Pullout Testing of Soil Nails in Gneissic Residual Soil

A.C.N.B. Arêdes, E.A.G. Marques, A.H.C. Oliveira

Abstract. Soil nailing has proved to be an efficient and cost-effective stabilization technique, consisting in installing passive reinforcement in the soil that provides the material with tensile and shear strengths. The fundamental parameter in analyzing the mechanical behavior of this type of structure is the frictional resistance of the soil-nail interface, denominated q_s. This paper presents the results of pullout tests performed on a slope located on the campus of the Federal University of Viçosa, in Viçosa-MG, Brazil. Drilling boreholes enabled the identification of four different types of soil with predominant composition of fine sand and silt, all characterized as a gneissic residual soil. Different lengths and methodologies were studied in the pullout tests with the aim of assessing the impact these factors have on shear strength. The values of q_s obtained in the tests were similar to the ones reported by other authors. Even when running tests with low pressures, the results showed that the first grouting reinjection stage was able to provide a significant gain in the pullout resistance of the nails. Another point of observation was that, even though there are reasonable estimated values of q_s in the literature, the conduction of pullout tests is essential for the confirmation of the values to be used in each situation.

Keywords: gneissic residual soil, nail types, pullout test, reinjection grouting, shear resistance of the soil-nail interface, soil nailing.

1. Introduction

1.1. Principles of soil nailing

Among the techniques of soil stabilization, soil nailing is one that has been widely used for its efficiency, competitive cost-effectiveness, flexibility, and easy production. This method consists in inserting passive inclusions into the soil that provide it with additional tensile and shear strengths.

In the study of the mechanical behavior of soil nailing, it is assumed that the reinforced massif can be divided into an active zone, bounded by a failure surface, and a passive zone that is considered the resistant zone, where the nails are anchored.

The main mechanism of interaction between the nails and soil is associated with the mobilization of the frictional resistance of the soil-reinforcement interface, denominated q_s. Therefore, the pullout resistance is a fundamental parameter for the design of soil nail walls.

According to Ortigão (1997) and Hong *et al.* (2013), some factors can affect the value of q_s, such as ground conditions, effective overburden stresses of the soil nails (depth and overload), drilling method and hole cleaning, grout injection method and grout characteristics, as well as environmental factors, such as temperature and humidity.

The friction between the nail surface and surrounding soil can be determined through the application of empirical and theoretical methods, the elaboration of empirical correlations with results obtained in field trials, as well as through the conduction of field pullout tests.

Pullout testing is considered to be the most appropriate method to study soil-nail interaction, being widely employed for quality control in construction and performance evaluation of soil nail walls (Babu & Singh, 2010a and 2010b). The test consists in using a hydraulic jack to apply tensile loads to the nail anchored in the ground, then recording the displacement of the nail head for each applied load. The maximum axial tensile load exerted on the soil nail is obtained from the load-displacement curve.

There is no Brazilian standard that regulates the conduction of pullout tests, but several authors - such as Ortigão (1997), Ortigão & Sayão (2000), Zirlis *et al.* (2003), Springer (2006), Feijó (2007), and Beloni (2011) - have already presented recommendations for the procedure and how it should be controlled in soil nailing constructions.

The mobilization of shear strength upon the contact between the soil and the nail is not uniform. However, as a simplification, the value is assumed to be constant along the length of the reinforcement, resulting in a constant value of pullout resistance (q_s) that is calculated using Eq. 1. For nails larger than 10 m, the value of (q_s) varies in a non-linear manner along its length.

$$q_s = \frac{F_{\max}}{\pi D \cdot L_{anchored}} \tag{1}$$

where $F_{\max}$: maximum axial tensile load on the nail; D: drilling diameter; and $L_{anchored}$: anchored length of the nail.

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Submitted on April 10, 2019; Final Acceptance on October 1, 2019; Discussion open until August 31, 2020.
DOI: 10.28927/SR.431085

In this context, this paper presents results of pullout tests performed on a gneissic residual soil with the aim of determining the value of q_s. The objective of this study is to analyze the results of the tests, comparing them with values found in the literature, and to evaluate the variations in the nail's shear strength that result from the use of different nailing characteristics.

1.2. Values of q_s

Many studies present field pullout tests of soil nails conducted in Brazil and worldwide. Springer (2006) performed 25 pullout tests on a gneissic residual soil in Niterói - RJ, Brazil, obtaining results of q_s that ranged from 94 kPa to 240 kPa for nails without reinjection, and varied between 159 and 231 kPa for nails with 1 reinjection stage.

Beloni *et al.* (2017) conducted pullout tests with 12 nails without reinjection in a mature gneissic residual soil composed of sandy clay, located in Viçosa - MG (Brazil), obtaining values between 47 kPa and 82 kPa.

Seo *et al.* (2017) performed field pullout tests to analytically determine the shear behavior between the soils and grout, especially the soil-dilation effect that occurs during shearing. For this study, three experimental fields with different soil types were selected: colluvial soil, weathered granite soil, and fill soil. Two different construction methods were also analyzed: gravity grouting and pressure grouting. In the weathered granite soil, three different anchored lengths (2.0 m, 3.0 m, and 4.0 m) were used to verify the effect of the nail's length. All types of soil nails were installed in the vertical direction. After the pullout tests, the diameters of the soil nails were measured, being in around 13 cm with gravity grouting and 16 cm with pressure grouting. In this study, increased diameters were adopted to calculate the value of q_s.

