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Experimental execution of vertical soil nails in Brasília's collapsible soil

Ejecución experimental de anclajes verticales en el suelo colapsable de Brasilia

Max Barbosa
Technical Director, Solotrat Centro Oeste, Brasilia, Brasil, max.barbosa@sco.eng.br

André Assis
Professor, University of Brasília, Brasília, Brasil, aassis@unb.br

Renato Cunha
Professor, University of Brasília, Brasília, Brasil, aassis@unb.br

ABSTRACT: The pullout resistance of nails is a crucial parameter in the analysis of soil nail walls, represented by the q_s parameter. Barbosa et al. (2022) compiled pullout tests on nails, comparing the sectorized post-grouting technique with the conventional gravity grouting method. Their study revealed superior results with the sectorized post-grouting technique. However, certain factors in the executed works were determined by the executing company's experience rather than systematic testing. The drilling method, exclusively using water as a drilling fluid instead of compressed air, and the absence of additives in the cement grout were among these fixed factors. Additionally, despite exhumation, there was no investigation into the final effective diameter and roughness profile, both significant for interface shear. Notably, all tests were conducted on sub-horizontal nails, as the executing company was unaware of evidence suggesting experimentation with vertical nails. Recognizing the gaps in the previous study and equipped with knowledge from Seo et al. (2012) and Seo et al. (2017), the author decided to experimentally execute vertical nails. This decision aimed to validate the empirical model proposed by Barbosa et al. (2022) while addressing the identified limitations and utilizing a well-characterized experimental field with flexible drilling methodologies, varied cement grouts, and equipment and labor for exhumation.

KEYWORDS: Soil nail, vertical pullout test, sectorized post-grouting, collapsible soil

1 INTRODUCTION

Pullout tests are procedures that characterize nails and their executive methodologies through pullout resistance, represented by the parameter q_s, the base parameter for analysis of containments in soil nailing retaining structures.

Barbosa et al. (2022) characterized the pullout resistance of nails performed using the sectorized post grouting technique, which presented superior results to nails performed using the conventional technique, gravity grouting, for non-problematic soils. This work generated an empirical model for predicting the pullout resistance of nails performed by sectorized post grouting. In any case, there were some fixed factors in the works carried out that were decided according to the experience of the geotechnical contractor company, not necessarily with previous tests:

- Drilling method, in which all works were carried out with equipment that used water as drilling fluid, instead of compressed air, a method also widely used for making nails;
- The cement grout was without additives, composed only of water and cement;
- Although there was exhumation, there was no investigation of the final effective diameter and roughness profile, an important factor for interface shear resistance (Barton, 1973);
- All tests were performed in sub-horizontal nails, since studies by Seo et al. (2012) and Seo et al. (2017) were not known to the geotechnical contractor at the time of the execution of the works.

As it was disposed to the authors a previously characterized experimental field, as well as equipment for executing soil nails that presented the possibility of varying the executive drilling methodology, varying the cement grout trace, equipment and labor for exhuming nails and knowledge regarding the studies carried out by Seo et al. (2012) and Seo et al. (2017), it was decided to investigate these gaps and validate the empirical model proposed for the soil of Brasília, Brazil, by performing experimental vertical soil nails.

To minimize testing costs, we used recommendations from Hong et al. (2013), with a shorter anchored section (≥2.00 m) for controlled conditions, such as this experimental campaign.

2 MATERIALS AND METHODS

To carry out the field study, it was planned to organize the nails in a systematic way to allow the observation of variables not considered in previous tests. Initially, a previously characterized experimental field was selected, where it would be possible to exhume the nails to investigate the interaction between the effective final diameter at the site and the roughness profile. Considering previous studies on the use of additives in cement grout for soil nails (Pitta & Zirlis (2000); Miranda (2019)), the results between nails with and without expanding additives were compared, regarding pullout resistance. There was also variation in the drilling methodology to observe possible influences on the pullout resistance of the nails in Brasília.

As for the minimum number of tests, it was determined considering the size and complexity of the study, as well as the level of uncertainty. Six scenarios were planned, resulting in eighteen nails executed, distributed according to the grouting and drilling methods:

- Scenario 1: Commonly executed nail (gravity grouted nail), by air drilling;
- Scenario 2: Nail made with cement grout and additives, by air drilling;
- Scenario 3: Nail performed with sectorized post grouting, by air drilling;
- Scenario 4: Common nail execution (gravity grouting), by water drilling;
- Scenario 5: Nail made with added cement grout, by water drilling;
- Scenario 6: Nail performed with sectorized post grouting, by water drilling.

