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Load capacity evaluation of different typologies of short and small diameter piles

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Technical Note

Keywords
Unsaturated soils
Static load test
Small diameter piles
Loading capacity

Abstract

It is common to observe residences with a high number of pathologies related to differential settlements in the municipality of Cruz Alta, Rio Grande do Sul, Brazil. Motivated by this perspective the first Geotechnical Engineering Experimental Field was implemented in the municipality. Standard penetration test and cone penetration test was conducted to characterize the subsoil and execute 17 excavated piles: nine compression piles and eight reaction piles. This technical note presents and discusses the results of the geotechnical load capacity obtained with the static load test in three different pile conditions: conventional piles, floating piles, and reinforced piles by inserting a crushed stone layer compacted at the bottom of the drilling. The piles evaluated have a length of 3 m and a diameter of 30 cm. The piles are immersed in a layer of unsaturated laterite soil. Conventional piles are extensively executed in the municipality due to the limited equipment of the companies offering this service. In summary, the piles presented low bearing capacity, however, the reinforced piles proved to be a viable alternative in terms of increased resistance. The conventional piles presented low load capacity and significant settlements. The insertion of the reinforcement at the tip of the pile resulted in a resistance gain in the range of 31%. The study of floating piles was important to understand the behavior of the pile base. This technical note will enable the geotechnical understanding for future researchers or designers who will work with this soil condition in the state of Rio Grande do Sul, Brazil.

1. Introduction

The behavior of piles in unsaturated soils subjected to axial loading has been the subject of field research, physical models, and numerical simulations (Stewart et al., 2011; Vanapalli & Taylan, 2012; Liu & Vanapalli, 2021; Wu & Vanapalli, 2022). In tropical climatic regions, it is commonly the occurrence of unsaturated soils directly influenced by mineralogical and drainage conditions (Camapum de Carvalho & Gitirana Junior, 2021). This condition denotes the importance of the study of foundations in unsaturated soils.

Studies have demonstrated the importance of foundation studies in unsaturated soils in Brazil (Rebolledo et al., 2019; Pereira et al., 2019; Monteiro et al., 2021; Chaves et al., 2022). In the Brazilian geotechnical practice, two are the ABNT standards that regulate the execution of the pile load tests: NBR 12131 (ABNT, 2006) and NBR 6122 (ABNT, 2010). The first specifies the types of tests and the executive procedures and the second defines the number of load tests to be performed. NBR 6122 (ABNT, 2010) specifies that the load tests must be carried out on the first piles on site to validate the length prediction procedures or adapt them according to the results of these load tests.

Customs and practices for pile execution in the Cruz Alta municipality, is to execute small diameter and short length excavated piles due to its ease of execution compared to superficial foundations. However, there are cracks in buildings that are the result of improperly dimensioned foundations. From this perspective, the first geotechnical engineering experimental field was implemented at the University of Cruz Alta, whose objective is to explain the behavior of piles submitted to axial compression through static load tests. Nine excavated piles with a diameter of 0.30 m and a length of 3.00 m, were designed and tested under compression on site. Eight piles with a length of 6.00 m and a diameter of 0.30 m were executed for the reaction system.

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In this context, static load tests (*SLT*) were conducted with slow loading, in three concrete piles, as per the usual practice, resisting by the side and tip friction. It is important to note that *SLT* can be methodologically presented in several stages: test preparation, test equipment control, in-situ pile test on the construction site, analysis, and decision making. Three floating piles, executed with expanded polystyrene discs at the tip, were later dissolved. Finally, to increase the cutting-edge strength of the analyzed system, the other piles included a layer of compacted crushed stone and subsequent concreting at the base of the foundation. Add to the results two cone penetration tests (*CPT*), and four standard penetration tests (*SPT*) without water circulation were conducted for the subsoil investigation, and deformed samples were removed from a depth of 2.00 m for physical characterization tests.