According to Seo *et al.* (2017), the results for the colluvial soil (classified by the Unified Soil Classification System - USCS - as ML) showed values of q_s that varied from 96 to 120 kPa. In the weathered granite soil (USCS - SM), the pullout resistance observed ranged from 128 to 160 kPa, and, for the fill soil (USCS - SC), the average value of q_s was approximately 72 kPa.

Oliveira *et al.* (2017) presented a study of an area located in Ipatinga - MG, Brazil. In order to carry out this study, pullout tests were performed on 7 soil nails (1 without reinjection grouting, 3 with 1 stage of reinjection grouting, and 3 with 2 stages of reinjection grouting). All nails had 5 m of anchored length in a silty fine sand soil. The authors obtained mean q_s values of 53.36 kPa for nails without reinjection, 62.17 kPa for nails with 1 reinjection stage, and 79.77 kPa for nails with 2 reinjection stages.

Ghadimi *et al.* (2017) investigated the effects of overburden, injection pressure, and soil strength parameters on the bond strength of nails *in situ*. For this research, five different sites in Tehran, Iran, were studied, with a total number of 20 pullout tests of soil nails. The soils on all sites had a percentage of fine-grained soil < 10 %, a predominant composition of sand, gravel content > 37 %, and reached q_s values up to 600 kPa.

Hong *et al.* (2017) presented an analysis of the influence of a few parameters (overburden pressure, grouting pressure, and degree of saturation) on the pullout resistance of soil nails installed in a typical fully-decomposed granite or sand. Eight pullout tests of soil nails were conducted *in situ*. The authors presented the results obtained from laboratory and field tests, with a q_s value around 85 kPa.

Other researchers (França, 2007; Bhuiyan *et al.*, 2019) presented the results obtained from pullout tests carried out with a soil nail wall prototype built in a laboratory, which enabled the verification of conditions not often found *in situ*. França (2007) obtained values of pullout resistance of 145 kPa for medium-plasticity clayey-sand (USCS - SC). Bhuiyan *et al.* (2019), in turn, used Stockton Beach sand (silica sand) under varying conditions of overpressure and injection pressure, finding a maximum axial tensile load on the nail that ranged from 4.5 kN to 25 kN, with no specification of the exact diameter of the nails.

Silva (2018) used statistical analysis correlation to estimate the pullout resistance (q_s) in cohesive soils, based on results of percussion drilling (standard penetration test) and pullout tests. The research was carried out with 20 soil nails located in São Paulo - SP, Brazil, in 5 layers of different soils with lengths of 10 m, from which 7 m formed its free length and 3 m corresponded to the anchored length. The author proposed a correlation between N_{SPT} and q_s according to Eq. 2.

$$q_s = 65.80 + 1.68 N_{SPT} \tag{2}$$

Noor & Jamain (2019) based themselves on a case study to highlight the pullout and creep behavior of soil nailing. The soil nails were installed in three different construction sites, each consisting of a different type of soil (medium-stiff clayey silt, silty sand fill, and sandy silt set in rock). The selected nails underwent testing up to the point where the pre-determined working load reached 1.5 times its original value. According to the results, the silty sand fill generated a lower value of pullout resistance that ranged from 8.75 to 26.00 kPa. The medium-stiff clayey silt displayed values of pullout resistance of 50.40 kPa, while the soil nails installed in the sandy silt with rock yielded the highest value of pullout resistance, ranging from 127.32 kPa to 305.60 kPa.

2. Materials and Methods

2.1. Description of the location

This study was conducted in a cut slope in a gneissic residual soil, and was performed during the expansion of P. H. Rolfs avenue, located on the campus of the Federal University of Viçosa, in Viçosa, Minas Gerais, Brazil (Figs. 1 and 2). This research was brought about by the collapse of