The experimental field was chosen in a location previously characterized and used by Mendoza (2013), where the presence of typical local soil, porous collapsible clay, was observed.

2.1 *Experimental field characteristics*

Such soil found in the Brasília region is characterized by its distinctive characteristics, shaped by the local climate, which includes alternating periods of drought and precipitation, and an average annual temperature above 20°C. These climatic conditions promote leaching and laterization processes, which result in the formation of microaggregates with a sandy texture, connected by clay cement bridges, forming a porous structure with permeability typical of fine granular soils (10^{-5} to 10^{-6} m/s), being metastable. After collapse, the soil has low shear strength and high compressibility.
Porous clay is generally found near the surface, averaging 15 to 30 meters thick, although sites up to 40 meters thick have also been observed. The water table in the region is deep, with some points exceeding 40 meters deep.
The characterization of the experimental field carried out by Solotrat Centro-Oeste Mendoza (2013) included SPT, SPT-T and DMT tests to characterize the local soil. The resulting profile showed a layer of sandy clay of soft consistency and red color from 0 to 5.0 meters deep, followed by a layer of sandy silt of medium consistency and brown color from 5.0 to 8.0 meters, a layer of sandy silt of hard consistency and white color from 8.0 to 9.0 meters, and finally a layer of silty clay of medium consistency and dark brown color from 9.0 to 14.0 meters. The water level was found to be 4.5 meters deep.

2.2 *Executive campaign characterization*

Figures 1 and 2 present organization of the nails executed on the experimental field. The characteristics of the different grouting methods can be seen in Figures 3 to 5.
All nails were tested and exhumed, with roughness and actual diameters measured, taking advantage when the water table was low enough for partial excavation without the need for shoring. Table 1 summarizes the planned scenarios, where GG are gravity grouted nails without additives, GA are gravity grouted nails with addition of expanding additives and GR are nails performed with the sectorized post grouting technique.

