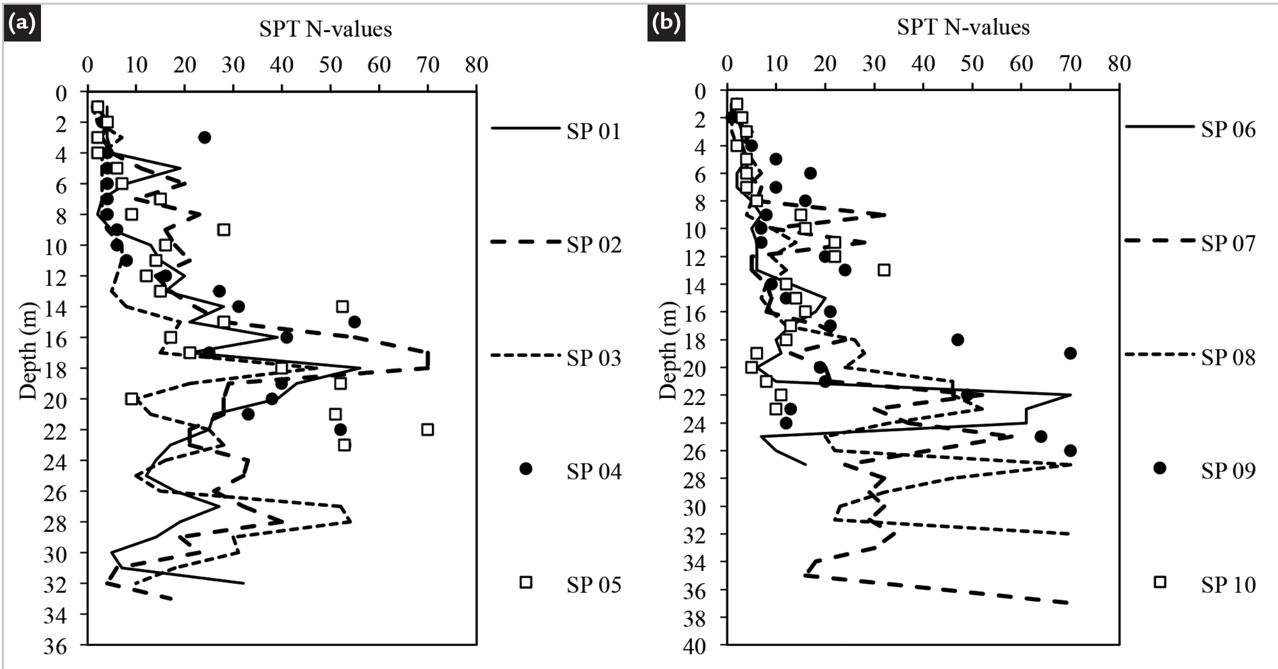

Figure 2 – SPT N-values along soil depth for drillings (a) SP 01 to SP 05 and (b) SP 06 to SP 10.

As shown in Figure 2, the SPT N-values varied between 1 and 7 up to a depth of 4 m, except for drilling SP 04, with a SPT N-value of 24 around 3 m below ground level. Between 5 m and 13 m in depth, the SPT N-values varied up to 32, and above 14 m in depth, the SPT N-values varied between 8 and 70.

The horizontal load tests were conducted following the recommendations of the Brazilian technical standard NBR 12131/2006 (Piles – Static load test – Method of test) for the rapid test. The loading was conducted in sixteen stages, each of them maintaining the load for 10 minutes, with the respective displacements being measured during each stage. At maximum load, displacements were measured at 10 min, 30 min, 60 min, 90 min, and 120 min.

The used measurement system consisted of a hydraulic jack-pump set and two 0.01 mm precision gauges and a 5 cm stroke, installed on a metal beam at the same level of application of the loads. Two precision gauges were also used to check the stability of the reaction anchor system, which consisted of concrete blocks.

The unloading comprised five stages, with displacements being measured every 10 min, except for the last stage, where two measurements were made (at 30 min and 60 min). It is worth mentioning that in each stage, the load corresponded to 10% of the pile horizontal workload and in the unloading stages, to 32% of pile horizontal workload. Figure 3 illustrates the load test performed *in loco*.

Figure 3 – Horizontal load test performed *in loco*.