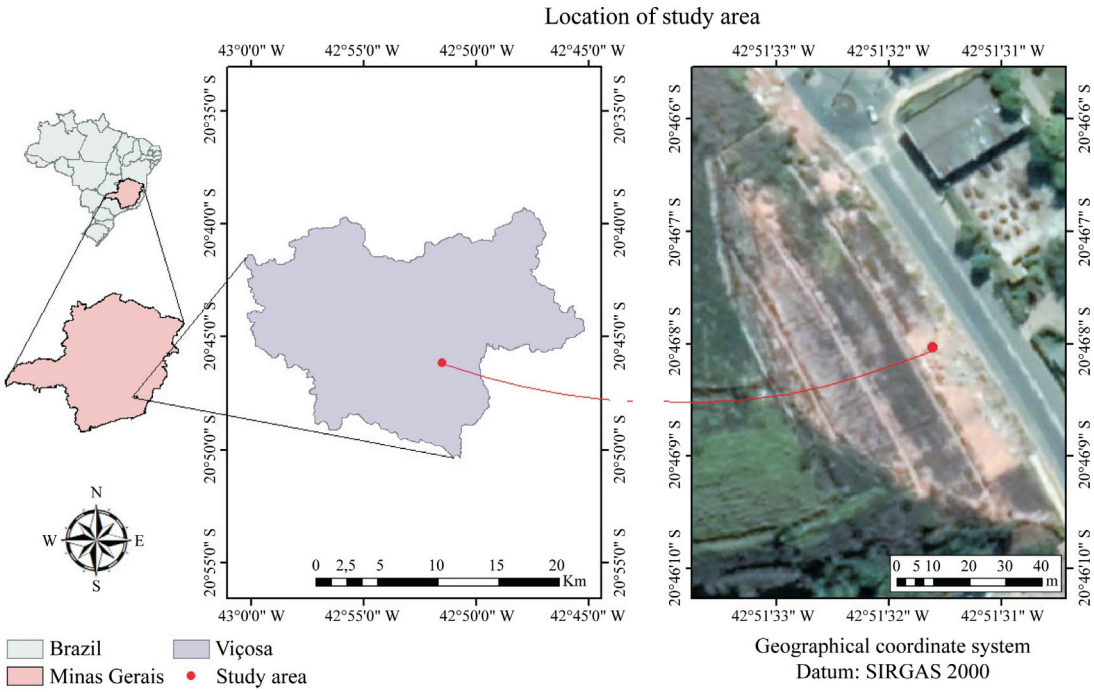

Figure 1 - Location of study area. Source: Google Earth.

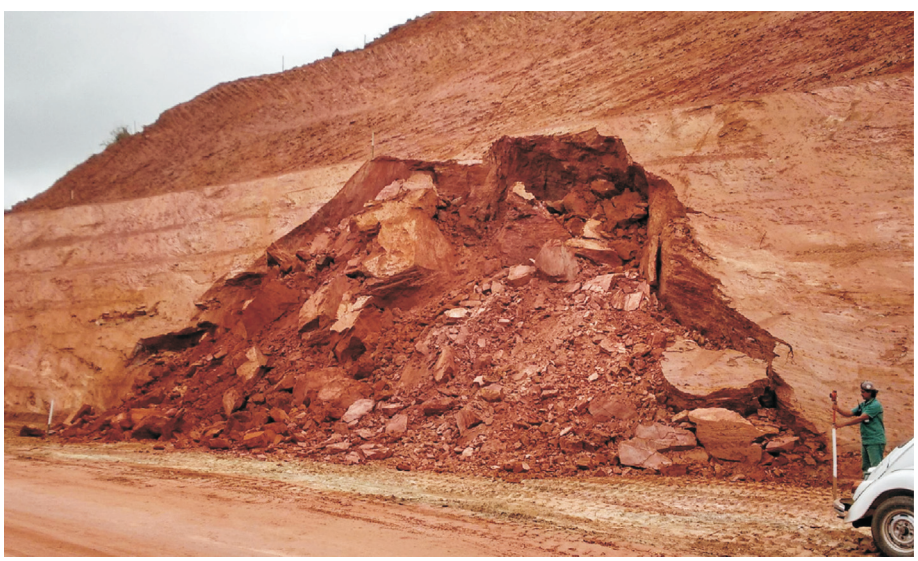

Figure 2 - Front view of failure occurred in the studied area.

this slope that occurred during the dry season of 2015, between July 4th and 6th. At the time when the slope movement occurred, there were no drainage devices installed on the slope. A back analysis of this slope failure was presented by Arêdes *et al.* (2017).

The topography of the site was determined using a Terrestrial Laser Scanner (RIEGL VZ 400), a GNSS receiver (JAVAD) and a digital camera (Nikon 600D). Eight boreholes, with a maximum depth of 10 m, were drilled using a mechanical auger to identify the types of soil present in the geological-geotechnical cross-section that was built to perform slope stability analysis and to allow characterization of the site. Disturbed soil samples were collected at every 25 cm of drilling, and a visual-tactile examination was performed. The plan and cross-section were processed using Topograph (2012) and AutoCAD (2016) software.

2.2. Laboratory tests

Using PVC tubes (40 cm in height x 35 cm in diameter), four undisturbed samples were collected from the slope for laboratory tests. Following these tests, geotechnical characterization of the soils was performed to deter-

mine particle size distribution (ABNT, 2016d), particle unit weight (ABNT, 2016c), liquid limit (ABNT, 2016b), and plastic limit (ABNT 2016a).

The shear strength parameters of the soils were obtained from direct shear testing with natural water content, following the recommendations from ASTM (2011).

2.3. Pullout tests

The twelve holes drilled to install the nails were arranged in a single line with an average horizontal spacing of 1.5 m (Fig. 3). Among the twelve holes, six were drilled with 6 m length and an average diameter of 100 mm (nails 1 to 6 - Fig. 3), while the other six were drilled with 4 m length and the same average diameter (nails 7 to 12 - Fig. 3). Drilling of nails 2, 3, and 4 was done with a hydraulic drilling rig, while all other nails were drilled with a mechanical auger. After the drilling process, a PVC pipe was used to wash the holes until clean water came back through the orifices. The soil nails were installed at a 15° downward horizontal inclination.

To produce the nails, seven-meter-long CA-50 steel bars with 20 mm diameter were used in the holes that were 6 m in length, whereas five-meter-long bars were used for the ones with lengths of 4 m. Centralizers made of polyvinyl chloride (PVC) were installed along the length of each nail bar (spaced 1.5 m apart) to ensure that the nail bar was positioned in the center of the hole and that a minimum thickness of grout covered it completely.

