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Effects of installation method on the behavior of driven piles and piles bored using a manual auger in tropical collapsible soil

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Technical Note

Keywords
Collapsible soil
Load-displacement curve
Pile construction method
Static load test

Abstract

Understanding the effects of installation method on a deep foundation is fundamental for analyzing load test results and improving foundation design based on soil profile characteristics. This study analyzed 40 load-displacement curves of driven piles and piles bored using a manual auger, measured 20 cm in diameter and 3 or 6 m in length. Piles were constructed at the Experimental Field of Geotechnical Engineering, State University of Londrina. The soil is classified as silty clay, exhibits collapsible behavior up to a depth of 7 m, and has low resistance in surface layers, according to the results of particle size analysis and the standard penetration test. Load tests were carried out under static conditions using mixed loads. Natural moisture conditions were used in the test, and pre-wetted conditions in the retest. For three bored piles, these conditions were reversed. Pre-wetted conditions resulted in loss of failure load, highlighting the collapsible nature of the soil. Conversely, piles tested under natural moisture conditions exhibited higher failure load. Load-displacement curves showed shapes consistent with the expected for the analyzed pile types. This consistency supports the discussion on the effect of the construction method on pile behavior, demonstrating that soil removal during excavation for pile boring mobilizes side friction, whereas, in driven piles, soil compaction enhances toe resistance, particularly for piles constructed by concrete pounding as compared with concrete casting.

1. Introduction

Pile foundations support building loads through toe bearing or side friction mobilized along the shaft-soil interface. In low-resistance soils, foundations typically rely on side resistance, whereas foundations constructed on resistant soils or rock tend to transfer loads directly to the toe (Cambefort, 1964; Randolph & Wroth, 1978; Aoki, 1985; Massad, 1992).

The pile installation method significantly affects soil behavior around the pile and therefore influences the load-bearing capacity. For instance, bored piles, which involve soil excavation, often lead to soil decompression, resulting in stress relief and greater reliance on friction mobilization along the shaft. Conversely, displacement piles, such as driven piles, displace and compact the surrounding soil, enhancing toe resistance and reducing shaft friction dependency (Branco, 2006; Lobo et al., 2009; Cabette et al., 2015; Almada et al., 2019; Oliveira et al., 2023). Thus, the installation method plays a critical role in defining how resistance mobilization occurs, shaping the overall pile behavior under real field conditions.

Assessing pile behavior is essential, especially in collapsible soils that undergo sudden volume changes upon moisture increase, which can lead to foundation settlement and structural instability. Predicting pile behavior through calculations is useful, but field load tests offer a more accurate representation of resistance mobilization, helping to better understand load transfer mechanisms at the shaft and toe (Alledi et al., 2015; Christoni et al., 2019; Melchior Filho et al., 2020).

Given these considerations, this study aims to evaluate the impact of pile installation methods on the load-bearing behavior of small-diameter driven and manually bored piles installed in the tropical collapsible soil of Londrina, Paraná, Brazil. Static load tests were conducted under both natural moisture and pre-wetted soil conditions to compare

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load-displacement responses of driven and bored piles. By investigating these behaviors, this study provides insights into how installation techniques affect pile performance, particularly under conditions prone to soil collapse.

2. Site characterization

The piles were constructed and tested at the Experimental Field of Geotechnical Engineering (EFGE) (23°30′S 50°05′W), State University of Londrina, Paraná, southern Brazil. The soil of the city typically exhibits a silty clay profile, with high porosity, high void ratio, elevated permeability, high solid unity weight and low moisture content. Table 1 summarizes soil some of geotechnical properties in the experimental field.

Londrina's soil is collapsible up to 7 m depth, with subsidence index greater than 2%, as reported by Teixeira et al. (2004) and Zanin et al. (2021). Such behavior causes deformations, owing to the action of the weight of the soil layer when subjected to an increase in saturation degree, which may compromise foundation performance (Zanin et al., 2021). As for soil strength, it is typically low in surface layers and increases progressively with depth. This characteristic is confirmed by standard penetration test N values (N_{SPT}), as depicted in Figure 1. The images also show pile dimensions.

3. Piles

This study evaluated 21 piles installed at the Experimental Field of Geotechnical Engineering, State University of Londrina, including 12 driven piles and 9 piles bored using a manual auger. Pile construction was performed in accordance with the national standard ABNT NBR 6122:2022 - Design and construction of foundations (ABNT, 2022).