In order to obtain coefficients A_y and B_y of Matlock and Reese's equation (Matlock and Reese, 1961) and the relative pile-soil stiffness parameter (T) for the propositions developed in this study which would be consistent with the horizontal load tests experimental values, the authors used the Least squares method and the Generalized reduced gradient (GRG) algorithm.

And to obtain the propositions for the correlation regarding parameter nh based on SPT N-values, a range of displacements was taken as a reference (from 0.59 mm to 1.53 mm), considering the largest displacements obtained in each load test. This was used to obtain nh values through retro-analysis. The mean SPT N-value was also considered for the superficial soil layer (soil depth between 0 m and 2 m), where the largest horizontal displacements usually occur. Then two equations that correlated the variables nh and SPT N-values were obtained through nonlinear regression, for the considered range of displacements.

As to the two proposed correlations (Propositions 1 and 2), the first one was for soils of diverse types, which considered results from 14 horizontal load tests: 4 executed by the authors, 1 by Marzola (2016), 1 by Araújo (2013), 3 by Zammataro (2007), 3 by Miranda Jr. (2006), and 2 by Del Pino Jr. (2003). The second proposition considered 9 PCH results, but from piles executed exclusively in sandy soils: 5 performed by the authors, 1 by Marzola (2016), 1 by Araújo (2013), and 2 by Del Pino Jr. (2003).

In the validation step, data regarding piles PCH 10, HC1-A (from Araújo, 2013), called Case A, and PC1-DP and PC4-DP (from Del Pino Jr., 2017), called Case B, were used. Table 2 presents the characteristics of Case A and Case B piles. Figure 4 shows the soil profiles obtained through the percussion drilling for Cases A and B.

Table 2 – Characteristics of piles from other works used in the validation step.

Case	Author	Pile	Type	Features
A	Araújo (2013)	HC1-A	Continuous flight auger pile	Ø 600 mm, e = 200 mm, L = 10 m(*)
B	Del Pino Jr. (2017)	PC1-DP, PC4-DP	Mechanically augered bored piles	Ø 320 mm, e = 158 mm, L = 8.71 m

(*) Ø = pile diameter; e = distance from point of application of horizontal load to ground level; L = pile lenght.

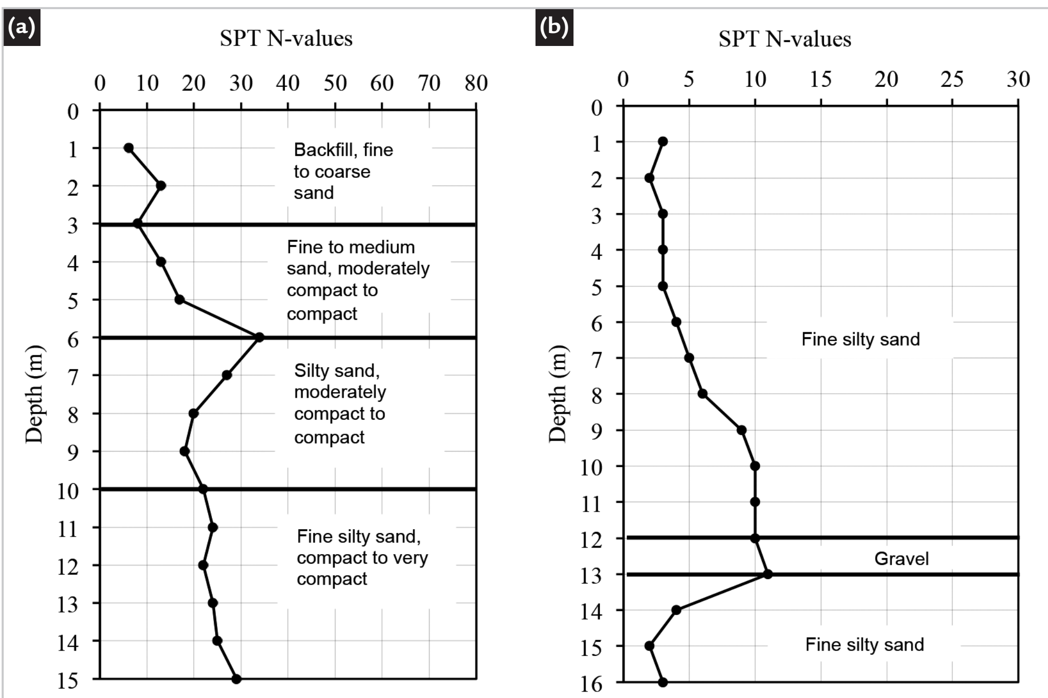

Figure 4 – Soil profiles from other authors used in the validation stage: (a) Case A and (b) Case B.