In order to study the effect of the grout injection method on the shear resistance of the soil-nail interface, three types of nail were examined: without reinjection grouting (sleeve grout) and with 1 or 2 stages of reinjection grouting. The reinjection grouting was achieved with a tube-à-manchette attached to each steel bar. The tube-à-manchette used in this study consisted of a grout pipe that had 20 mm diameter and was perforated with small holes (grout injection points) at intervals of 1 m, which were enclosed by a sleeve of adhesive tape.

After the nail was prepared (Fig. 4a), it was inserted into the hole, leaving a gap of 1 m from the surface for the purposes of the pullout test. To prevent the cement grout from filling the first meter of the hole, the bar was wrapped with foam along this length.

The grout (cement CP-32 II-E), with a water/cement ratio of approximately 0.7, was released upwards at low pressure to perform the sleeve grout using the same PVC pipe used for washing the hole. The first stage of reinjection grouting was performed 24 h after the execution of the sleeve grout, and, during this step, the pressure grouting had a value of approximately 235 kPa. In this phase, a volume of grout corresponding to 4 bags of cement was injected for 5 min into the soil nails with 3 and 5 m of anchored length, respectively.

The first reinjection stage of the nails in which two reinjection stages would be carried out was not performed satisfactorily. During the course of the pressure grouting, in addition to the injection valves having ruptured and caused the valves that would be used in the second stage to break, too, part of the grout also came back through the hole. Thus, the applied pressure was relieved and the expected grout bulb was not formed. The test results for these nails (1, 4, 7, and 12) were considered incomplete reinjections and were disregarded in this study.

Table 1 summarizes the information related to each soil nail.

The setup (Figure 4b) of the pullout test was composed by the following equipment: pieces of wood (I), welded steel plate (II), hydraulic jack cast with a capacity of 50 tons (III), set for locking the steel bar (IV), steel plate for supporting extensometers (V), mechanical strain gauges

Figure 3 - Position of the soil nails.

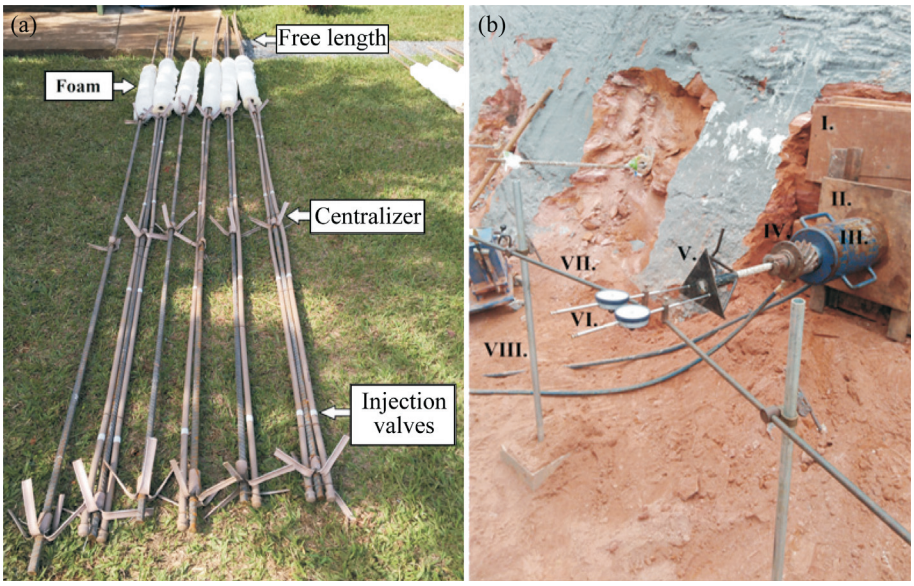

Figure 4 - Components of the pullout test: (a) Bar for insertion into the prepared hole. (b) Arrangement of the pullout test system.

Table 1 - Summary of nails information.

Soil nail	Total length of the steel bar (m)	Total length inserted into the hole (m)	Anchored length (m)	Diameter (mm)	Equipment used in drilling	Grouting method
1	7.00	6.00	5.00	100	Mechanical auger	Sleeve grout + 1 incomplete reinjection stage
2	7.00	6.00	5.00	100	Hydraulic drill	Sleeve grout + 1 reinjection stage
3	7.00	6.00	5.00	100	Hydraulic drill	Only sleeve grout
4	7.00	6.00	5.00	100	Hydraulic drill	Sleeve grout + 1 incomplete reinjection stage
5	7.00	6.00	5.00	100	Mechanical auger	Only sleeve grout
6	7.00	6.00	5.00	100	Mechanical auger	Sleeve grout + 1 reinjection stage
7	5.00	4.00	3.00	100	Mechanical auger	Sleeve grout + 1 incomplete reinjection stage
8	5.00	4.00	3.00	100	Mechanical auger	Only sleeve grout
9	5.00	4.00	3.00	100	Mechanical auger	Sleeve grout + 1 reinjection stage
10	5.00	4.00	3.00	100	Mechanical auger	Sleeve grout + 1 reinjection stage
11	5.00	4.00	3.00	100	Mechanical auger	Only sleeve grout
12	5.00	4.00	3.00	100	Mechanical auger	Sleeve grout + 1 incomplete reinjection stage

(VI), arms for pivoting and adjusting the position of the extensometers (VII), and a concrete-based fixed support for the pivot arms (VIII).