Bored piles stand out for their ease of execution and low cost, being commonly used in small-scale construction projects. The construction method involves removing the soil with a drill, ensuring the release of stresses acting on the mass. However, the drill cannot remove all material from the hole, causing the soil to remain loose at the base of the excavation site, which reduces the friction between concrete and the pile tip (Almada et al., 2019). First, excavation is performed using a manual auger, where it is necessary to couple the rods to the desired depth. Next, the reinforcement is placed in preparation for concreting, which must be carried out on the same day as drilling (ABNT, 2022). In the current study, bored piles were filled with in-situ cast concrete with an average compressive strength of 13.0 MPa and a slump of 10 cm. Pile heads were capped with 30 × 30 × 30 cm^3 cap blocks (Fernal et al., 2003).

Driven piles are executed using the same equipment as Strauss piles, but without the need for casing and probing, only requiring an impact hammer. The procedure involves pounding a ram weighing between 300 and 600 kg, creating a hole with a diameter of 0.20 to 0.50 m. The hole is subsequently filled with concrete, following the same concreting specifications as for bored piles, in accordance with ABNT NBR 6122 (ABNT, 2022). The execution process ensures that the soil surrounding the hole is compacted, reducing soil permeability, and consequently, the potential for future collapse due to increased moisture content. Therefore, driven piles represent an interesting solution for foundations in collapsible soils, such as those found in Londrina.

In this study, driven piles were constructed by two methods, namely cast concrete and pounded concrete. In the first method, a hole was opened in soil by the free fall of a 400 kg ram measuring 20 cm in diameter. After the hole was opened, 50 L of No. 1 gravel was released into the hole and pounded. Later, casting was performed in situ using self-compacting concrete with an average compressive strength of 21.6 MPa and a slump of 17 cm (Campos et al., 2008).

Table 1. Geotechnical properties of experimental soil in Londrina, Paraná State, Brazil.

Properties	Soils conditions	Values
Porosity	-	45~55%
Void ratio	-	1.7
Solid unit weight	-	~30 kN/m^3
Liquid limit	-	~54%
Plasticity index	-	~11%
Moisture content	Unsaturated	~32%
Coefficient of permeability	-	3.52×10^{-5} m/s
Pre-consolidation stress	Saturated	46.9 kPa
	Unsaturated	53.3 kPa
Coefficient of consolidation	Saturated	1.67×10^{-2} cm^2/s
	Unsaturated	1.90×10^{-2} cm^2/s
Cohesion	Saturated	6.0 kPa
	Unsaturated	36.3 kPa
Angle of internal friction	Saturated	33.0°
	Unsaturated	25.3°

In the second method, a hole was made in the soil using a 400 kg ram with a nominal diameter of 20 cm and another ram with a nominal diameter of 18 cm. After the hole was opened, concreting was started with the casting of a volume of concrete corresponding to two wheelbarrows. Subsequently, the hole was pounded with the 18 cm diameter ram until the pile was filled. Concrete with an average compressive strength of 24.6 MPa and a slump of zero was produced in situ (Campos et al., 2008).

The Experimental Field of Geotechnical Engineering (EFGE) is separated by areas. In area 3, the bored piles were installed by Fernal et al. (2003), close to the borehole SP5, and in area 6, the driven piles were installed by Campos et al. (2008), close to the borehole SP10, according to Figure 2.

4. Load testing

Bored and driven piles were subjected to static load tests using mixed loads by the same authors (Fernal et al., 2003; Campos et al., 2008). Mixed loading is characterized by the application of a slow load up to 1.2 times the workload of the pile, followed by rapid loading from this point onward (ABNT, 2020). Loading followed the test procedure reported by Alonso (1997), with application of slow loading up to the

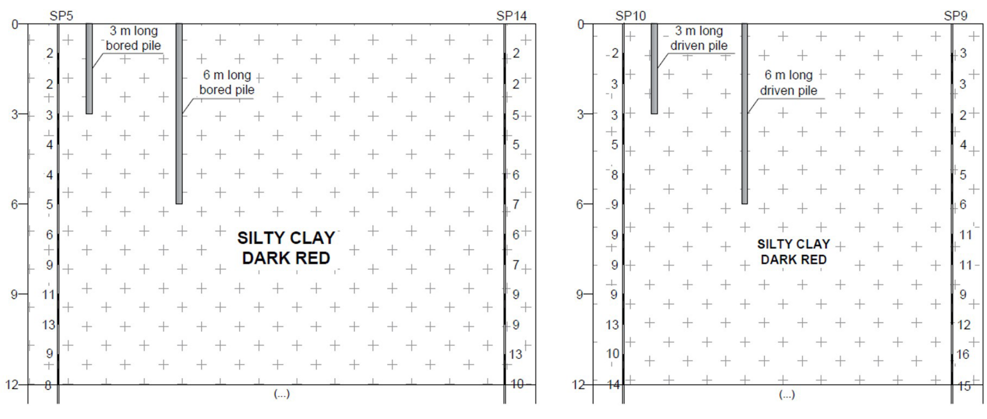

Figure 1. (a) Soil profile (boreholes SP5 and SP14) showing bored piles and (b) soil profile (boreholes SP10 and SP9) showing driven piles.

