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Contribution for a root pile installation control approach using a digital odometer

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Article

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Bearing Capacity

Abstract

A root pile is a form of injection pile (cast-in-place with pressure, with very distinct construction aspects from the known micropile type). During the mortar shaft development, these piles are inserted using distinct injection pressures of up to 500 kPa. Static load tests are typically used to control root piles, which can be an expensive and time-consuming testing procedure. Static load tests were performed on eight monitored piles with diameters of 350 and 410 mm to investigate root pile performance control during pile installation. This research presents a refined and developed alternative methodology for confirming root pile performance using a digital odometer attached to the drill rig's rotatory head. The methodology consists of monitoring variables obtained during pile installation related to pile bearing capacity. Moreover, empirical equations with simple and relevant applications to estimate root pile bearing capacity during installation are proposed. The developed equations produced results consistent with the values obtained from static load testing on the test piles. Therefore, the results suggest that the proposed methodology is a viable alternative for root pile performance control.

1. Introduction

Pile foundations have been used as load-bearing and load transferring systems for many years. More recently, the increased demand for housing and building has compelled companies to improve pile construction productivity, resulting in the development of numerous innovative pile installation techniques.

In the last decade, root piles have become a widespread alternative (Moura et al., 2015; Lima & Moura, 2016; Monteiro et al., 2019), especially in pile foundation strengthening and complex geological circumstances involving rock strata profiles (Ding et al., 2017). Single root pile testing is frequently included in project specifications for large construction projects. Compression static load testing is the most common type of root pile performance control and certainly, the most reliable method to determine bearing capacity and load–settlement relationships (Russo, 2012). The static load test is simple to perform and analyze. However, practical issues arise when performing static load tests with limited access, such as the reaction system setup, which can be time-consuming and expensive.

Many researchers have investigated the performance of root piles, such as Cadden et al. (2004), Huang et al. (2007), Moura et al. (2015), Lima & Moura (2016), Monteiro et al. (2019). Other studies were conducted focusing on other types of piles but also sharing other important conclusions (Lin et al., 2004; Liang & Yang, 2006; Herrera et al., 2009; Basu et al., 2010; Alzo'Ubi & Ibrahim, 2018; Pari et al., 2019). However, root pile installation control has rarely been studied directly. Monteiro et al. (2019) proposed an alternative approach to the root pile installation control, helping in the decision-making during field construction concerning the definition of the pile length to be installed. The preliminary methodology proposed by the authors consists of monitoring installation variables related to the root pile bearing capacity and using them as inputs of empirical equations developed in their research.

The undrained soil shear strength can be determined from the measurement of torque and assuming a prescribed shear stress profile along the potential cylindrical failure surface. Therefore, it can be emphasized that torque is a variable that must influence the soil shear strength (Cabalar et al., 2020; Baroni & Almeida, 2022). Regarding pile foundation construction, it can be verified that torque measurements are

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often performed during the installation of continuous flight auger piles. However, this measurement is not performed in the field during the root pile installation due to the lack of built-in equipment in the drilling system for torque measurement.

The current research establishes the literature gap filled by the alternative approach to the root pile installation control proposed by Monteiro et al. (2019) and proposes an improved method for assessing root pile performance. For this purpose, root pile installation variables related to bearing capacity were monitored, and data was collected in experimental fields using a wireless sensor (a speedometer coupled with four magnets) connected to the rotating head of a drill rig. The data was used to develop three empirical equations to estimate the ultimate bearing capacity (Q_{ult}) of root piles and evaluate their performance during installation.

The improvements in this research aim to obtain more accurate field data (i.e. with fewer embedded errors due to using four magnets instead of only one) and to develop a better model with better statistical performance than that proposed by Monteiro et al. (2019). This was achieved by upgrading data acquisition equipment, adding a few more piles to the monitored group, and introducing the injection pressure variable in the proposed empirical equations. The methodology was tested and calibrated on eight root piles with lengths between 7.7 to 18 m, installed in 5 different experimental fields in the city of Fortaleza, State of Ceará, Brazil. In order to conduct pile performance assessment during their installation, it is necessary to estimate Q_{ult}, which requires one (or more) expressions to determine minimum pile length. N_{SPT} blow counts, pile geometry, drill bit penetration (advancing) velocity, and drill bit linear velocity were monitoring variables suggested by Monteiro et al. (2019) to estimate pile length and Q_{ult}, which were also contemplated in the development of the current research.