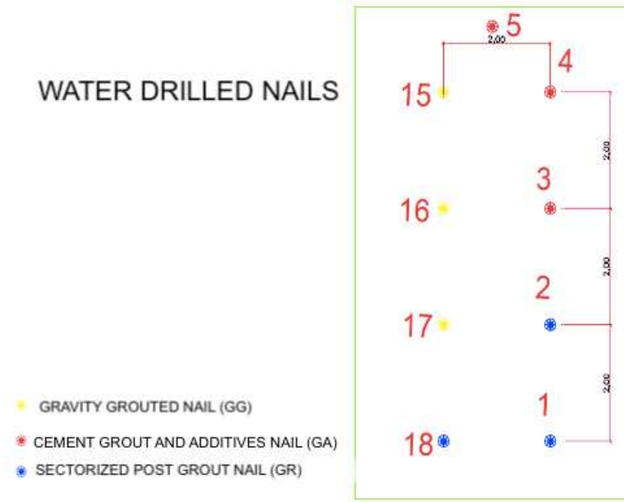

Figure 1. Layout of nails executed through water drilling, with legend

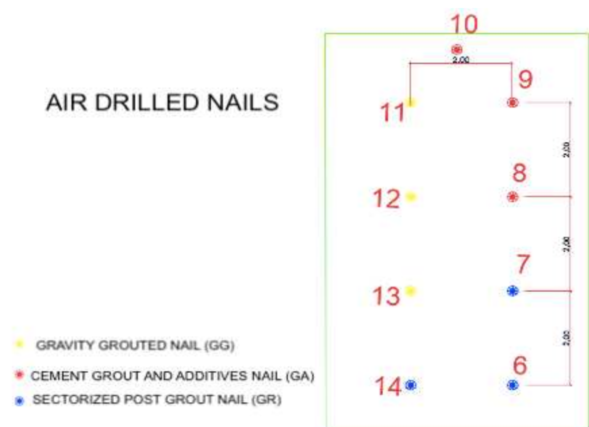

Figure 2. Layout of nails executed using air drilling, with legend

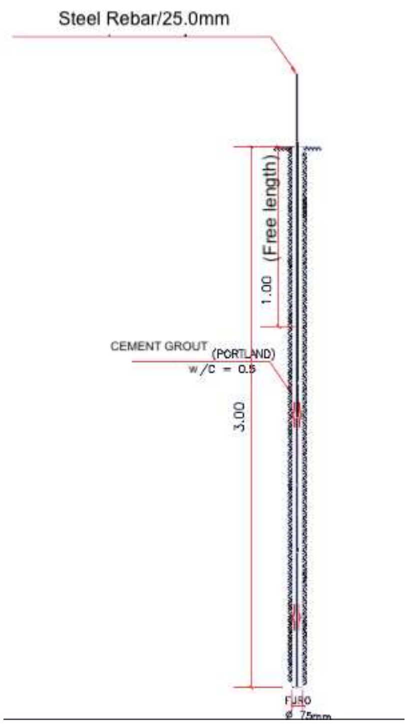

Figure 3. Detail of gravity grouted nails (GG), without additive (in yellow in Figures 1 and 2)

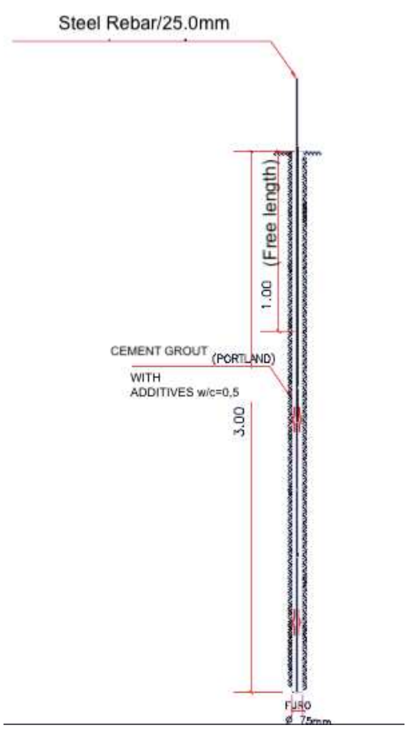

Figure 4. Detail of gravity grouted nails with additive (GA) (in red in Figures 1 and 2)

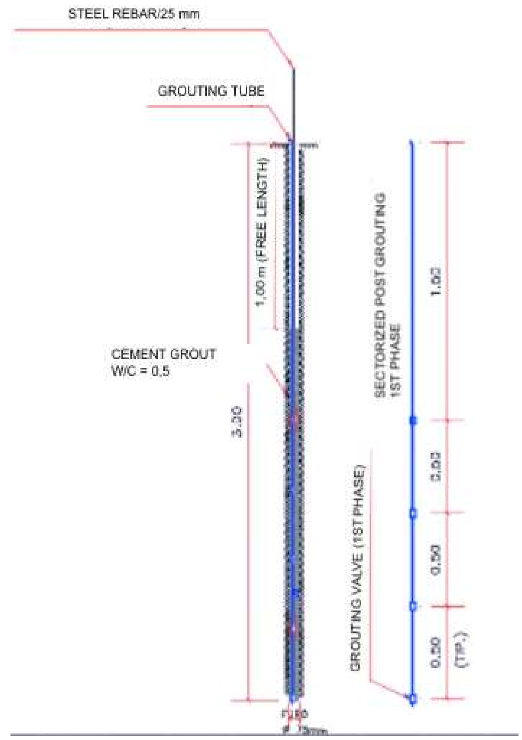

Figure 5. Detail of nail performed by the sectorized post grouting technique (GR), without additive (in blue in Figures 1 and 2)

Table 1 – Summary of execution scenarios

Scenario	Grouting Met.	Met. of execution	Nail number
1	GG	Air drilling	11, 12, 13
2	GA	Air drilling	8, 9, 10
3	GR	Air drilling	6, 7, 14
4	GG	Water drilling	15, 16, 17
5	GA	Water drilling	3, 4, 5
6	GR	Water drilling	1, 2, 18

2.2.1 *Pullout tests*

The tests were carried out 84 days after the execution of the nails, representing the cement grout reached a representative long-term compressive strength and for the nails to go through dry and rainy periods in Brasília, so that their pullout resistance would be more representative of long term. The free length was 1.0 m, necessary because when applying the tensile load to the bar, the soil surface is subjected to compression loads, which could result in inaccurate results (Seo et al., 2012). The test was carried out using the following devices:

- ASTM A36 steel reaction base, 30 mm;
- Hydraulic jack and oil pump with 30-ton capacity pressure gauge;
- Two dial indicators measuring axial displacements of the nail end with an accuracy of 0.1 mm, with a reference base at more than 5 diameters of the nail axis being tested, for representativeness of the readings.
- Calibrated hollow load cell, with digital data recorder;

Maximum load that can be applied is the calculation resistance of the steel bar (γ_f=1.0), seen in Eq. 1:

$$T \leq A\_S.FYK/\Gamma S = 213,42\ KN \quad (1)$$

where

T: ultimate load of the nail frame used in the test

A_s: cross - sectional area of the nail frame , 25 mm steel bar
f_{yk} : characteristic yield stress of the steel used
γ_s : weighting coefficient the strength of the nail frame ; for steel bars ($\gamma_s = 1.15$)

In any case, as each nail were only 2.0 m anchored, even when carried out through sectorized post grouting, the maximum test load, T, was a load of 150 kN. If the nail did not pullout until T, the test would continue with the same criterion until pulling out. Furthermore, as an auxiliary criterion suggested by Clouterre (1991) and Zhang et al. (2009), it was considered that the nail would have suffered pullout if there was 1 mm of displacement, with less than 1% increase in measured load, at a given loading stage.
The trial was carried out in stages. Before any measurement, an initial load (P_0) was applied to adjust the system clearances. This load was the minimum possible to be read accurately by the loading and reading set used, limited to 10% of the maximum expected load. Starting from the initial load (P_0), as many loading stages as were necessary were applied to obtain the load-displacement curve, with at least five stages of equal loading (20% of the maximum load predicted for the test - T), with 5 min at each stage.

q_s was calculated using Eq.2:

$$q_s = T/(L\_b.\pi.\varnothing h) \qquad (2)$$

where
L b: anchored length;
Øh.: diameter of the hole;
q_s : resistance of the soil-nail interface
The details of the tests can be seen in Figure 6.

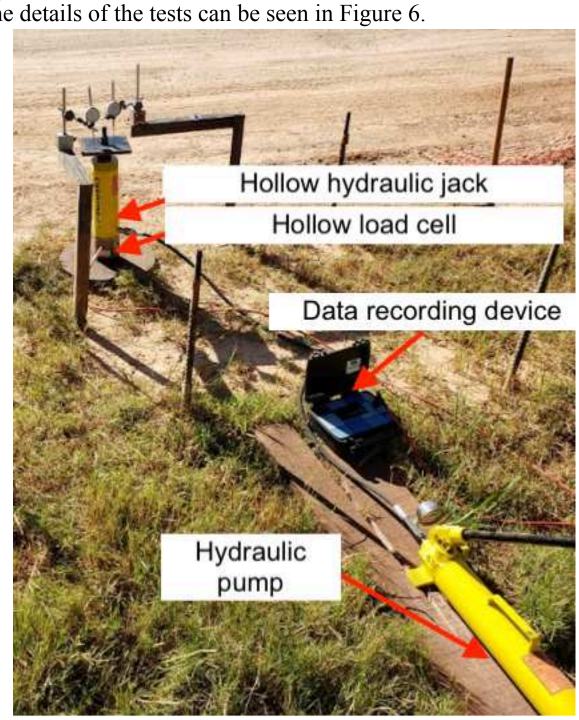

Figure 6. Components for performing pullout tests – load application device and measurement system

Following these guidelines, the study aimed to provide a comprehensive assessment of the pullout resistance of soil nails, contributing to more informed design and construction decisions for soil nails in Brasília.

3 RESULTS

The results of the pullout tests were categorized according to the drilling and grouting methods utilized. Due to the influence of the execution methods used on the final diameter and roughness of the soil-nail interface, the data obtained from the exhumation of the nails was also presented.
Table 2 presents the data obtained from the exhumation of these nails. Figure 7 summarizes the average pullout test results according to the drilling and grouting method used.