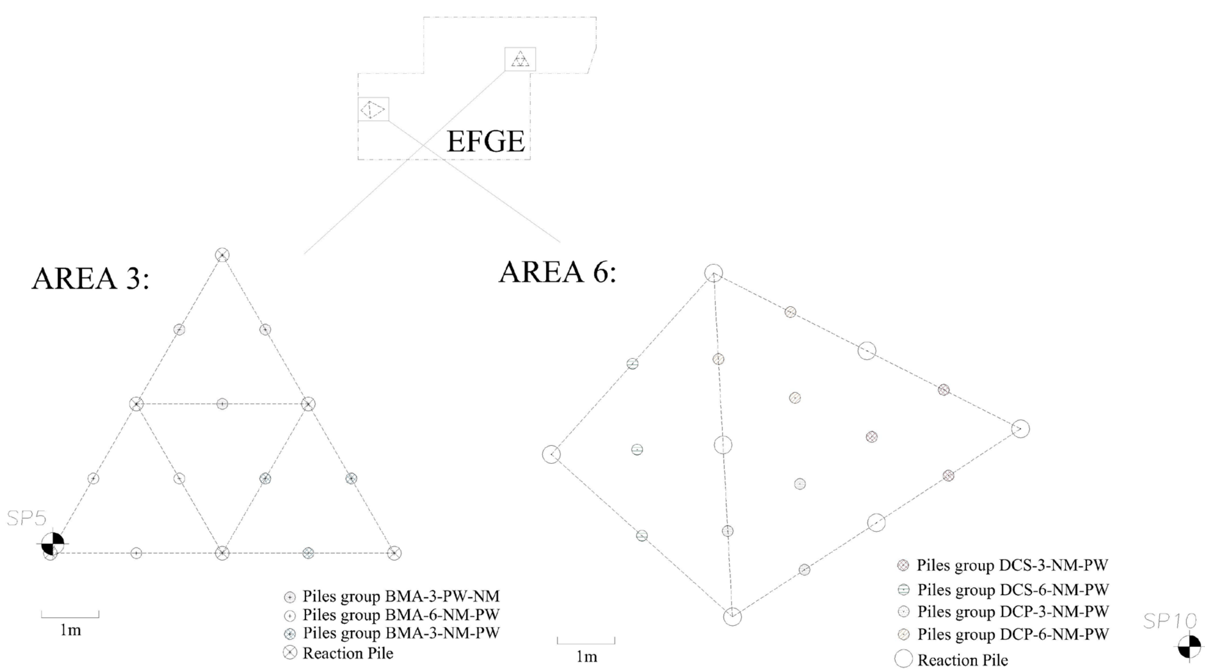

Figure 2. Experimental Areas 3 and 6, where bored and driven piles were installed, respectively.

workload estimated for the pile by the Décourt & Quaresma (1978) method and fast loading up to the maximum load of the test.

A double I profile beam anchored on two reaction piles was used in the load test. Loads were applied using a hydraulic jack and monitored by a load cell connected to a strain indicator, according to Figure 3.

For each pile, two load tests were carried out (test and retest). The test was performed with soil under natural moisture conditions (unsaturated, obtained during the SPT soundings) and the retest using pre-wetted soil, in order to verify the pre-wetting effect on the tropical collapsible soil of Londrina-PR. For pre-wetting, armholes were dug around the piles, as shown in Figure 3, and kept flooded for 48 h before and during the tests. As described by Branco (2006), flooding was maintained up to a depth of 7 m, ensuring that the entire length of the pile remained submerged. Three bored piles were selected and subjected to load tests in inverse order; that is, these piles were tested under pre-wetted conditions first and then retested under natural soil moisture conditions. This procedure was applied to assess the effects of the change on soil and pile behaviors.