2. Root pile installation procedure

The installation of root piles comprises the following stages, as shown in Figure 1: (i) determining pile location; (ii) positioning of equipment and verification of verticality and inclination angle; (iii) drilling; (iv) inserting reinforcement bar; (v) filling pile hole with mortar; (vi) removing drill pipe with simultaneous application of compressed air.

Root piles possess a specific installation procedure that, depending on local conditions and soil characteristics, provides various advantages over other piles. Some advantages of this type of pile can be described as minimal vibration, drilling in rock strata, and small-sized equipment, which allows it to be operated in sites with limited heights and on varying slopes. However, root pile performance is currently controlled only after installation via static load tests.

3. Methodology

In this study, a wireless digital speedometer was used to monitor the variables of interest during pile installation. Figure 2 shows the monitoring apparatus installed on the rotating head of the drill rig. The diameter of the rotary drill was manually informed to the speedometer in each case so that the sensor (oedometer) could log each complete lap performed by the rotary drill (with the help of the four magnets). Each time a magnet passes by the sensor, it registers a quarter of the linear length of the circumference previously informed to the speedometer. This approach allowed monitoring the linear distance the rotary drill performed during pile installation.

The drilling rod used to drill the last meter of pile length was also subdivided into sections of 10 and 20 cm (as shown in Figure 3), aiming to track the advancing velocity (V_a) and

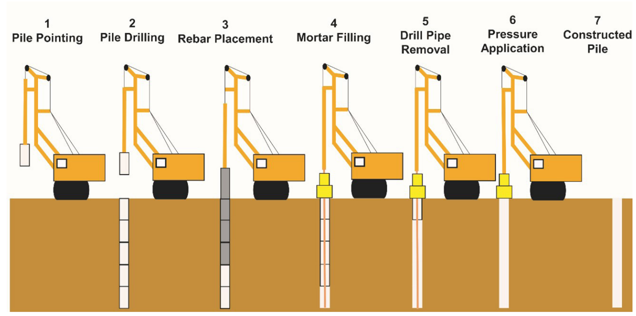

Figure 1. Root pile installation stages.

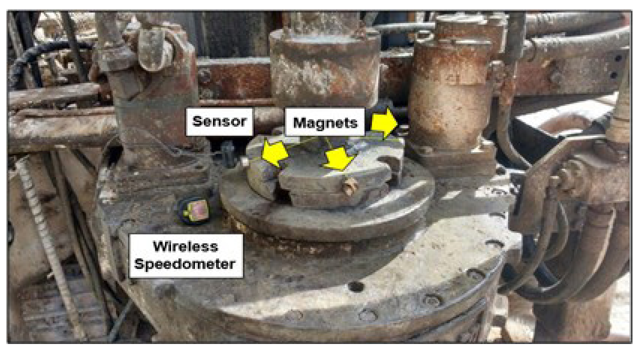

Figure 2. Monitoring equipment.

Figure 3. Marked sections on the last meter of the drilling rod.

linear velocity (V_b) of the rotary drill during the drilling of these sections. This installation control procedure was only applied during the last meter of pile length due to constructive productivity. In case this procedure is implemented for the entire pile shaft, a considerable constructive production reduction would be observed.

Many semi-empirical bearing capacity methods present a relation between pile bearing capacity and N_{SPT} values. In some methods, the N_{SPT} value of the soil underneath the pile toe is considered for computing the toe bearing capacity (Meyerhof, 1976; Décourt & Quaresma, 1978; Bazaraa & Kurkur, 1986; Shariatmadari et al., 2008). On the other hand, other often employed methods consider only the soil at the toe level (Aoki & Velloso, 1975; Cabral, 1986; Alonso, 1996), which will depend on the pile failure mechanism being considered. Therefore, in this research, the latter assumption was considered. It could also be mentioned that pile diameters range from 0.31 to 0.41 m, which are relatively small diameters regarding the pile stress bulb below the pile tip level.

The number of rotations performed was calculated as the relationship between the linear distance traveled by the rotary drill and its circumferential length. This was used to determine the frequency (i.e., number of rotations per minute) and the rotary drill's angular velocity (ω_r), as shown in Equation 1. Since the rotary drill and the drill bit are mechanically attached (as seen in Figure 2), their angular velocities (ω_r and ω_b) are equivalent:

$$2\pi f = \omega_r = \omega_b \tag{1}$$

The drill bit's radius (R_b) is a known variable. Hence, the drill bit's linear velocity (V_b) can be obtained (Equation 2):

$$V_b = \omega_b R_b \tag{2}$$

The development of the empirical equations for the performance control of root piles during installation was initiated by selecting variables that would be comfortably obtained in the field since the goal is to propose an empirical method with simple application in the performance assessment process.