2. Materials and methods

2.1 Characterization of the geotechnical engineering experimental field

Nine short (3 m) and small diameter (0.30 m) excavated piles were executed in the experimental field (Figure 1a). The distribution of piles in the plan and work after execution is presented in Figure 1b. As shown in Figure 1c, the piles were separated into three distinct typologies, namely: conventional piles, reinforced piles, and floating piles. Additionally, eight reaction piles with a length of 6.00 m and a diameter of 0.30 m were executed. The three conventional piles are characterized by lateral friction and tip resistance. The type corresponding to the three reinforced piles has the differential of a layer of crushed gravel at the bottom of the perforation with a thickness of 0.30 m. The floating piles aimed to evaluate the magnitude of the resistance by lateral friction. The constructive methodology of the flotation piles consisted of introducing four expanded polystyrene discs at the bottom of the perforation, which were dissolved before conducting the load tests. The discs had a diameter of 0.30 m and a thickness of 0.08 m each, totaling 0.32 m in height. It is important to highlight that the pile was exhumed after the load test, and the correct functioning of the executive process was verified (Figure 1d).

2.2 Soil characterization

Figure 2 presents the results obtained from the *SPT* and *CPT* tests. The local subsoil was characterized using four *SPT* tests without water circulation to determine the subsoil profile, tactile-visual identification of the different layers, and penetration resistance index (N_{SPT}).

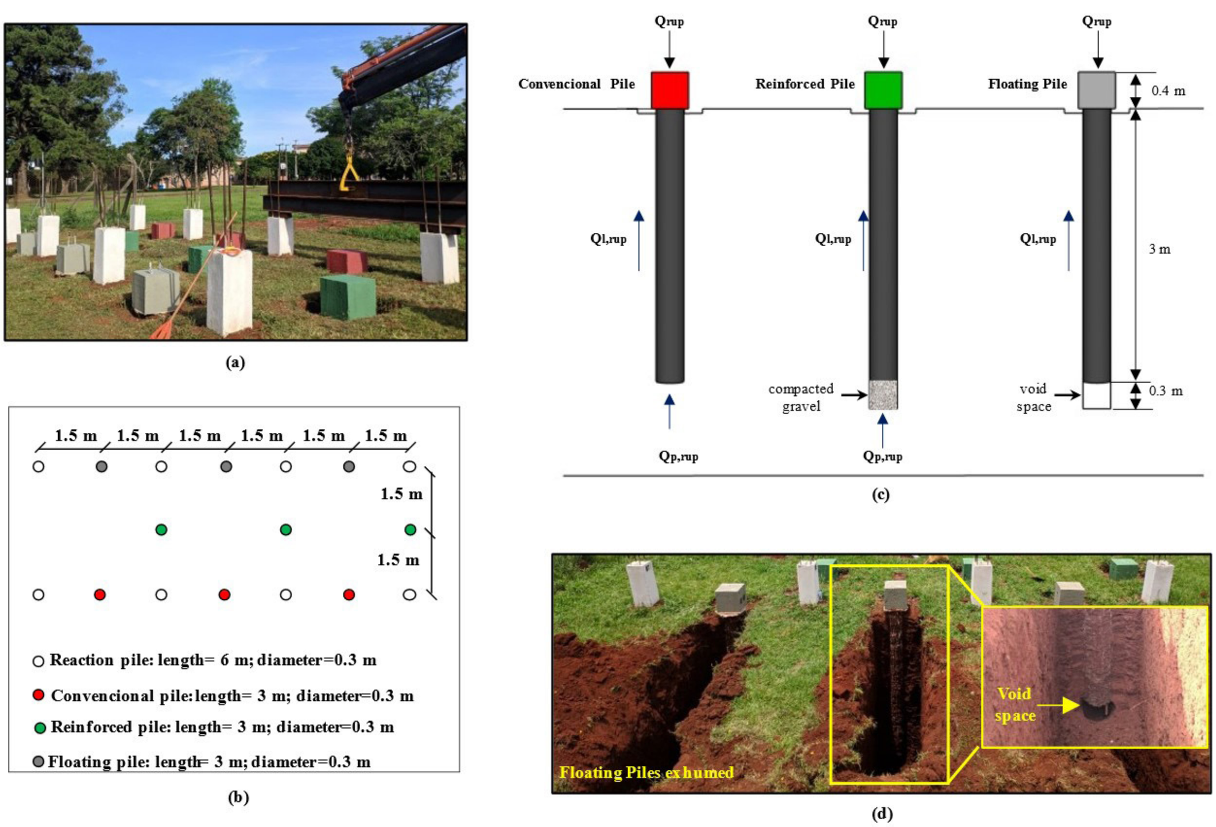

Figure 1. (a) piles executed; (b) arrangement of piles; (c) characteristics of structural elements and (d) exhumed floating pile.