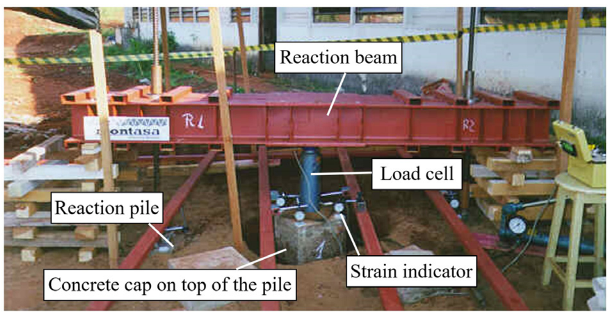

Figure 3. Representative image of the static load test used in the study.

A total of 40 load tests were conducted, including 21 tests and 19 retests. It is noteworthy that it was not possible to perform the pre-wetting retest on one bored pile because it exhibited signs of beam torsion and on one driven pile because of problems in the reaction system. Pile dimensions and test/retest conditions are shown in Table 2. Tests are coded with a combination of pile type, pile length, test/retest, and number of pile (1, 2, or 3). For example, BMA-3-NM-PW-1 refers to the first 3 m long pile bored using a manual auger, tested under natural moisture conditions, and retested under pre-wetted conditions.

For estimation of the geotechnical failure load of piles, the semi-empirical method of Décourt & Quaresma (1978) was used with the modifications proposed by Décourt (1996). The mean values of N_{SPT} from borings carried out near piles were used. For bored piles, the means were calculated from values between SP5 and SP14, whereas for driven piles, means were calculated between SP9 and SP10.

Table 2. Pile dimensions and test/retest conditions.

Piles	Code	Diameter (m)	Length (m)	Test		Retest	
				NM	PW	NM	PW
Bored by manual auger (BMA)	BMA-3-NM-PW-1	0.20	3	x	-	-	x
	BMA-3-NM-PW-2			x	-	-	x
	BMA-3-NM-PW-3			x	-	-	x
	BMA-6-NM-PW-1	0.20	6	x	-	-	x
	BMA-6-NM-PW-2			x	-	-	x
	BMA-6-NM-PW-3			x	-	-	nr
	BMA-3-PW-NM-1	0.20	3	-	x	x	-
	BMA-3-PW-NM-2			-	x	x	-
	BMA-3-PW-NM-3			-	x	x	-
Driven uncased cast in situ (DCS)	DCS-3-NM-PW-1	0.20	3	x	-	-	x
	DCS-3-NM-PW-2			x	-	-	x
	DCS-3-NM-PW-3			x	-	-	x
	DCS-6-NM-PW-1	0.20	6	x	-	-	x
	DCS-6-NM-PW-2			x	-	-	nr
	DCS-6-NM-PW-3			x	-	-	x
Driven uncased cast in situ with pounding (DCP)	DCP-3-NM-PW-1	0.20	3	x	-	-	x
	DCP-3-NM-PW-2			x	-	-	x
	DCP-3-NM-PW-3			x	-	-	x
	DCP-6-NM-PW-1	0.20	6	x	-	-	x
	DCP-6-NM-PW-2			x	-	-	x
	DCP-6-NM-PW-3			x	-	-	x
Total	21	-	-	21		19	

Legend: see List of symbols and abbreviations.

5. Results and discussion

5.1. Bored piles

The load-displacement curves of BMA-3-NM-PW and BMA-6-NM-PW are shown in Figure 4, and those of BMA-3-PW-NM are shown in Figure 5.

In Figure 5, the piles BMA-3-PW-NM-1, 2 and 3 was tested in pre-wetted soil and retested in natural soil.

5.2. Driven piles

The load-displacement curves for DCS-3-NM-PW and DCS-6-NM-PW piles are shown in Figure 6. The curves for DCP-3-NM-PW and DCP-6-NM-PW samples are depicted in Figure 7.

5.3. Influence of installation method

5.3.1. Test under natural moisture conditions

The excavation of bored piles causes soil decompression, relieving stresses. Consequently, the shaft friction created between the soil and pile length overcomes the toe resistance. Thus, the pile bears load by mobilizing side friction; in practice, the portion of toe resistance may not be considered in failure load calculation. Poor toe cleanliness, stemming from incomplete spoil removal, results in a considerable volume of unconsolidated material at the toe, impairing pile resistance (Branco, 2006). In this case, for toe resistance to be mobilized, large displacements would be necessary. However, in small piles, failure is reached before mobilization of toe resistance, as observed in load-displacements in Figure 4, where the curves of bored piles exhibited a more closed shape with a more defined side mobilization.