Two variables related to pile bearing capacity were obtained during the monitoring of test piles: (i) drill bit's linear velocity (V_b), which is associated with shaft bearing capacity (Q_s); and (ii) drill bit's advancing velocity (V_a), associated with toe bearing capacity (Q_{toe}).

Following what was suggested by Monteiro et al. (2019), in addition to V_a and V_b, other variables were also considered: Toe resistance index ($N_{SPT,toe}$, which corresponded to the average N_{SPT} value at the pile tip, that is, last meter); Average shaft resistance index ($N_{SPT,shaft}$, average N_{SPT} values along pile shaft); Pile diameter (D); Pile length (L); Pile perimeter (U); and Pile toe cross-sectional area (A_p). Energy corrections were not applied to the N_{SPT} values in this research. However, Décourt et al. (1989) describe that the Brazilian SPT average efficiency is about 72%.

In static load tests, the ultimate bearing capacity (Q_{ult}) is reached when a rapid movement happens under constant or slight load increase. However, it is quite uncommon for a pile to reach a plunging failure load (Fellenius, 2021). In this study, static load tests were performed, and Van der Veen's extrapolation was applied (van der Veen, 1953) since a distinct plunging ultimate load (Q_u) was not obtained for most of the monitored piles.

In order to correlate the monitored variables and pile ultimate load (Q_u), it was necessary to estimate the load distribution along shaft and toe (Monteiro et al., 2019). The Brazilian standard NBR 6122 states that shaft resistance should correspond to 80% of the total load for bored piles, and the rest should be provided by the toe (ABNT, 2010).

Since no instrumentation of the static load tests was performed in this research, three distinct scenarios were considered: (i) shaft resistance carrying 80% of total bearing capacity and toe resistance, the other 20%, as suggested by NBR 6122 ($Q_{u,\ 80/20}$); (ii) toe resistance carrying 10% and shaft resistance, 90% of total load capacity ($Q_{u,\ 90/10}$); and (iii) shaft alone carries the load (100% of total bearing capacity, $Q_{u,\ 100/0}$). These are all viable alternatives, and choosing the expression to be applied in a real case will depend on the personal decision of the engineer, who could also use them all to evaluate potential field situations.

Multiple linear regression analysis (MLR) was used to establish the relationship between one dependent variable and several independent variables, following the generic expression shown in Equation 3:

$$Y = a_0 + a_1 X_1 + a_2 X_2 + \ldots + a_n X_n \tag{3}$$

where:

Y is the dependent variable (in this case, Q_{toe} or Q_s);
$X_1, X_2, \ldots, X_n$ are the independent variables;
$a_1, a_2, \ldots, a_n$ are coefficients of the independent variables (regression coefficients); and
a_0 is a constant that represents the portion of Y not explained by the independent variables.

The final expressions were obtained through the least-squares method (slightest deviation between observed and predicted values) and should be solved considering multiple linear functions of three variables, X_1, X_2, and X_3 (Equations 4 to 7):

$$\sum Y = n.a_0 + a_1 \sum X_1 + a_2 \sum X_2 + a_3 \sum X_3 \tag{4}$$

$$\sum YX_1 = a_0 \sum X_1 + a_1 \sum X_1^2 + a_2 \sum X_1 X_2 + a_3 \sum X_1 X_3 \tag{5}$$

$$\sum YX_2 = a_0 \sum X_2 + a_1 \sum X_2 X_1 + a_2 \sum X_2^2 + a_3 \sum X_2 X_3 \tag{6}$$

$$\sum YX_3 = a_0 \sum X_3 + a_1 \sum X_3 X_1 + a_2 \sum X_3 X_2 + a_3 \sum X_3^2 \quad (7)$$

Using the field data as inputs for variables Y, X_1, X_2, and X_3, the multiple linear regression model was implemented, and the coefficients a_0, a_1, a_2, and a_3 were determined. An exponential model with log-transformation of variables was used in this step, considering that the relation between bearing capacity variables in usual prediction methods is not linear. Equations 8 and 9 show how this log transformation was implemented:

$$Y = a_0 * X_1^{a_1} * X_2^{a_2} * \ldots * X_n^{a_n} \quad (8)$$

$$ln(Y) = ln(a_0) + a_1 * ln(X_1) + a_2 * ln(X_2) + \ldots + a_n * ln(X_n) \quad (9)$$