As can be seen in Figure 4, the soil in Case A (Figure 4a) consisted of a fine-to-coarse sand, moderately compact to compact, with SPT N-values ranging from 6 to 30. Soils in Case B (Figure 4b) were also predominantly sandy, except for one gravel layer, located between12 m to 13 m below ground level.

3. Results and discussion

Figure 5 shows the results for all horizontal load tests (Figure 5a) and also the results for the two piles that had the largest (PCH 3) and the smallest (PCH 8) residual displacements (Figure 5b).

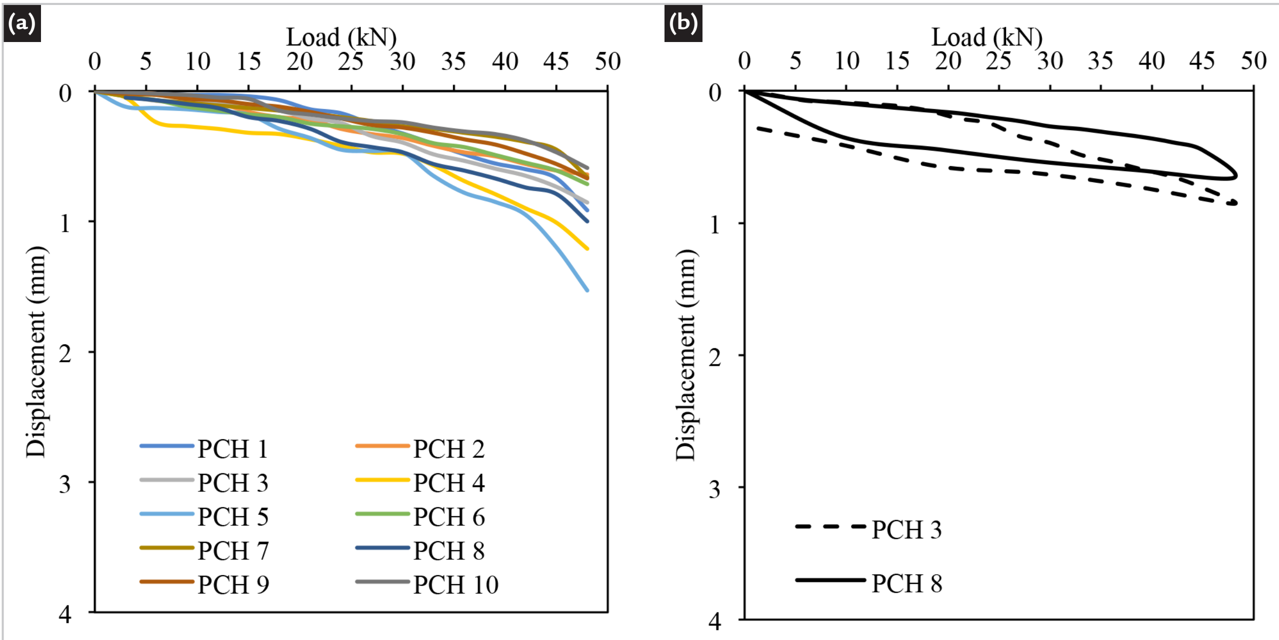

Figure 5 – Load versus displacement curves obtained in the horizontal load tests: (a) for all performed PCHs (PCH 1 to PCH 10) and (b) for the largest (PCH 3) and smallest (PCH 8) residual displacements, considering loading and unloading stages.

As shown in Figure 5, the displacements measured in the horizontal load tests varied between 0.24 mm and 0.48 mm for the pile workload (30 kN) and between 0.59 mm and 1.53 mm for the maximum test load. The smallest residual displacement occurred in PCH 8, which was zero, and the largest for PCH 3 (0.26 mm).

Since the curves in Figure 5 presented a linear behavior and the displacement levels were quite small, it is possible to state that no piles failed and that all of them were working in the elastic regime.