The resulting loose soil at the perforation base, i.e., close to the pile toe, compromises the contact between concrete and natural soil. In a study by Masutti et al. (2023), the difference in load-bearing capacity was analyzed among three small-diameter excavated piles with improvements in the pile toe: conventional, floating pile and reinforced pile with a compacted crushed stone layer at the bottom of the borehole. The results showed that adding reinforcement at the pile tip resulted in a 31% increase in load-bearing capacity compared to the other piles.

In the installation of driven piles, the ram pushes the soil downward and to the sides, promoting soil displacement and contributing to compaction at the toe and around the shaft. Given that soil is not removed in this process, there is better adhesion between concrete and soil, thereby favoring mobilization of toe resistance. This behavior becomes evident in the load-displacement curves in Figures 5 and 7, where

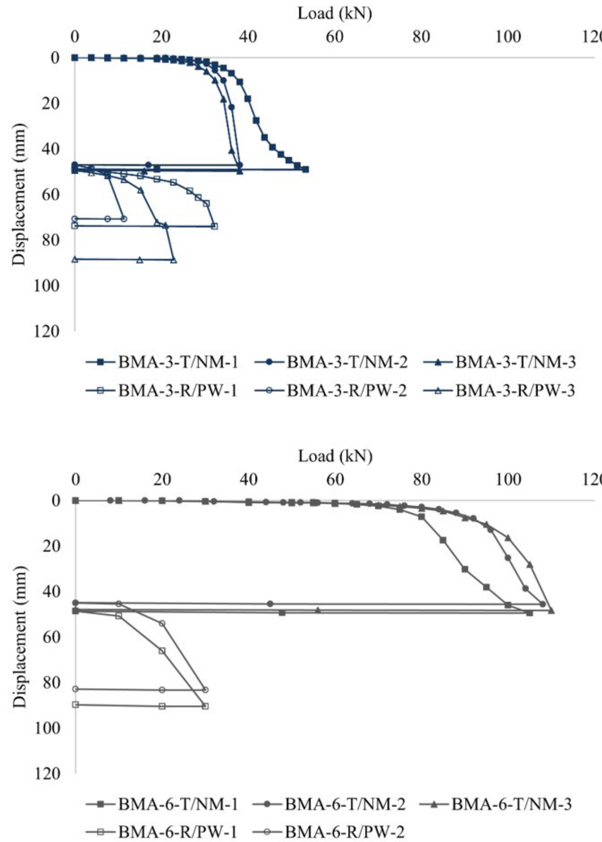

Figure 4. Load-displacement curves of piles bored by manual auger measuring 3 or 6 m in length (BMA-3-NM-PW and BMA-6-NM-PW) tested under natural moisture conditions (T/NM) and retested in pre-wetted soil (R/PW).

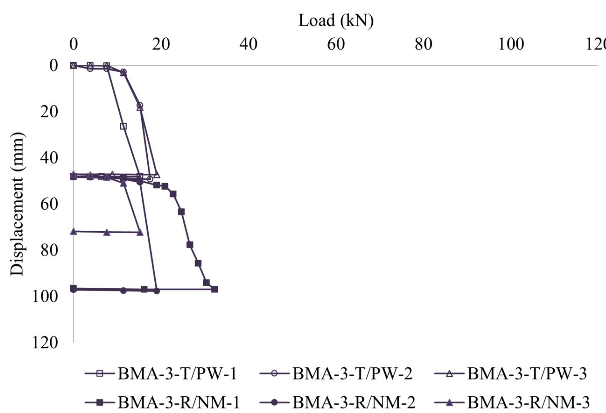

Figure 5. Load-displacement curves of piles bored by manual auger measuring 3 m in length (BMA-3-PW-NM) tested in pre-wetted soil (T/PW) and retested under natural moisture conditions (R/NM).

the curves of driven piles had a more open conformation, with mobilization of toe resistance.