Hence, the three empirical equations to assess performance control of root piles during the installation step were established as below (Equations 10, 11, and 12):

$$Q_u = Q_s + Q_{toe} \quad (10)$$

$$Q_{toe} = a_o^{'} . (A_p)^{a_1} . (V_a)^{a_2} . (N_{SPT,toe})^{a_3} \quad (11)$$

$$Q_s = a_o^{''} . (V_b)^{a_4} . (U.L)^{a_5} . (p)^{a_6} . (\bar{N}_{SPT,\ shaft})^{a_7} \quad (12)$$

where:
p is the injection pressure.

4. Site description and soil profile

In this study, root pile foundations were installed and monitored in five construction sites in northeastern Fortaleza, State of Ceará, Brazil. Standard penetration tests and rock core borings were conducted at all five sites.

At site A, where test piles P1 and P2 were installed, the groundwater level is found at -3 m. A clayey silt layer is found between the ground surface and a depth of 5 m, with N_{SPT} values varying from 16 to 60. Below, there is a 10-m-thick layer of sandstone with *RQD* (Rock Quality Designation index) ranging from 43% to 54%, with N_{SPT} values ranging from 48 to 60. (Figure 4)

At Site B, where test piles P3 and P4 were installed, a clayey sand layer is found between the ground surface and a depth of 11 m, with N_{SPT} values varying between 3 and 60. Then, a 5-m-thick layer of silty clay soil, with N_{SPT} values ranging from 29 to 60, is found. The bedrock was located at -16 m and the groundwater level at -1.2 m. (Figure 5)

Site C (test pile P5) has its groundwater level located between -6.7 m to -7.4 m. A silty sand layer is found between the ground surface and -4 m, with N_{SPT} values varying between 2 and 4. An 8-m-thick clayey sand layer is found below this silty sand, with N_{SPT} values between 4 and 9. Finally, a layer of sandy clay with N_{SPT} values from 9 to 42 was located, between -12m and -22 m. (Figure 6)

Site D (test piles P6 and P7) has a 11-m-thick top layer of silty sand, with N_{SPT} values between 6 and 60. Below, an 8-m-thick layer of clayey silt with N_{SPT} values from 7 to 59 is encountered. Water is found between -3.85 m and -4 m. (Figures 7 and 8)

Finally, Site E (test pile P8) has a clayey sand upper layer, identified from ground surface to -10 m, with N_{SPT}

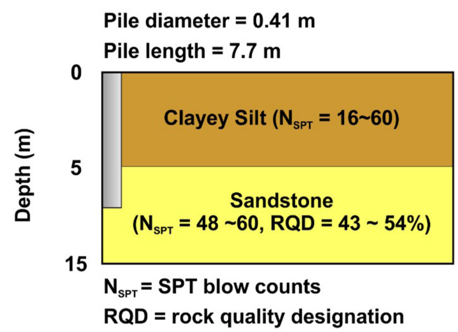

Figure 4. Soil profile at Site A (test piles P1 and P2).

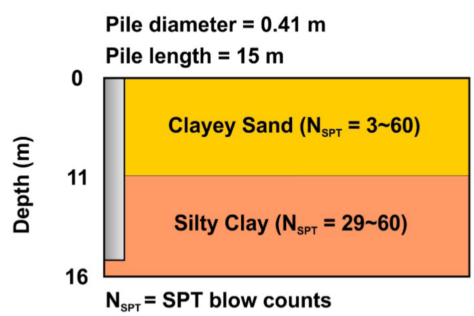

Figure 5. Soil profile at Site B (test piles P3 and P4).

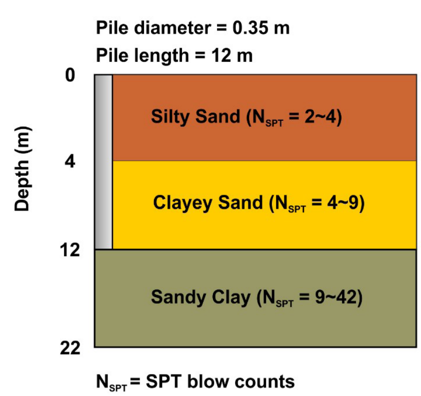

Figure 6. Soil profile at Site C (test pile P5).