Using the Least squares method, the coefficients Ay and By were determined for all piles as 0.10 for A_y and 0.65 for B_y ($R^2 = 0.78$). This method was called Modified II. Method Modified I was developed by the authors and described in a different study but was not included in the analyses performed in this research.

Figure 6 illustrates the comparison between displacements predicted using method Modified II (i.e., proposed coefficients Ay and By) and Cintra's method (Cintra, 1982) and experimentally measured displacements for piles PCH 1 and PCH 9. Cintra's method is considered by the authors to be the most complete method to estimate horizontal displacements under loads applied above the soil surface, this being the reason it was included among the methods assessed herein.

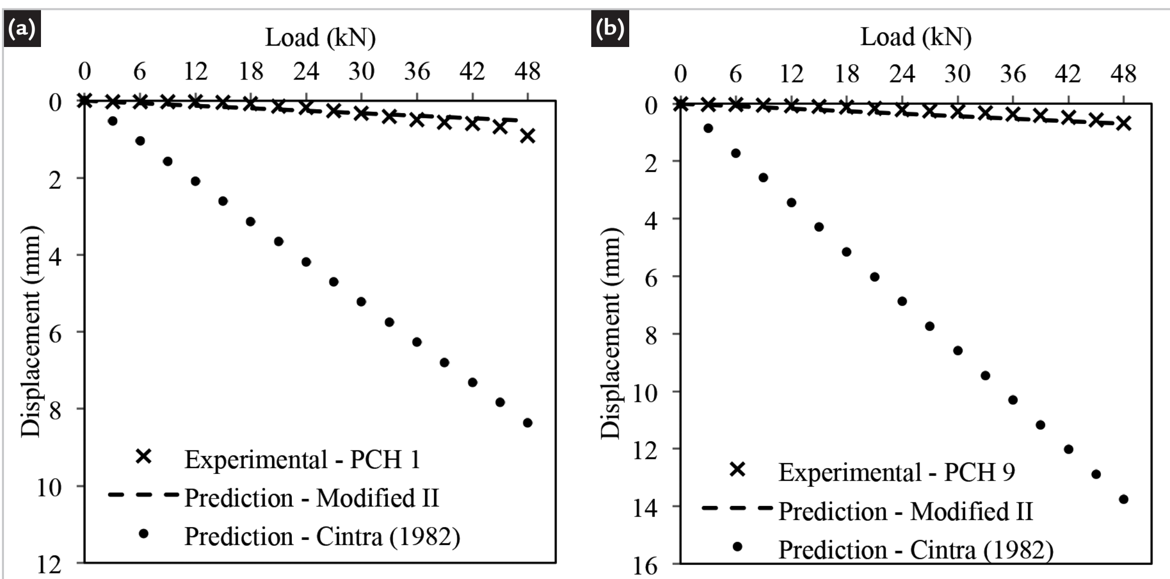

Figure 6 – Comparison between displacements predicted by coefficients A_y and B_y (Modified II method), Cintra's method, and experimentally measured displacements for piles PCH 1 and PCH 9.

As seen in Figure 6, the percentage difference between the displacements predicted by method Modified II and those obtained experimentally for piles PCH 1 and PCH 9 considering a pile workload of 30 kN was of 56% (~ 0 mm). These piles had the smallest and largest percentage differences obtained in this study. Predictions made using Cintra's method resulted in a percentage difference of 1,507% for PCH 1 and of 2,967% for PCH 9. Figure 7 shows the correlation obtained for n_h for different soil types and Figure 8, for sandy soils exclusively.