Considering the failure loads, Figure 8 presents a comparison between the results of bored and driven piles

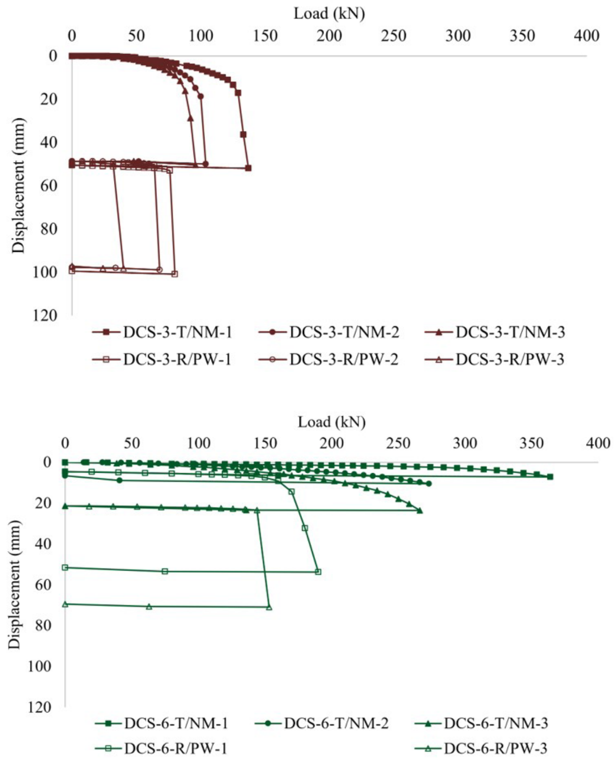

Figure 6. Load-displacement curves of driven uncased piles cast in situ measuring 3 or 6 m in length (DCS-3-NM-PW and DCS-6-NM-PW) tested under natural moisture conditions (T/NM) and retested in pre-wetted soil (R/PW).

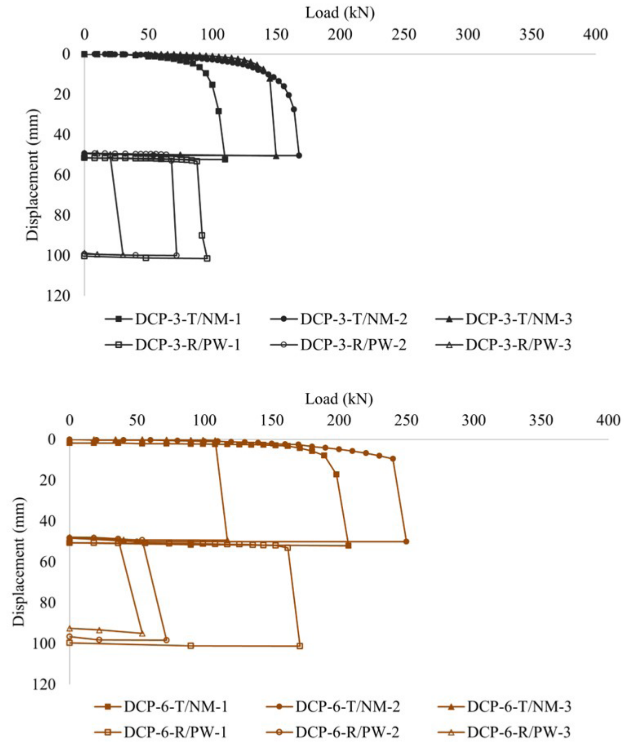

Figure 7. Load-displacement curves of driven uncased piles cast in situ with pounding measuring 3 or 6 m in length (DCP-3-NM-PW and DCP-6-NM-PW) tested under natural moisture conditions (T/NM) and retested in pre-wetted soil (R/PW).

tested under natural soil moisture conditions. The values were determined based on the failure criterion in NBR 6122, except for pile DCS-6-T/NM-1, which was obtained through extrapolation using the criterion proposed by van der Veen (1953) and modified by Aoki (1976).

The results showed that driven piles are more resistant than bored piles of the same dimensions, supporting at least twice the load capacity at both pile lengths (3 m and 6 m). This increased capacity is attributed to soil compaction during the installation of driven piles, which likely contributes additional toe resistance.

In comparing DCS and DCP piles, it was shown that concrete pounding promoted an increase in resistance. This difference in installation method was beneficial, as pounded piles achieved higher failure loads even in the smaller dimension, being more resistant than bored piles of the same geometry. In fact, pounding improved shaft friction, effectively promoting the formation of lateral bulbs along the pile's length.

On the other hand, with 6 m piles installed by simple concrete casting (DCS) had higher loading capacities than 6 m long DCP piles, but it is important to note that DCS-6-NM samples were not tested up to the settlement level (about 50 mm) due to limitations in the reaction system of load tests, and because of that high displacement loads were not sufficient to cause failure.