Table 2 – Results of exhumed nail effective diameters (Øefet), average roughness angle (AMR), q_s and q_{scor} (corrected for the exhumed effective diameter), for all nails

Nail number	Type	Met . of drill.	Øefet. (cm)	AMR (°)	q_s (kPa)	q_{scor} (kPa)
1	GR	Water	14.39	42.6	278.86	150.03
2	GR	Water	13.94	38.1	289.26	141.70
3	GA	Water	12.80	14.3	176.89	103.65
4	GA	Water	11.78	25.3	212.27	135.14
5	GA	Water	9.77	23.7	149.83	115.02
6	GR	Air	11.46	26.7	249.72	163.43
7	GR	Air	12.19	33.7	264.29	162.61
8	GA	Air	9.77	19.7	151.92	116.62
9	GA	Air	10.82	24.1	93.65	64.91
10	GA	Air	10.19	16.3	195.62	143.98
11	GG	Air	10.92	41	258.05	177.23
12	GG	Air	9.45	19.7	249.72	198.19
13	GG	Air	9.87	18.7	185.21	140.74
14	GR	Air	12.32	27.3	218.51	133.02
15	GG	Water	12.41	18	280.94	169.73
16	GG	Water	11.24	35	266.37	177.80
17	GG	Water	12.83	33	273.66	160.00
18	GR	Water	15.31	35.3	295.51	154.02

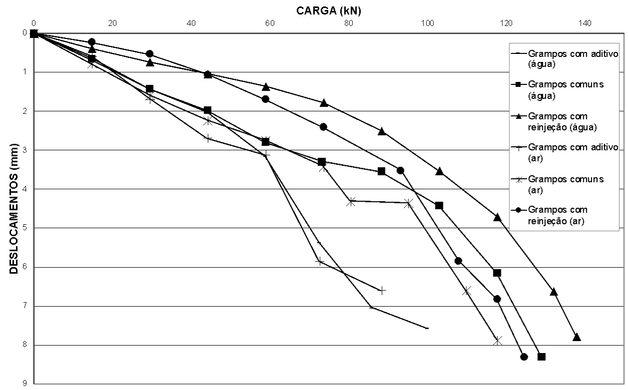

Figure 7. Graph of load (kN) vs displacements (mm) of the average pullout tests

4 DISCUSSION

To compare the executive methods of the nails, comparisons were made between the same grouting techniques for the different drilling techniques and subsequently the comparison between the grouting techniques that obtained the best results for each type of nail, since in all cases the water drilling method achieved superior results.

In the vertical pullout tests, it was possible to observe drilling with water for GG nails, GA nails and GR nails obtained superior results in pullout resistance. It is assumed that these better results come from the unblocking of pores around the hole during the cleaning provided during the use of the water drilling method as the drilling fluid, so that there is a way for the grout to flow and fill any voids or gaps in the possible radius of action, dependent on the cohesion and viscosity of the cement grout (Barbosa, 2018), leading to a larger diameter, a higher AMR and, possibly, a better soil-nail interaction. However, there were significant differences between the different types of nails tested, according to the grouting technique, as can be seen in Figures 8 to 10.

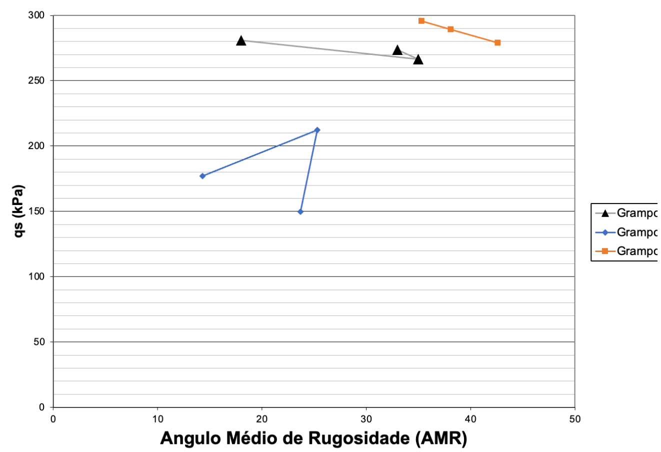

Figure 8. Average Angle of Roughness (AMR, in degrees) vs. qs (kPa) for water drilled GG, GA and GR nails.