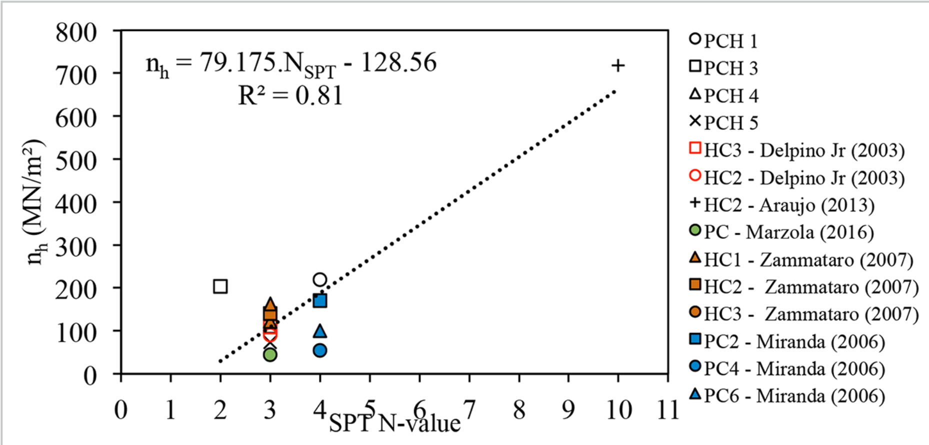

Figure 7 – Proposition 1: Correlation n_h *versus* SPT N-values for distinct types of soil.

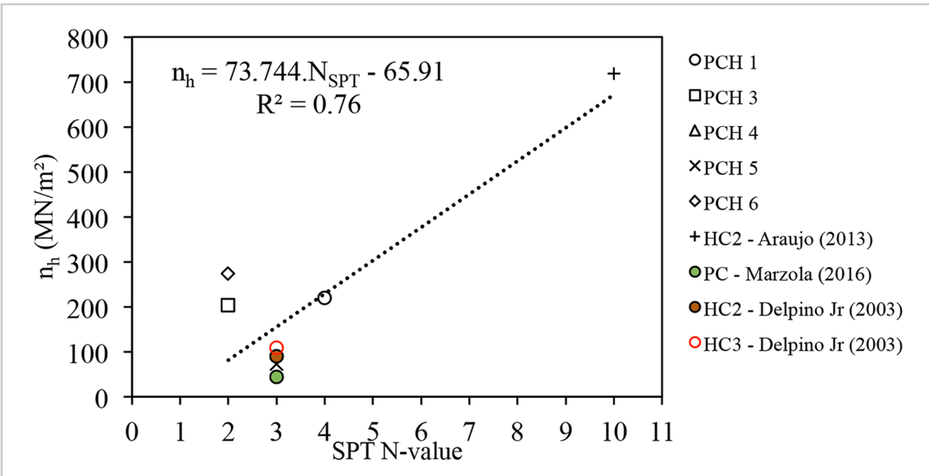

Figure 8 – Proposition 2: Correlation n_h *versus* SPT N-values for sandy soils only.

As mentioned before, the authors used the data regarding the pile related to PCH 10 and the piles described in Table 2 in order to validate: (i) Proposition 1 (correlation nh versus SPT N-values for different types of soil); (ii) Proposition 2 (correlation nh versus SPT N-values for sandy soils only); (iii) Modified II method (for coefficients A_y and B_y); and (iv) for the relative pile-soil stiffness parameter (T = 0.90). Results are displayed in Figures 9, 10 and 11. It is worth mentioning also that Proposition 2 showed an inconsistency for SPT N-values lower than two.

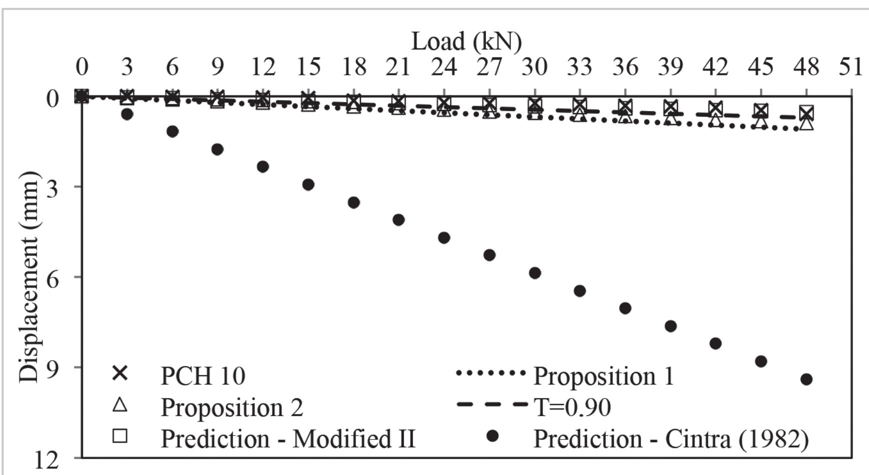

Figure 9 – Comparison between propositions to predict displacements for PCH 10 and experimental results.