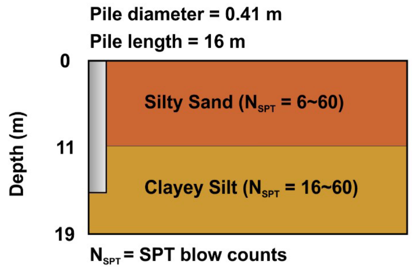

Figure 7. Soil profile at Site D (test pile P6).

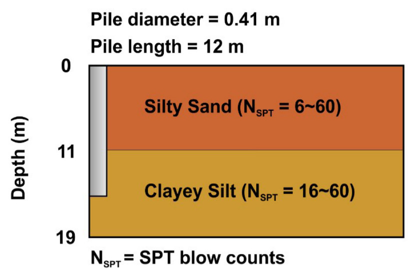

Figure 8. Soil profile at Site D (test pile P7).

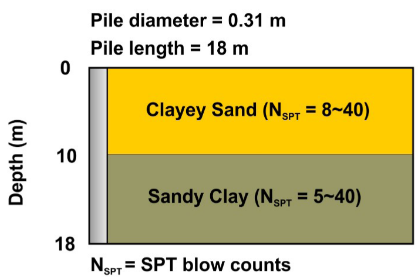

Figure 9. Soil profile at Site E (test pile P8).

values from 8 to 40. A sandy clay layer with N_{SPT} values of 5 to 40 is also found to have a depth of 18 m (Figure 9).

5. Static load tests

The test piles were subjected to static load tests ten days after installation, and the vertical settlement was assessed by four dial gauges installed on their heads (two on each side). The piles were connected to two reference beams, and the load was applied in increments of 20% of the expected final load and then sustained until the settlement rate between two consecutive readings was not higher than 5%.

The piles were unloaded in five stages after reaching the maximum load (except for pile P5). The geometry of the 8 test piles, maximum applied load, injection pressure, and maximum displacement measured are shown in Table 1. The curves "applied load versus settlement" obtained from the static load tests for test piles P1 to P4 are shown in Figure 10. Figure 11 shows the results for test piles P5 to P8.

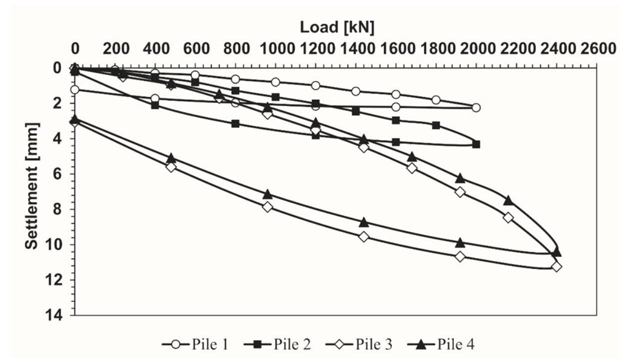

Figure 10. Results from static load tests for piles P1, P2, P3, and P4.

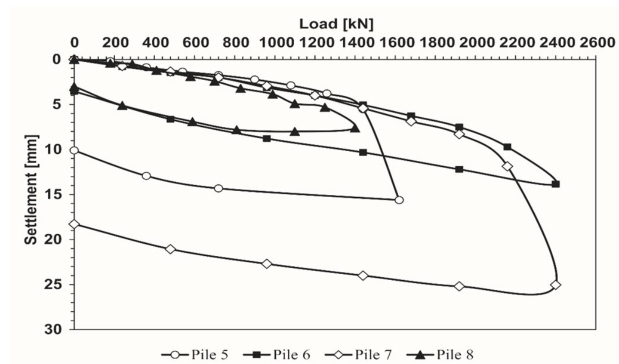

Figure 11. Results from static load tests for piles P5, P6, P7, and P8.

Test piles P5, P6, and P8 had the friction along the shaft completely mobilized, evidenced by a sudden increase in the settlements around the maximum applied load. Piles P1, P2, P3, P4, and P7 showed similar behavior, with settlements primarily controlled by shaft resistance.

For most test piles, a distinct plunging ultimate load (Q_u) was not obtained, so the Van der Veen extrapolation was applied. The extrapolated values for Q_u are presented in Table 2.