The *SPT* tests were performed in the light of NBR 6484 (ABNT, 2001). *SPT*-01 was executed up to 30 m in depth. The others (*SPT*-02, *SPT*-03, and *SPT*-04) were interrupted at 6.00 m since this was the depth of interest for the research, twice the length of the piles. The water table level is at a depth of 14.50 m from the ground level; confirming that the piles are embedded in unsaturated soil. The soil is composed of a layer of red-colored silty clay with increasing compactness along the depth. The geotechnical profile of the site presents low resistance to penetration, indicating a soil with low support capacity depending on the imposed demand. With the *CPT* results, a soil classification along depth was performed using Robertson's (2010) proposal. Indicating that the soil profile is composed of clay, mixed sands, and sand. Being different from that obtained by the *SPT* test, this fact may be linked to the fact that the methodology for interpreting the *CPT* is not based on tropical soils. Note that the clay layer presents relatively low cone strength values (3 to 5 MPa) and low friction sleeve (6 to 40 kPa). The sand layer is characterized by the opposite pattern to the clay, with high values of cone strength and friction sleeve.

Table 1 presents the soil characterization and classification results for the 2 m depth. The ratio between the plasticity index and the fraction smaller than 0.002 mm results in a colloidal activity index of 0.27. Indicating that the clay is inactive, corroborating with the results of X-ray diffraction that indicated the presence of the kaolinite mineral that does not present expansive characteristics. The soil was classified using the *MCT* (Miniature Compaction Tropical) methodology developed for tropical soils by Nogami & Villibor (1995). The results indicate that the soil belongs to the class of clayey soils with lateritic behavior (*LG'*). Through the Unified Soil Classification System (*USCS*) the soil belongs to the ML group, silt with low compressibility.

Table 1. Soil characteristic at a depth of 2 m.

Parameters	Value
X-ray diffraction	kaolinite and gibbsite
Liquid Limit (%)	49
Plastic Limit (%)	32
Plasticity Index- PI (%)	17
Real specific weight of the grains (kN/m^3)	27.96
Natural specific weight (kN/m^3)	15.16
Void index	1.41
% gravel (>2.0mm)	0
% coarse sand (0.6 – 2.0 mm)	1
% average sand (0.2 – 0.6 mm)	11
% fine sand (0.06 – 0.2 mm)	11
% silt (2 μm – 0.06 mm)	15
% clay (%< 2 μm)	62
Brazilian MCT	LG'
USCS	ML