The pullout was carried out in stages, each corresponding to an additional application of load. During these stages, readings of the extensometers were taken at specific times: 0 s, 15 s, 30 s, 1 min, 2 min, 4 min, 8 min, 15 min and 30 min. After the thirty-minute reading, the stabilization of the displacement readings (Eq. 2) was checked. If this condition was satisfied, the end of the stage was characterized; otherwise, readings for 1 h, 2 h, and 4 h (and so on) were performed, doubling the value until stabilization was achieved. In Eq. 3, l_i represents the reading taken at each of the loading stages.

$$\frac{l_i - l_{i-1}}{\sum_{l=0}^{i} l} \times 100 \leq 5\,\% \tag{3}$$

At the end of each stage, the procedure was repeated with a new application of load and another cycle of read-

ings. In order to obtain sufficient data for the elaboration of the load-displacement curve, the increments for each loading step were estimated from the maximum pullout force expected for the soil. It was possible to notice that the frictional resistance in the soil-nail interface was overcome when the applied load did not stabilize and great displacements occurred.

3. Results and Discussion

3.1. Pluviometric data

The pluviometric information about the site, referring to this study's period of interest (July 4th to 6th, 2015), was obtained from the website of the Brazilian National Institute of Meteorology (INMET). Their data are generated daily in the weather station of Viçosa-MG, located on the campus of the Federal University of Viçosa, at a distance of 1.5 km from the slope site.

According to INMET (2016), there was 0 mm of rainfall in the city of Viçosa during this period, with the previous rainfall registered on June 16th with 4 mm, as shown in Fig. 5.

3.2. Geological and geotechnical site characterization

A visual-tactile examination of the disturbed samples was used to elaborate a representation of the geological-geotechnical cross-section of the slope, aligned with two boreholes, as shown in Fig. 6a. The field investigation revealed four different types of soil, all characterized as gneissic residual soil with many relict structures: faults, foliation (preserved), and manganese lenses. The mineralogy was mainly composed of quartz, feldspar, and mica. The groundwater table was not found during drilling.

Soil 1 was characterized as a fine silty sand and was dark red and purple in color; Soil 2 presented a silt-sandy texture and had an ochre color; Soil 4, which showed a lighter coloration that was rosier with grayish tones, displayed kaolinized levels and was classified as a silt with fine sand; finally, Soil 3, which was a mixture of soils 1 and 2, had variegated colors. Figure 5b shows the interface between Soils 2 (above) and 1 (below) displayed on the failure plane, with some relict faults planes transversal to the cut slope.

3.3. Laboratory tests

Table 2 presents a summary of the results of geotechnical characterization of four soil samples.

After fitting the linear Mohr-Coulomb failure envelope to the direct shear test results, the friction angle (ϕ) and cohesion intercept (c) were obtained for the envelopes containing the maximum values of shear stresses and the post-peak values, as shown in Table 3.

3.4. Pullout tests

During the testing routine, the hydraulic jack presented a deficiency that prevented the conduction of pullout tests on soil nails 4 (5 m, 1 incomplete reinjection) and 10 (3 m, 1 reinjection). As previously mentioned, the results of nails with 1 incomplete reinjection (nails 1, 4, 7, and 12) were disregarded in this study. Thus, only seven of the tests that were originally planned could be effectively considered valid. Figure 7 shows the results of the pullout tests, where unfilled markers represent the nails with 5 m of an-

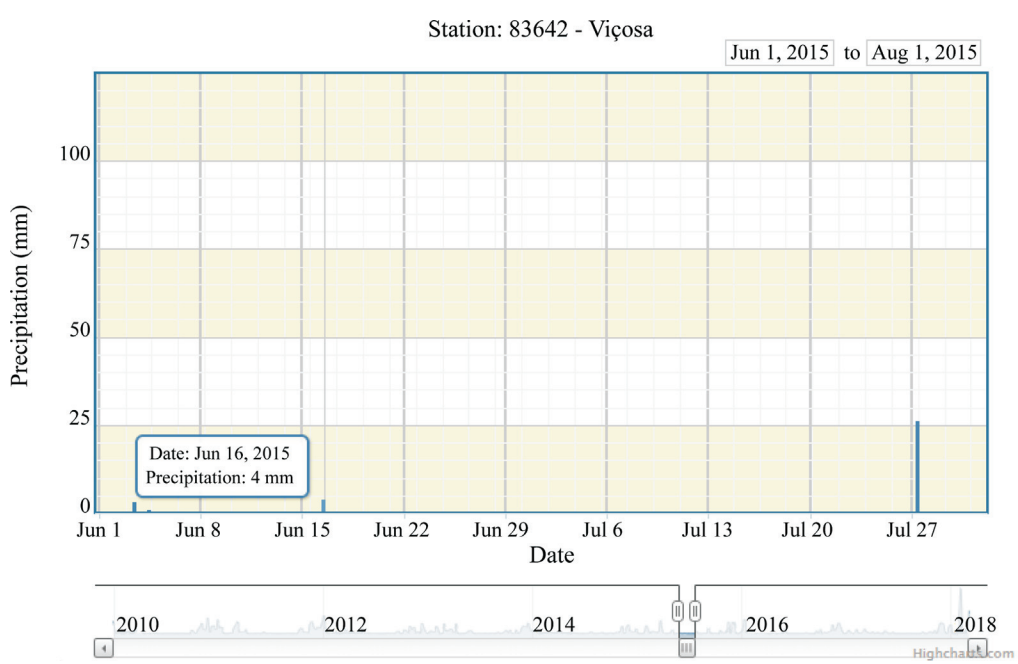

Figure 5 - Precipitation information about Viçosa between June 1st and August 1st. Source: INMET, 2019.