6. Monitoring results

The piles were monitored, and the variables of interest were logged during the installation phase. Information related to the drill bit's linear velocity (V_b) and drill bit's advancing velocity (V_a) was captured by the data acquisition device (a speedometer) while drilling the marked section (i.e., the last meter of the drilling rod). Part of the data used in this research was cataloged by Monteiro et al. (2019), and the primary dataset was changed through data from different test piles. Monitored data is shown in Table 3.

In this study, in soil depths where N_{SPT} values were high and the installation had no remarkable hindrances, the N_{SPT} were designated as 60 (the arbitrated maximum). Also, it is worth mentioning that due to unexpected events in the field, adjustments in the marked sections were necessary for test piles P3, P4, P5, P6, and P7 (see Table 3).

Table 1. Results of performed load tests.

Site	Test pile	*L (m)*	*d (m)*	Max. applied load (kN)	Settlement (mm)	*p* (kPa)
A	P1	7.7	0.41	2000	2.24	400
	P2	7.7	0.41	2000	4.32	400
B	P3	15.0	0.41	2400	11.24	300
	P4	15.0	0.41	2400	10.38	300
C	P5	12.0	0.35	1620	15.61	300
D	P6	16.0	0.41	2400	13.85	300
	P7	12.0	0.41	2400	25.04	300
E	P8	8.0	0.31	1400	7.60	300

Table 2. Extrapolated ultimate load (Q_u).

Site	Pile	Q_u (kN)
A	P1	3000
	P2	3200
B	P3	3100
	P4	2900
C	P5	1550
D	P6	2450
	P7	2150
E	P8	1800

Test piles P1 and P2 (both installed in Site A) had higher excavation times (i.e., lower advancing velocities) because pile toes reached the bedrock (sandstone). Test piles P5 (Site C) and P7 (Site D) were installed in soils with similar USCS classifications (clayey silt, silty sand, clayey sand, and sandy clay), and fair compliance between N_{SPT} values and advancing velocity (V_a) was detected for both sites. When comparing test piles P5 and P7, V_a was 7.4% smaller, and N_{SPT} values for pile toe were higher for P7. This led to the conclusion that there is an inversely proportional correlation between these two variables: the higher the standard penetration resistance, the lower the advancing velocity.

During the installation of test piles P5 and P7, high values for the variable frequency (*f*) were observed. It is evident that this variable has a direct relationship with drill bit's linear velocity (V_b). Thus, the smaller the N_{SPT} value, the higher the frequency (*f*) and the drill bit's linear velocity. Therefore, pile load bearing capacity can be deemed to be inversely proportional to the drill bit's linear velocity (V_b) and to the frequency (*f*).

Table 4 displays the average values of the monitored variables and the ultimate load for each test pile.

7. Development and validation of the empirical equations

A multiple linear regression analysis was used to develop the empirical equations. Test piles P1, P2, P3, P5, and P7 were randomly selected to obtain the equations (calibration step), and test piles P4, P6, and P8 were used in the validation phase.

As mentioned in section 3, the three contemplated scenarios were named as $Q_{u,\,80/20}$, $Q_{u,\,90/10}$, and $Q_{u,\,100/0}$. Equations 13, 14, and 15 display the proposed expressions for the field performance control of root piles:

$$Q_{u,\,80/20} = \frac{81.61\,.(A_p)^{0.015}\;.(N_{SPT,\,toe})^{0.404}}{(V_a)^{0.08}} + \frac{1{,}666.94\,.(U.L)^{0.0064}\;.(p)^{0.0036}\;.(\bar{N}_{SPT,\,shaft})^{0.1578}}{(V_b)^{0.5492}} \tag{13}$$

$$Q_{u,\,90/10} = \frac{40.80\,.(A_p)^{0.015}\;.(N_{SPT,\,toe})^{0.404}}{(V_a)^{0.08}} + \frac{2{,}168.02\,.(U.L)^{0.0022}\;.(p)^{0.0044}.(\bar{N}_{SPT,\,shaft})^{0.15}}{(V_b)^{0.5271}} \tag{14}$$

$$Q_{u,\,100/0} = \frac{2{,}508.88\,.(U.L)^{0.0064}\;.(p)^{0.0037}\;(\bar{N}_{SPT,\,shaft})^{0.1402}}{(V_b)^{0.5492}} \tag{15}$$

In the proposed equations, the variables had a tangible, physical meaning: the higher the perimeter, pile length, or average shaft resistance index, the higher the shaft resistance. In contrast, the greater the drill bit's linear velocity, the lower the shaft resistance.