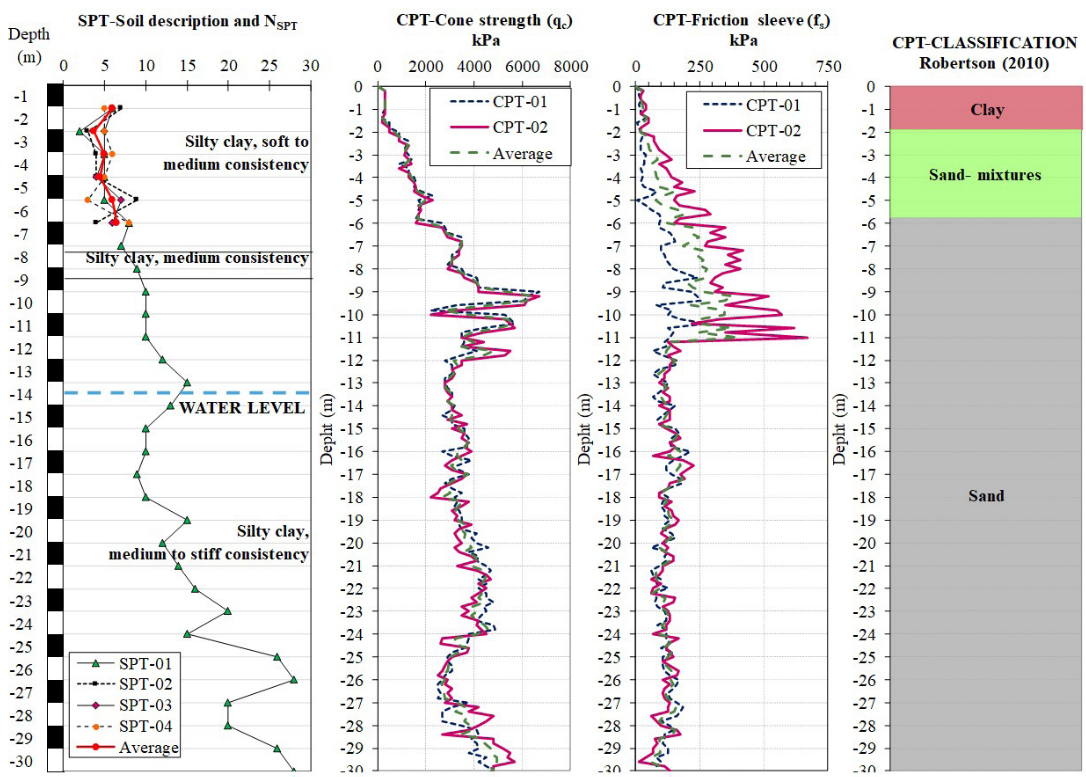

Figure 2. Analysis of the typical subsoil profile by *SPT* and *CPT* tests.

3. Analysis and results

Figure 3 shows the results from the *SLT* for the conventional (*C*), reinforced (*R*), and floating piles (*F*). For conventional piles the load increments were estimated according to the recommendations of NBR 12131 (ABNT, 2006), therefore, the stages conducted were of 30 kN. When the first test was conducted on the *C-1* pile, the load test ended with a maximum load of 75 kN, at which the strain readings did not stabilize, indicating a potential rupture. For this element, the average settlement was 21.04 mm. After the preliminary experience with the stages adopted for the *C-1* pile, the load increments for the other piles in this group were reduced to 10 kN to analyze the highest number of experimental data. However, in conventional piles, the settlements did not stabilize for the last load stage applied, characterizing the conventional failure of the pile. It can be observed that in the unloading section there was no elastic recovery, which is another indication that the resistive capacity reached its limit. This typology showed a discrepancy of around 37.5% for the maximum load capacity achieved in the test. Despite the proximity of the structural elements, a variation in soil characteristics may have occurred, which would justify the higher strength observed for pile *C-3*. The *SLT* was conducted up to the 105 kN stage for the reinforced piles, with settlements in the range of 2.6 to 4.4% of the pile diameter. When comparing the reinforced pile with the conventional pile (*C-1* and *C-2*) the average strength gain is 31%. For the floating piles, the *SLT* was conducted until settlements 1.5 to 1.9% of the pile diameter, where a load capacity of 83 kN was obtained for *F-1* and *F-2* and 67.5 kN for *F-3*. The floating piles present settlements 89 to 93% lower than those obtained for the conventional piles. It is estimated that by applying the load stages a kind of compaction occurs at the pile toe, reducing the void index and consequently increasing the degree of saturation. This increase can reduce the suction in the region justifying the high magnitude settlements observed in conventional piles.

Figure 4 shows the results obtained in *SLT* using different methods. The data suggests proximity between the experimental results and those obtained by the methods of van der Veen (1953) and Van der Venn modified by Aoki (1976). The results should be considered that the *SLT* was taken to small stiffness values, indicating conventional pile failure. In line with this hypothesis, the good fit obtained with the methods of van der Veen (1953) and Van der Venn modified by Aoki (1976) indicates a poorly defined curve with failure load values close to those obtained experimentally. This premise agrees with Décourt and Niyama's (1994) suggestion that the Van der Veen method is only applicable to piles where the load test is taken to 2/3 of the failure load and in displacement piles. The application of the Stiffness method (Décourt, 1998, 2008) made it possible to infer that the insertion of a crushed stone layer increased the ultimate strength promoting a higher bearing capacity.

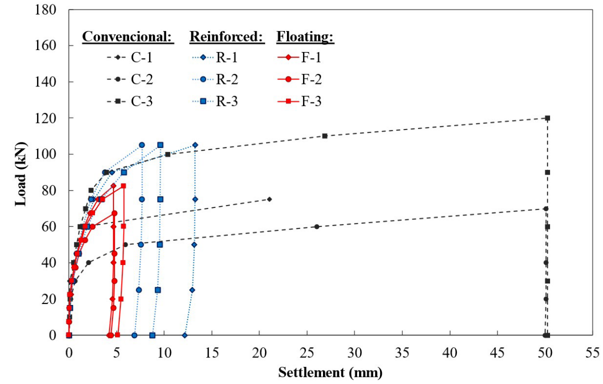

Figure 3. Settlement versus load curve.