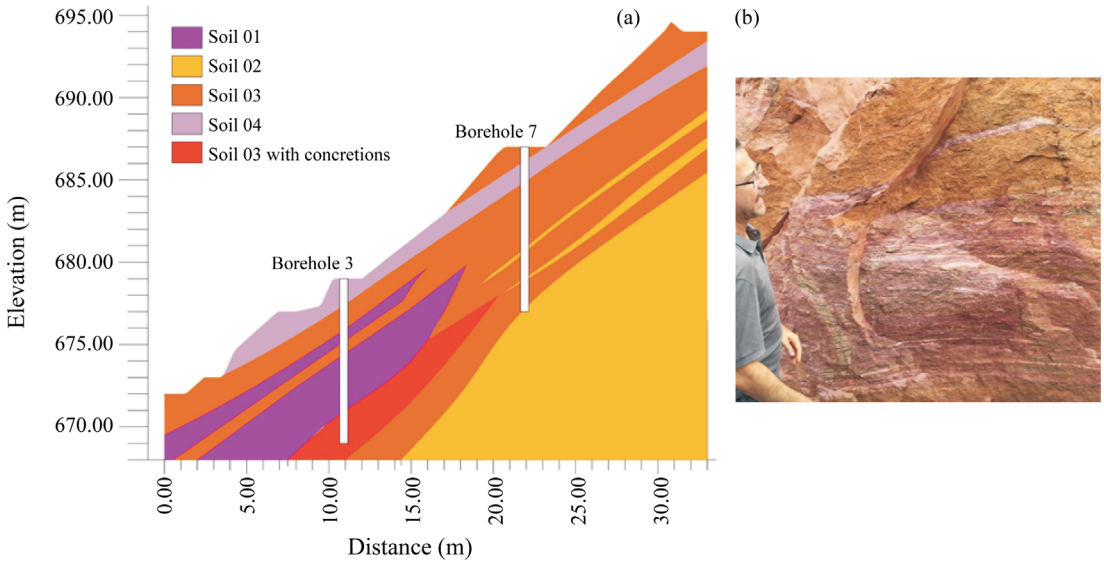

Figure 6 - Geotechnical characterization of the study area. (a) Geological-geotechnical cross-section. (b) Detail of the interface between the layers of Soils 03 (upper) and 01 (lower) and failures.

Table 2 - Results of geotechnical characterization of the samples.

Soil	Particle size distribution (%)			Atterberg limits (%)			γ_s (kN/m^3)
	Clay	Silt	Sand	LL	PL	PI	
1	3	23	74	38	21	17	26.61
2	9	49	42	55	30	25	27.58
3	5	33	62	44	28	16	27.34
4	3	35	62	39	27	12	26.41

chored length, and filled markers represent the tests with 3 m of anchored length.

A summary of the valid results is shown in Table 4. The maximum values of axial tensile load were obtained from the point of greatest curvature in the graphs of Fig. 7 that is, the maximum tensile force supported by the nail without excessive displacement.

When analyzing the results of the tests performed on soil nails with anchored length of 5 m, it is possible to see that, for soil nails without reinjection (3 and 5), the average maximum force was 108 kN. The two nails were placed with different drilling methods - one with a hydraulic drilling rig and the other with a mechanical auger -, but there was no significant difference in the maximum strengths. Nails with 1 reinjection (2 and 6), in turn, had an average pullout force of 148 kN. For soil nails 3 and 5, the drilling was performed differently and no effect of this procedure was observed on the maximum strengths.

Table 3 - Strength parameters.

Soil	Parameters	Maximum	Residual
1	Cohesion intercept (kPa)	29	21
	Friction angle (°)	26	24
2	Cohesion intercept (kPa)	79	1
	Friction angle (°)	34	44
3	Cohesion intercept (kPa)	41	23
	Friction angle (°)	20	21
4	Cohesion intercept (kPa)	25	19
	Friction angle (°)	16	12

During the testing of nails 2 and 6, due to deficiencies in the pullout support system, eccentric efforts were generated in the bar, which may have caused an increase in resistance. Nevertheless, the results of these tests were not excluded from the analysis, since their values were similar to the ones found in the literature for similar soils (Springer, 2006; Beloni, 2011; D'Hyppolito, 2017), and were consistent with the other tests performed in this study.