As mentioned before, the authors used the data regarding the pile related to PCH 10 and the piles described in Table 2 in order to validate: (i) Proposition 1 (correlation nh versus SPT N-values for different types of soil); (ii) Proposition 2 (correlation nh versus SPT N-values for sandy soils only); (iii) Modified II method (for coefficients A_y and B_y); and (iv) for the relative pile-soil stiffness parameter (T = 0.90). Results are displayed in Figures 9, 10 and 11. It is worth mentioning also that Proposition 2 showed an inconsistency for SPT N-values lower than two.

According to Figure 9, the proposition that provided the best predictions when compared to the experimental displacements for PCH 10 was the Modified II method, with a percentage difference of 38% (0.09 mm), considering a workload of 30 kN. Predictions made using Cintra's equation (Cintra, 1982) showed a percentage difference was of 2,344%. All the other propositions in this study resulted in very consistent and coherent predictions when compared to the experimental results.

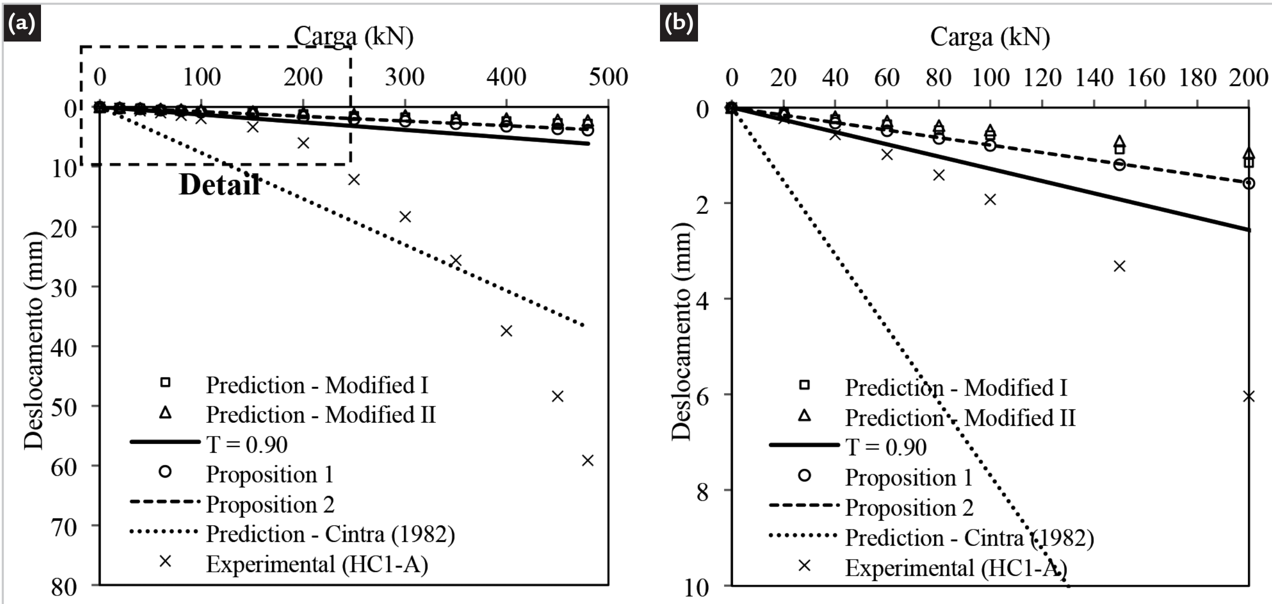

Figure 10 – Case A. Validation for pile HC1-A (Araújo, 2013): (a) complete load versus displacement curve; (b) detailed view of the curve.