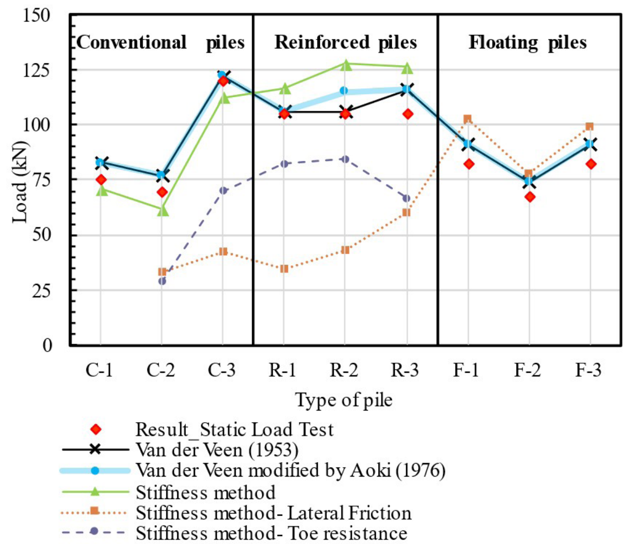

Figure 4. Comparison between the extrapolation methods.

It is estimated that the lower experimental results obtained for conventional piles by the stiffness method come from the consideration that the settlement that leads the pile to conventional rupture corresponds to 0.1 of the element diameters. Evaluating the results of the floating piles it is estimated that the Stiffness method is underestimating the load capacity results by lateral friction. Another fact that corroborates that the tip is being overestimated is that the excavated piles are short and inserted in porous soil with little resistance.

4. Conclusion

This Technical Note presents the results of the compressive behavior of short and small diameter excavated piles. The granulometric characterization tests demonstrate that the soil surrounding the pile is a silty-sandy clay. The low N_{SPT} values in the first meters support the theory that these results are typical of lateritic soils.

The results of the *SPT* tests show significant dispersion, even though they are all conducted in the same location. It is emphasized that the load capacity in pile compression can be evaluated from theoretical-empirical equations, where it is possible to discriminate the base component and the component by lateral friction. The appeal of this technical note is to work in the light of field measured data (static load tests).

Regarding the load versus settlement curves, the *C* piles presented a high dispersion from the *C-3* pile, which presented load approximately 50 kN higher than the others. The study of *F* piles indicates the remarkable relevance of lateral friction resistance in the load capacity of foundations by excavated piles, even if these are short and with a small diameter. This premise corroborates the statement of Kulhawy (1991), where the author indicates that peak strength is responsible for only approximately 5 to 20% of the load capacity of excavated piles. The load results do not show dispersion for the three *R* piles, as they all reached 105 kN as measured maximum strength. The compaction of 0.30 m of crushed stone at the bottom of the perforation contributed to the increase in strength of the *R* piles. This typology had a load capacity 35.50% higher than the results obtained by floating piles and 18.90% higher when compared to conventional piles. Reinforced piles are a simple, affordable, and efficient form to increase the strength of short piles due to the ease of execution. The method of van der Veen (1953) and Van der Veen modified by Aoki (1976) proved inadequate in load tests approaching rupture. The Stiffness method made it possible to evaluate lateral friction and tip resistance separately. Evaluating the *SLS* obtained for the floating piles it is verified that the Stiffness method may be underestimating the lateral friction.

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

Gustavo Corbellini Masutti: conceptualization, data curation, visualization, writing – original draft. Patricia Rodrigues Falcão: conceptualization, data curation, methodology, supervision, validation, writing – original draft. Magnos Baroni: formal analysis, funding acquisition, investigation, methodology, project administration, supervision, validation, writing – original draft. Rinaldo José Pinheiro Barbosa: supervision, validation, data curation, writing – reviewing & editing. Tiago de Jesus Souza: methodology, data curation, supervision, validation, writing – reviewing & editing.

Data availability

The datasets produced and analyzed during the current study are available upon reasonable request to the corresponding author.

List of symbols

C	conventional Piles
CPT	cone penetration test
F	floating piles
LG'	clayey soils with lateritic behavior
MCT	Miniature Compaction Tropical
N_{SPT}	penetration resistance index
$Q_{p,rup}$	load transfer by the toe
$Q_{l,rup}$	load transfer by the friction
Q_{rup}	applied load at the top of the pile.
R	reinforced piles
SLT	static load test
SPT	standard penetration test
USCS	Unified Soil Classification System

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