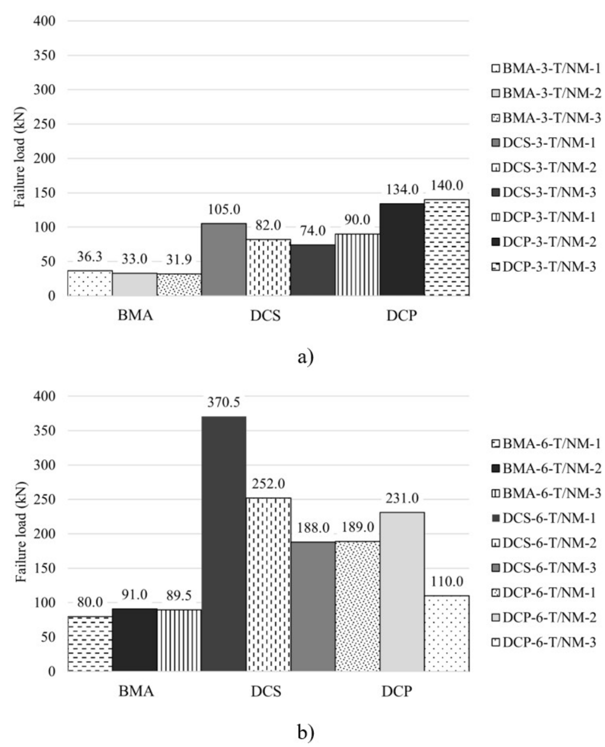

Figure 8. Failure load of bored and driven piles measuring (a) 3 m and (b) 6 m in length tested under natural soil moisture conditions (T/NM).

5.3.2. Retest in pre-wetted soil conditions

Considering the failure loads, Figure 9 presents a comparison between the results of bored and driven piles retested in pre-wetted soil conditions. All the values were determined based on the failure criterion in NBR 6122.

The failure loads of BMA-3-NM-PW and BMA-6-NM-PW were lower in the retest in pre-wetted soils than under natural moisture conditions. This finding can be explained by some factors. For instance, the retest can modify soil properties and pile resistance. Moreover, the pre-wetting load test was conducted in the rainy season (November/2002). Additionally, the studied soil has collapsible characteristics and, because of that, an increase in moisture results in loses soils capacity.

For driven piles, tests were also carried out in the rainy season, with wetter soils (January to March/2004), and retests were carried out in the following months (February to April/2004). Nevertheless, there was a difference in resistance between the test conducted under natural conditions and the retest with pre-wetting. In the latter, the piles lost their capacity to bear loads with increasing soil moisture, as well.

Again, the bored piles had lower resistance than driven piles, achieving lower failure loads with smaller displacements (Figure 4). Even in the case of loss in rupture load, driven piles proved to be more resistant to the imposed load demands, particularly DCP piles measuring 3 m in length. Overall, it was observed that improvements in pile construction method resulted in different behaviors to mobilized loads and, consequently, higher load capacity. Given that piles had similar moisture contents, the comparison demonstrates that the construction process influenced pile resistance, even under conditions of soil pre-wetting.

5.3.3. Test in pre-wetted and retest under natural moisture conditions

Considering the piles bored by manual auger, tested in pre-wetted soil and retested in natural soil, their failure loads are represented in Figure 10.

It should be noted that the test of these piles was carried out in the dry season (August/2001) and the retest was carried out in the rainy season (January/2003). Therefore, the difference in bearing capacity between test and retest was not significant, given that soil moisture conditions during the load test were influenced by rainfall.

However, differences in load capacity were observed between BMA-3-NM-PW (Figure 8a and 9a) and BMA-3-PW-NM (Figure 10), which were tested in the same period (dry season) but under different soil moisture conditions. The load increments used in BMA-3-NM-PW were greater than those used in BMA-3-PW-NM and this were resulted in higher failure loads to the first one, in both soil conditions. Failure was better delineated under conditions of natural moisture, given that soil was dry before the load test, as demonstrated by Zanin et al. (2021).