For soil nails with 3 m of anchored length, the load-displacement curves demonstrated that nails that used only sleeve grout (soil nails 8 and 11) had an average pullout force of 44 kN. Due to an overestimation of the maximum strength attributed to nail 11, its corresponding curve was obtained from a small number of stages. Even so, it was

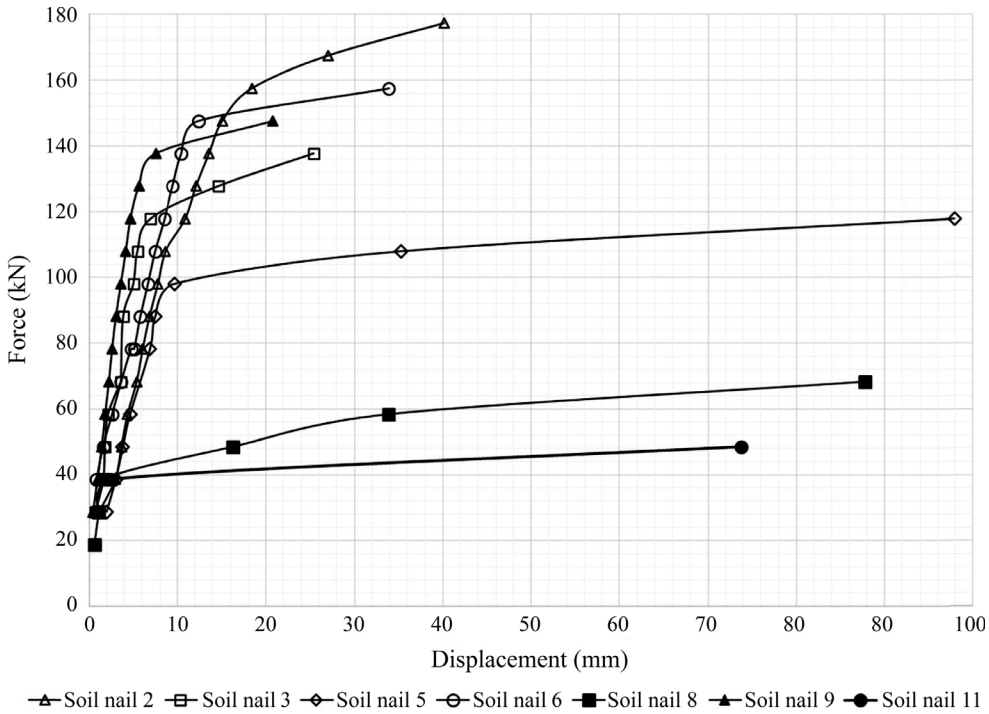

Figure 7 - Force *vs.* displacement of the soil nails.

Table 4 - Results of maximum load and corresponding displacement in the pullout tests of the soil nails.

Soil nails	$L_{anchored}$ (m)	Grout method	F_{max} (kN)	Displacement (mm)
2	5	1 reinjection	148	18.38
3	5	without reinjection	118	6.93
5	5	without reinjection	98	9.69
6	5	1 reinjection	148	12.38
8	3	without reinjection	48	16.27
9	3	1 reinjection	128	5.60
11	3	without reinjection	39	2.48

clear that the rupture occurred when this value of load was applied. With the execution of 1 reinjection, nail 9 showed a pullout force of 128 kN, a result that was not obtained for any of the other nails.

Table 5 lists the average maximum force values ($F_{max,\ mean}$) and the average pullout resistance ($q_{s,\ mean}$) grouped according to anchored length and grouting method (hole filling).

Based on the results shown in Table 5, a gain of approximately 200 % in strength can be observed in the nails with 1 reinjection and 3 m of anchored length. For the nails with 5 m of anchored length, this value was 37 % higher, as shown in Table 6. Thus, it is possible to notice a more sig-

Table 5 - Average pullout resistance results according to anchored length and grouting method.

Number of nails	$L_{anchored}$ (m)	Grouting method	$F_{max,\ mean}$ (kN)	$q_{s,mean}$(kPa)
2	5	1 reinjection	148	94
2	5	Without reinjection	108	69
1	3	1 reinjection	128	136
2	3	Without reinjection	44	47

Table 6 - Increase in pullout resistance in soil nails with 1 reinjection towards the staple without reinjection.

Anchored length (m)	Increased pullout resistance in relation to nails without reinjection grouting
3	193 %
5	37 %

nificant effect of the reinjection on the shorter soil nails, which can be justified by the higher volume of grout per meter inserted during the reinjection grouting.

Souza *et al.* (2005) reported that the increase in pullout resistance with the first-phase reinjection was equivalent to 78 % in pullout tests of soil nails with 6 m of anchored length, while Springer (2006), observed an increase of 50 % in nails with 3 m of anchored length. Hong *et al.* (2013) analyzed the effect of grouting pressure on the shear resistance of the soil-nail interface, registering an increase of approximately 47 % in nails injected with a pressure of 140 kPa (1.2 m of anchored length) when compared to the ones injected with zero pressure (gravity only). Seo (2017) observed that the maximum tensile forces obtained in the tests increased by almost 25 % in colluvium soils and weathered granite that underwent injection pressure, considering nails with 2 m of injection.

The tests performed in the present study with nails that had 3 m of anchored length showed a much higher increase when compared with the results reported by those authors, even though the results were lower for nails with 5 m of anchored length.

Despite the injected volume being the same for both nail lengths studied, which resulted in an injected volume per meter that was lower in nails with 5 m of anchored length, it was possible to observe that the five-meter soil nails with 1 reinjection had a strength that was 16 % higher than the three-meter nails (Table 5). For soil nails without reinjection grouting, this difference was around 45 %, also in favor of nails with a greater length. Such a behavior was expected, but this comparison is important to show the magnitude of the influence of nail size on pullout resistance.