V_a could be considered negligible for the database analyzed. However, this variable can present a more significant relationship to the pile tip bearing capacity for a more extensive dataset. On the other hand, V_b presents a reasonable correlation with the pile shaft bearing capacity. One of the limitations of this research is associated with the quantity of the analyzed dataset. However, it is essential to mention that minimal experimental data are available on loading full-scale root piles due to the difficulties and cost of full-scale load tests. It is worth mentioning that this work proposes a simplified procedure for the installation control of root piles, helping

Table 3. Data logged for monitored variables.

Site	Pile	Drilled length (m)	Time (s)	V_a ($\times 10^{-3}$ m/s)	f (Hz)	ω_b (rad/s)	V_b (m/s)	$N_{SPT,toe}$	$N_{SPT,shaft}$
A	P1	0.1	38.00	2.63	2.01	12.60	1.95	60	50
		0.2	51.00	3.92	2.50	15.72	2.44		
		0.2	78.00	2.56	2.15	13.50	2.09		
		0.2	72.00	2.78	2.25	14.13	2.19		
	P2	0.1	27.00	3.70	1.76	11.08	1.72	60	52
		0.2	50.00	4.00	2.67	16.76	2.60		
		0.2	56.00	3.57	1.36	8.55	1.33		
		0.2	54.00	3.70	2.65	16.62	2.58		
B	P3	0.1	11.22	8.91	2.55	16.00	2.48	60	33
		0.1	8.27	12.10	1.15	7.24	1.12		
		0.2	19.28	10.40	0.99	6.21	0.96		
	P4	0.1	4.76	21.00	2.00	12.57	1.95	60	32
		0.2	9.78	20.40	1.95	12.24	1.90		
		0.2	15.84	12.60	1.20	7.56	1.17		
C	P5	0.2	29.00	5.20	3.99	25.10	3.89	10	6
		0.2	43.00	4.70	4.06	25.48	3.95		
D	P6	0.3	30.00	1.00	2.05	12.86	1.99	39	22
		0.2	27.00	7.40	2.44	15.32	2.37		
	P7	0.3	38.00	7.90	1.61	10.14	1.57	22	22
		0.2	44.00	4.50	4.38	27.52	4.27		
E	P8	0.1	16.00	6.25	1.79	11.25	1.69	40	19
		0.2	39.00	5.13	1.71	10.77	1.62		
		0.2	41.00	4.88	1.71	10.73	1.61		
		0.2	37.00	5.41	1.72	10.81	1.62		

Table 4. Average monitoring variables values.

Pile	Drilled length (m)	Time (s)	v_a (m/s)	Frequency (Hz)	ω (rad/s)	V_b (m/s)	$N_{SPT,toe}$	$N_{SPT,shaft}$	Q_u (kN)
1	0.175	59.75	2.97	2.23	13.99	2.17	60	50	3000
2	0.175	46.75	3.74	2.11	13.25	2.05	60	52	3200
3	0.133	12.92	10.50	1.56	9.81	1.52	60	33	3100
4	0.167	10.13	18.00	1.72	10.79	1.67	60	32	2900
5	0.175	36.00	4.95	4.03	25.29	3.92	10	7	1550
6	0.250	28.50	8.70	2.24	14.09	2.18	39	22	2450
7	0.250	41.00	6.20	3.00	18.83	2.92	22	22	2150
8	0.175	33.25	5.41	1.73	10.89	1.63	40	19	1800

in the decision-making during field construction with the definition of the pile length to be installed.

Since most of the root pile bearing capacity was mobilized essentially by shaft resistance, due to the installation process and proposed scenarios of load mobilization, the pile essentially behaves as a friction pile. Therefore, it is expected that N_{SPT}, along with the shaft and V_b values, presents higher exponent values when compared to the V_a parameter exponent value. The geotechnical interpretation of these equations is that the pile shaft bearing capacity is preponderant. Therefore, pile tip mobilization is significantly lower than pile skin friction mobilization.

The proposed equations were tested with new data (validation dataset – test piles P4, P6, and P8), and the outputs (predicted values) were compared with results from performed load tests, as shown in Table 5.