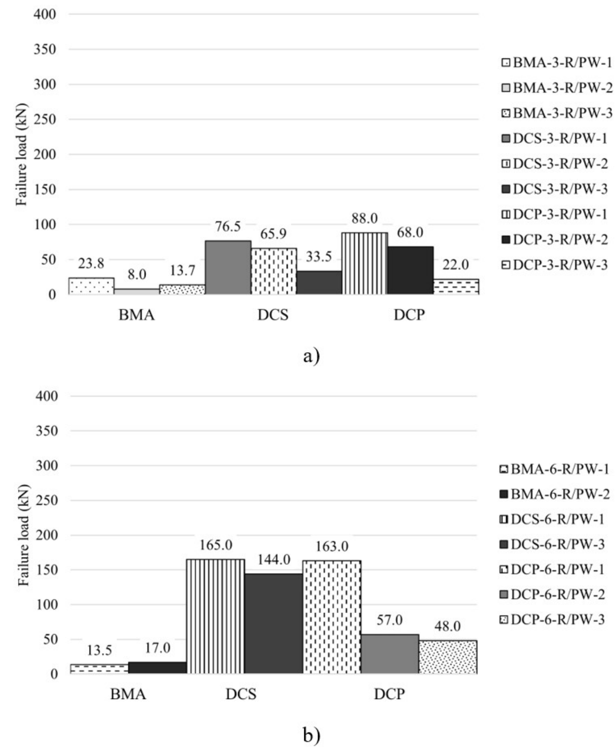

Figure 9. Failure load of bored and driven piles measuring (a) 3 m and (b) 6 m in length retested in pre-wetted soil (R/PW).

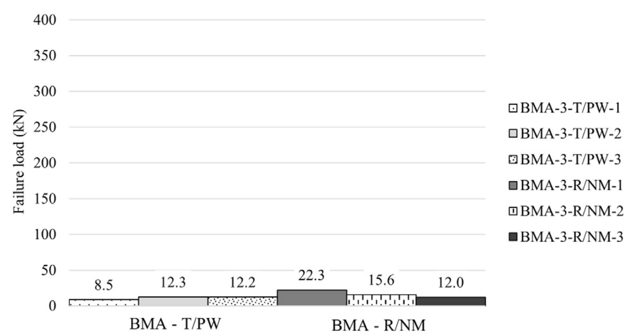

Figure 10. Failure load of bored piles measuring 3 m in length tested in pre-wetted soil (T/PW) and retested under natural moisture conditions.

6. Conclusion

In this study, 21 small-diameter piles installed in the collapsible tropical soil of Londrina, Paraná, were subjected to static compression loading under natural moisture conditions and pre-wetting. Of these piles, 9 were bored with a manual auger and concreted in situ; 6 were driven using a ram and concreted by casting in situ; and the remaining 6 were driven and concreted with concrete pounding in situ.

The objective was to analyze the effect of the installation method on the behavior of these piles in collapsible soil, where an increase in saturation resulted in reductions in failure load. Evidence of this was observed as piles achieved higher failure loads under natural soil moisture conditions than in retests with soil pre-wetting, across all installation methods applied here.

Regarding differences between bored and driven piles, it was found that soil excavation causes decompression and, consequently, stress relief, which promotes friction mobilization. Driving, on the other hand, displaces the soil, aiding in compaction at the toe and along the pile sides, leading to an increase in toe resistance. In this context, the load-displacements curves of bored piled showed a closed shape with lower failure loads achieved at smaller displacements, while the curves of driven piles exhibited a open shape, achieving higher failure loads for the same pile geometry.

Moreover, driven piles installed with concrete pounding demonstrated greater resistance than those with concrete casting, exhibiting better performance, higher failure loads and less deformation after pre-wetting. These findings suggest driven pile with concrete pounding as a viable option for designing small-scale projects, such as houses and low-rise buildings in collapsible soils with similar properties that those found in Londrina.

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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

Amanda Regina Foggiato Christoni: conceptualization, data curation, formal analysis, writing – original draft. Cristina de Hollanda Cavalcanti Tsuha: conceptualization, supervision, validation, writing – review & editing. Antonio Belincanta: conceptualization, supervision, validation. Carlos José Marques da Costa Branco: conceptualization, investigation, methodology, formal analysis, supervision, validation. Raquel Souza Teixeira: conceptualization, investigation, methodology, formal analysis, supervision, validation, writing – review & editing.

Data availability

All data produced or examined in the course of the current study are included in this article.

Declaration of use of generative artificial intelligence

This work was prepared with the assistance of generative artificial intelligence (GenAI) ChatGPT with the aim of grammatically and orthographically reviewing the Introduction and Conclusion sections. The entire process of using this tool was supervised, reviewed and when necessary edited by the authors. The authors assume full responsibility for the content of the publication that involved the aid of GenAI.

List of symbols and abbreviations

nr	not retested
BMA	Piles bored by manual auger
DCP	Driven piles uncased cast in situ with pounding
DCS	Driven piles uncased cast in situ
EFGE	Experimental Field of Geotechnical Engineering
N_{SPT}	Standard penetration test (SPT) *N*-value
NM	Natural moisture
PW	Pre-wetting
R	Retest
SP	Borehole
T	Test

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