Figure 8 shows a comparison between mean values of q_s for nails without reinjection (57.7 kPa) and nails with 1 stage of reinjection (115.0 kPa), using values presented in the literature and considering tests with 3 and 5 m of anchored length. The values observed in the present study were compared with results obtained from similar soils by the aforementioned authors. The values for soil nails without reinjection were closer to the ones reported in other studies, mainly those by Oliveira *et al.* (2017) and Noor & Jamain (2019).

The values of q_s obtained by Beloni *et al.* (2017), also in Viçosa-MG, were 25 % higher than those observed for nails without reinjection in this study. These authors found a mean q_s value of 75.5 kPa, and this variation can be justified by differences in the anchored length and by the variability of soil parameters.

3.5. Design aspects

The study of this site presented by Arêdes *et al.* (2017) attested to the overall stability of the slope, making it unnecessary to perform soil nailing to stabilize the slope. Therefore, a decision was made to implement a small concrete foot wall and to fill the spaces generated by the failure with rip-rap. In addition, a drainage system was installed on the berms.

Figure 9 shows the current lateral view of the slope.

4. Conclusions

In this research, we tried to evaluate the influence of nail length, and drilling and hole-filling methods on the

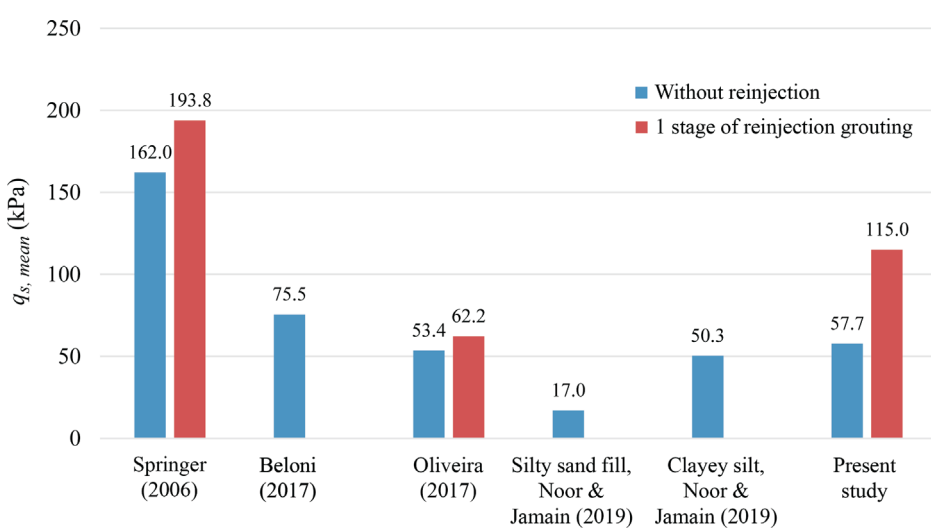

Figure 8 - Comparing values of $q_{s,mean}$ from this study with some results found on literature.

Figure 9 - Current lateral view of the slope.

frictional resistance of the soil-nail interface. The conclusions drawn from this study are summarized below:

a) Even having been performed at low pressure, the first reinjection phase was able to provide a significant gain in pullout resistance of around 200 % for three-meter nails and 37 % for five-meter nails. This increase can be explained by the filling of the voids caused by exudation of the cement grout and the formation of bulbs near the position of the valves. The difference between the three and five-meter nails arose from the lower grout volume applied per meter in the reinjection phases, compromising the comparison between nails of different lengths and same number of reinjection phases. In future studies and projects, it would be advisable to use volumes that are proportional to the lengths;

b) The methodology used to conduct two reinjections with the insertion of two tubes-à-manchette was not efficient. The adhesive tape used as sleeve did not provide adequate resistance, which resulted in its rupture during the first injection phase in both tubes, causing a return of part of the grout, a consequent pressure relief, and no formation of the expected bulb. A more resistant and flexible material, such as rubber, should be used for manufacturing the valves, which will cause them to open with the injection pressure and to close at the end of it, requiring only a tube-à-manchette;

c) The literature offers reasonable values for estimating q_s. However, it is essential for pullout tests to be performed before or during the evaluation of nailing work in order to validate these values and adjust them, if necessary;

d) Even if the pullout test is the method that provides values that are closest to reality, it is still a procedure that is very susceptible to errors in execution. The values obtained from it are very sensitive to the inexperience of operators, inaccuracy of the equipment, reading errors, poorly-supported reaction system, and many other factors. However, that does not make its conduction unnecessary, and it is only through good practice that these problems will be controlled.

Acknowledgments

This study was partially financed by the Coordination of Superior Level Staff Improvement - Brazil (CAPES) - Finance Code 001, and by the FACEV Foundation, through a partnership coordinated by Professor Eduardo Marques.

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List of Symbols

c: cohesion intercept
D: drilling diameter
PI: plasticity index
F_{max}: maximum axial tensile load on the nail
$L_{anchored}$: anchored length of the nail
LL: liquid limit
PL: plastic limit
l_i: reading performed at each of the loading stages of the pullout test
$q_{s,\ mean}$: mean value of pullout resistance
q_s: frictional resistance of soil-reinforcement interface
γ_s: particle unit weight
ϕ: friction angle
USCS: Unified Soil Classification System