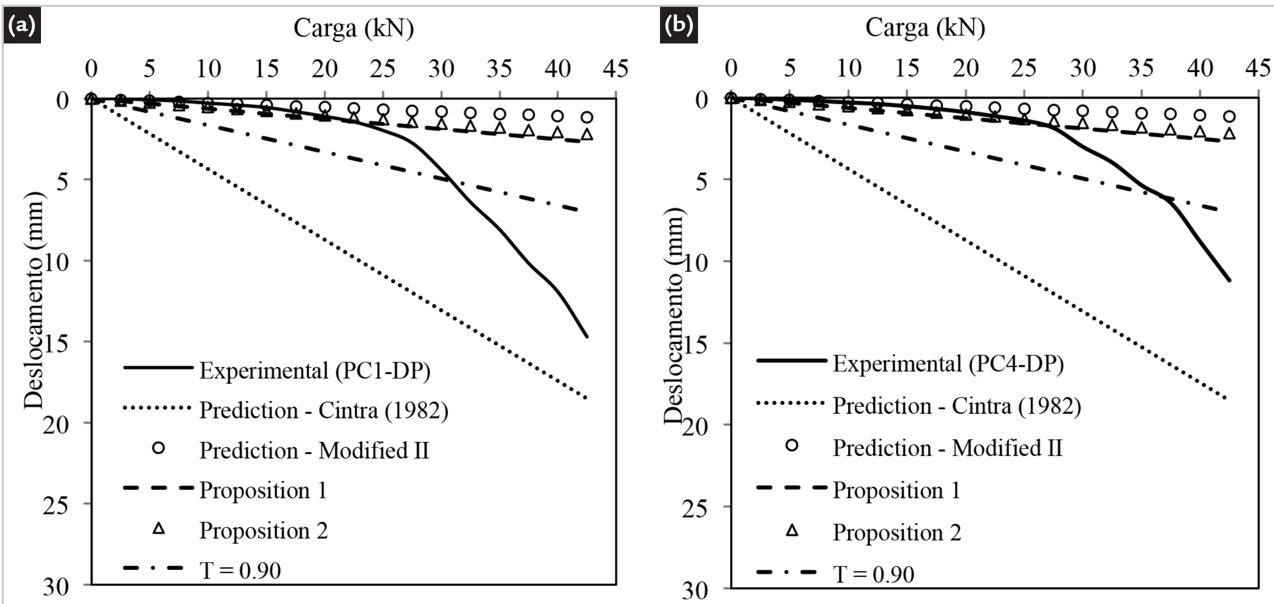

Figure 11 – Case B. Validation for piles (a) PC1-DP and (b) PC4-DP.

As seen in Figures 10 and 11, among the propositions presented in this study, the one providing the best convergence for Case A was that of T parameter (T = 0.90), with a percentage difference of 33% (0.63 mm) when compared to the experimental results for HC1-A pile under a load of 100 kN.

Regarding Case B, the proposition which resulted in the best convergence for PC1-DP pile was also the T parameter (T = 0.90), with a percentage difference of 12% (0.53 mm). As to PC4- DP pile, the best one was Proposition 1, with a percentage difference of 37% (0.96 mm), considering the load of 30 kN, which is the workload of the piles assessed in this research. It should be highlighted that all propositions here presented also had a particularly satisfactory performance for small horizontal displacements.

4. Conclusions

In this study, propositions were made to predict horizontal displacements based on modifications in (i) Matlock and Reese's equation (1961) – coefficients A_y and B_y –, (ii) relative pile-soil stiffness parameter (T), and (iii) horizontal reaction coefficient (n_h).

Analyzing the convergence of the results from the horizontal displacements in relation to pile diameter (y/D), the predictions for PCH 10 pile converged to a y/D of 0.1% and for HC1-A pile (Case A), to 0.6%. For the piles in Case B (PC1-DP and PC4-DP), the average y/D ratio found was 1.2%. Thus, it was verified that all the propositions presented herein were coherent with experimental values for small horizontal displacements as occurred in the analyzed dataset.

Acknowledgements

The authors would like to thank the Post-graduate Program in Civil Engineering at the Department of Hydraulic and Environmental Engineering (POSDEHA), the Federal University of Ceará, the Brazilian Federal Agency for Support and Evaluation of Postgraduate Education (CAPES), and the companies Tecnord and Rocha Brasil.

References

ABAGNARA, V. ***Modellazione e analisi di pali sotto carichi orizzontali.*** 2009. 463 f. Tesi (Dottorato in Ingegneria delle Costruzioni) - Facoltà di Ingegneria, Università degli Studi di Napoli Federico II, Napoli, 2009.

ABREU, J. A. ***Avaliação do comportamento de grupos de fundação carregados lateralmente em solo poroso colapsível e tropical do distrito federal.*** 2014. 177 f. Dissertação (Mestrado em Geotecnia) – Faculdade de Tecnologia, Universidade de Brasília, Brasília, 2014.