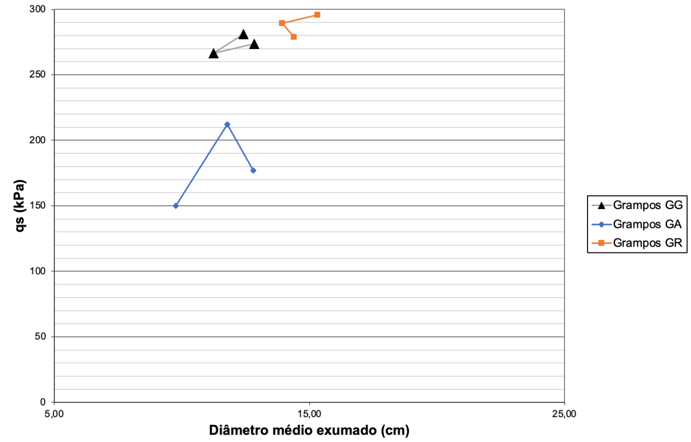

Figure 9. Graph Average exhumed diameter (Ø exu , in cm) vs. qs (kPa), for water drilled GG, GA and GR nails.

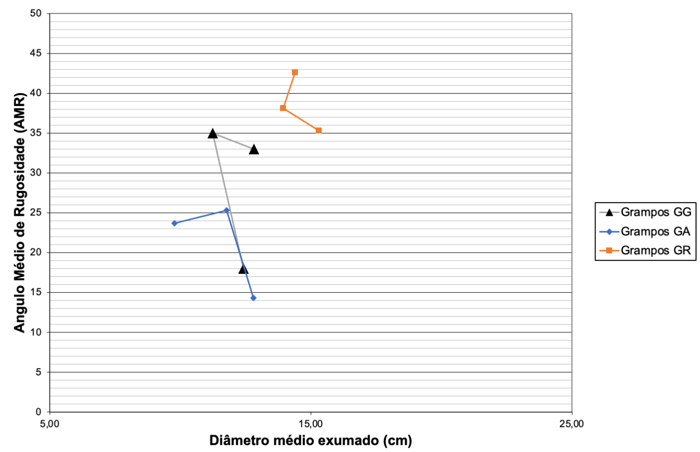

Figure 10 - Graph Average exhumed diameter (Ø exu , in cm) vs Average Angle of Roughness (AMR, in degrees), for GG, GA and GR nails drilled in water.

The analysis of Figures 8 to 10 highlighted that the GR nails, executed with post grouting, presented the best results in pullout resistance. The average pullout strength was 5% higher compared to GG nails and 60% higher compared to GA nails for the Brasília collapsible porous clay. A significant difference was observed between the GG and GA nails, with the former presenting 52% better results, even with an average exhumed diameter that was only 6% larger. This difference suggests a greater influence of AMR on pullout resistance, highlighting the limitations of Eq . 2 in considering the roughness of the nails, as mentioned in Hong (2011).

Furthermore, the simple compressive strength of cement grout, common and with additives, was compared, showing a 16% higher resistance in the common cement grout compared to the grout with additives. This demonstrates adherence to Moosavi et al. (2005), who indicated that cement grouts with lower resistance to simple compression result in lower expansion and pullout resistance. There was also an exponential relationship between the compressive strength of the cement grout and the pullout strength, highlighting the importance of quality control of cement grout.

The difference in pullout strength between the GG and GR nails was smaller than expected, despite the larger average exhumed diameter and AMR of the GR nails. This can be attributed to the experimental campaign of vertical nails, which showed similar or inferior results to sub-horizontal nails due to grouting pressure. The stability of the holes was observed during the experimental execution, demonstrating the integrity of the holes from the installation of the nails to the pullout tests.

5 CONCLUSIONS

The results of the experimental run indicate that water drilling is more effective for all grouting techniques studied when installing nails in Brasília's soil, especially due to the resulting increase in average diameter. On the other hand, the use of additives in cement grout expanding is not recommended, as it can reduce the simple compression strength of the cement grout and result in less rough interfaces between the soil and the nail.

The hypothesis that a rougher, larger-diameter soil-nail interface is more suitable for soil-nailed applications was confirmed, as it provides greater pullout resistance. Although Equation 2 offers a theoretical basis for representing the pullout resistance of nails, relating q_s to the applied force for a given diameter and surface area of the nail, it is necessary to consider the roughness and quality of the soil-nail interface. This was evidenced in the comparison between GA and GG clips, where the small difference in average diameters did not explain the large discrepancy in pullout strength q_s, requiring the use of data on average roughness angles (AMR) and simple compressive strength of cement grout to explain the difference.

GR nails, although recommended by the authors due to the predictability of mechanical behavior and greater robustness, did not prove to be the most economical, given that GG nails, which are faster to execute due to the absence of the post grouting process, offer good performance and are the most suitable for the Brasilia's porous clay.

6 ACKNOWLEDGEMENTS

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