Table 5 shows percentage errors between 0.2% (P6) and 65.1% (P8) were found. The predicted values for bearing capacity of test pile P4 were slightly higher than the reference values (bearing capacity obtained from static load tests) for two of the proposed load distribution scenarios (90/10 and 100/0), with an absolute error of 17.1%. For test pile P6, an absolute error of 16.7% was found when comparing predicted pile bearing capacity with reference values, which were slightly lower than what was estimated. As for test pile P8,

Table 5. Load test results and predicted values (from proposed equations) for the 3 considered scenarios.

Scenario	Pile 4			Pile 6			Pile 8		
	Q_s (kN)	Q_{toe} (kN)	Q_u (kN)	Q_s (kN)	Q_{toe} (kN)	Q_u (kN)	Q_s (kN)	Q_{toe} (kN)	Q_u (kN)
$Q_{u,80/20}$	2404	328	2732	2039	293	2332	2079	304	2383
$Q_{u,90/10}$	2811	164	2975	2309	146	2455	2642	152	2794
$Q_{u,100}$	3147	0	3147	2579	0	2579	2972	0	2972
Load test Q_u (kN)			2900			2450			1800

the predicted values were higher than the reference ones, with the most significant error (65.1%).

It is worth mentioning that using the proposed method in cases involving clayey soils must be done under careful judgment, for a considerable disturbance of the soil happens due to SPT blows. Eurocode 7 (BSI, 2007) recommends that, for fine soils, SPT tests should be taken into account only for qualitative assessments since no prevailing consensus regarding the precise effects of SPT blows on these soils has been reached.

Since the bearing capacity values obtained with the proposed equations showed a fair agreement with the reference values (static load tests), it was possible to conclude that there is indeed a correlation between pile bearing capacity and the adopted variables. It should be noted, however, that the aim of this research was to propose an alternative approach for the root pile installation control, with the goal of assisting engineers in the decision-making process during pile installation by employing variables that may be easily collected in the field as inputs.

8. Conclusions

A methodology based on monitoring variables to confirm the root pile length during installation was refined and developed. The technique is based on monitoring installation variables (drill bit's advancing and linear velocities) and classical concepts coupled with measurements made during fieldwork. The pressure injection variable was inserted into the empirical formulas, and enhanced monitoring procedures and equipment were implemented. The control methodology was based on the alternative approach of root pile installation control originally proposed by Monteiro et al. (2019), assisting in the decision-making process during field installation on the pile length to be constructed.

This approach is simple to implement and produces immediate interpretation. It is also specially designed for the real-world construction of root pile sites, providing a technically and economically viable preliminary installation control with reasonable accuracy regarding the root pile bearing capacity estimate during pile installation.

The non-destructive approach of this method allows engineers to perform and manage root pile performance control without damaging structures, saving valuable field resources. This is especially important when static load tests are unavailable for some reason because the predictions were remarkably comparable to those obtained by static load tests.

Nevertheless, it is crucial to note that this technique has a limited range of applications and is currently limited to root pile lengths of up to 20 m with a maximum bearing capacity of 2,500 kN. Further research is required and recommended so that the dataset can be expanded, and broader-spectrum equations can be determined.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

José Melchior Filho: conceptualization, methodology, data gathering, visualization, formal analysis, writing - original draft. Alfran Sampaio Moura: conceptualization, formal analysis, supervision, data validation. Fernando Feitosa Monteiro: formal analysis, investigation, writing - review & editing.

List of symbols

a_0	Dependent variables constant
a_n	Independent variables coefficients
a_1	Linear regression coefficient
a_2	Linear regression coefficient
a_3	Linear regression coefficient

a_4	Linear regression coefficient
a_5	Linear regression coefficient
a_6	Linear regression coefficient
a_7	Linear regression coefficient
a'_0	Linear regression constant
a''_0	Linear regression constant
A_p	Pile toe cross sectional area
D	Pile diameter
f	Frequency
L	Pile length
$N_{SPT}shaft$	Average shaft N-value
$N_{SPT}toe$	Toe resistance N-value
p	Air injection pressure
Q_s	Pile shaft resistance
Q_p	Pile toe resistance
$Qult$	Pile ultimate bearing capacity
Qu	Plunging ultimate load
R_b	Drill bit radius
RQD	Rock Quality Designation index
U	Pile perimeter
V_a	Drill bit advancing velocity
V_b	Drill bit linear velocity
ω_b	Drill bit angular velocity
ω_r	Drill rod angular velocity
X_n	Independent variables
Y	Dependent variable

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