ALBUQUERQUE, P. J. R.; CARVALHO, D.; KASSOUF, R.; FONTE Jr., N. L. Behavior of laterally top-loaded deep foundations in highly porous and collapsible soil. ***Journal of Materials in Civil Engineering,*** v. 31, n. 2, 2019.

ARAÚJO, A. G. D. ***Provas de carga estática com carregamento lateral em estacas escavadas hélice continua e cravadas metálicas em areia.*** 2013. 221 f. Dissertação (Mestrado em Engenharia Civil) – Centro de Tecnologia, Universidade Federal do Rio Grande do Norte, Natal, 2013.

BALLARIN, R. C. ***Análise estática de estacas carregadas lateralmente.*** 2016. 44 f. Trabalho de conclusão de curso (Bacharelado em Engenharia Civil) – Faculdade de Tecnologia, Universidade de Brasília, Brasília, 2016.

CINTRA, J. C. A.; ALBIERO, J. H. Determinação do coeficiente de reação horizontal do solo (nh) através de provas de carga lateral em estacas. *In*: CONGRESSO BRASILEIRO DE MECÂNICA DOS SOLOS E ENGENHARIA DE FUNDAÇÕES, 7., 1982, Recife. ***Anais [...].*** Recife: ABMS, 1982. v. 2, p. 123-138.

DEL PINO JÚNIOR, A. ***Análise do comportamento de estacas do tipo broca escavada com trado mecânico, solicitadas por esforços transversais.*** 2003. 164 f. Dissertação (Mestrado em Engenharia Civil) – Faculdade de Engenharia de Ilha Solteira, Universidade Estadual Paulista, Ilha Solteira, 2003.

FARO, V. P. ***Carregamento lateral em fundações profundas associadas a solos tratados:*** concepção, provas de carga e diretrizes de projeto. 2014. 349 f. Tese (Doutorado em Engenharia) – Escola de Engenharia, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2014.

GUO, W. D.; LEE, F. H. Theoretical load transfer approach for laterally loaded piles. ***International Journal of Numerical and Analytical Methods in Geomechanics,*** v. 25, n. 11, p. 1101-1129, 2001.

HETENYI, M. ***Beams on elastic foundation:*** theory with applications in the fields of civil and mechanical engineering. Ann Arbor: University Michigan Press, 1946.

MATLOCK, H. ; REESE, L. C. Foundation analysis of offshore pile supported structures. *In*: INTERNATIONAL CONFERENCE ON SOIL MECHANICS AND FOUNDATION ENGINEERING, 5., 1961, Paris. ***Proceedings [...].*** Paris: [*s. n.*], 1961. p. 91-97.

MICHE, R. J. Investigation of piles subject to horizontal forces : application to quay walls. ***Journal of the School of Engineering,*** Giza, n.4, 1930.

PHANIKANTH, V. S.; CHOUDHURY, D.; REDDY, G. R. Response of single pile under lateral loads in cohesionless soils. ***Electronic Journal of Geotechnical Engineering,*** v. 15, Bund-H, 2010.

SANTOS, I. C. P. *et al*. Efeito da interação solo-estaca na geração de momentos internos de uma estaca carregada horizontalmente. *In*: CONGRESSO BRASILEIRO DE MECÂNICA DOS SOLOS E ENGENHARIA GEOTÉCNICA, 18., 2016, Belo Horizonte. ***Anais[...].*** Belo Horizonte, Brasil: ABMS, 2016.

SILVA, A. L. S. ***Avaliação de previsões de deslocamento e carga de ruptura horizontal utilizando estacas escavadas de tamanho reduzido em perfil de solo areno-siltoso.*** 2017. 119 f. Dissertação (Mestrado em Geotecnia) - Centro de Tecnologia, Universidade Federal do Ceará, Fortaleza, 2017.

ZAMMATARO, B. B. ***Comportamento de estacas tipo escavada e hélice contínua, submetidas e esforços horizontais.*** 2007. Dissertação (Mestrado em Engenharia Civil) – Faculdade de Engenharia Civil, Arquitetura e Urbanismo, Universidade Estadual de Campinas, Campinas, 2007.

Received: 29 July 2021 - Accepted: 20 January 2022.