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Soil nailing stabilization of a failed hillside in Belo Horizonte (MG): modelling, design and execution

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Case Study

Keywords
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Slope instability
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Finite Elements Method (FEM)
Probabilistic analysis

Abstract

The metropolitan region of Belo Horizonte city is home to several high-risk areas with a significant number of mass movement occurrences. Additionally, there are cases of movements in areas that are not considered high-risk, where constructions exhibit a medium to high construction standard. This emphasizes that, in addition to disordered occupations, the terrains have a natural susceptibility to the process. Intervention in slopes through cuts and fills is an unquestionable necessity in geotechnical projects to reinforce unstable or damaged areas. This article explores the field of soil nailing and presents the necessary design practices for its utilization, including safety checks based on deterministic, probabilistic, and finite element analysis. The case study is based in Belo Horizonte, more specifically in the '*Buritis*' neighborhood, Brazil. The reinforced slope has a height of 18.5 meters and covers a total area of 1425 square meters. Based on different methodologies, the solution was validated as the most technically feasible, executable, and financially viable.

1. Introduction

The occurrence of landslides is mainly associated with exceptional rainfall events. Three days of cumulative precipitation exceeding 100 mm can be considered a triggering factor for landslides. However, days with more than six events of erosion processes are associated with intense daily rainfall (high rainfall intensity in a short period). The failure slopes in the southeastern region of Brazil, have been widely explored in the literature (Guidicini & Iwasa, 1976; Tatizana et al., 1987; Wolle & Carvalho, 1989; Wolle & Hachich, 1989).

The variety of geological, geomorphological, land use and occupation conditions present in the Belo Horizonte-MG region, combined with its climatic aspects, are responsible for triggering different types of mass movement processes. Even with such diversity of process it is possible to identify representative processes of the various instability situations encountered. According to Parizzi et al. (2004), Belo Horizonte records an average of 400 mass movements annually during the rainy season. Between December 2019 and January 2020, the recurrent intense rains in the region resulted in several mass movements, slope failures, and risk events throughout the metropolitan area, especially during the most critical weeks.

An alternative to reinforce the failed slope is soil nailing. In Brazil, the use of this technique gained prominence in the 1980s, mainly due to its high production speed resulting from shorter execution time, flexibility to adapt to various geometries, application in different types of soil, and the use of lightweight equipment (Ortigão et al., 1993; Souza et al., 2017).

The Brazilian geotechnical committee has recently undertaken the task of developing a new soil nailing standard. The primary objectives of this standard are to incorporate national expertise and provide a comprehensive text that does not prescribe specific methods and procedures. The newly established standard is known as NBR 16920-2 (ABNT, 2021). It is noteworthy that this is the inaugural soil nailing standard in Brazil.

Nowadays, a significant advancement in this technique has been applied in practice. In addition to traditional sub-horizontal soil nails, vertical soil nails close to the face of the retaining structure have been incorporated to the structure. These vertical elements improve the local superficial stability during the initial mass excavation phases and, primarily, reduces the horizontal deformations of the face – an inherent consequence of this type of structure (Souza et al., 2020).

Facing the advantage of this solution and its novelty, this works aims to present the design phases of a soil nailing project as an alternative retaining structure for the recovery and stabilization of the failed slope in the '*Buritis*' neighborhood located in Belo Horizonte-MG.

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2. Description of the study area

Silva et al. (1995) conducted an extensive study on the geological and geotechnical characteristics of the 'Buritis' neighborhood. The authors identified unfavorable geological and geomorphological conditions for land development, highlighting the following factors: i) the presence of schistosity and a southeastward dip of 45º in the local geological structure; ii) high weathering of phyllites; iii) the need to preserve arboreal vegetation along rivers; iv) the slope stability conditions favoring slopes facing northwest. Additionally, the authors recommended incorporating ample open spaces between buildings in construction projects.

Controversially to the Silva et al. (1995) recommendations, there is a significant concentration of buildings (mostly of vertical constructions) in the '*Buritis*' neighborhood where, due to steep slopes and unstable substrates, deep and costly building foundations were made – which increases the risk for landslide occurrence. The location and infrastructure of the 'Buritis' neighborhood are depicted in Figure 1a. Figure 1b presents the vulnerability map of the area, which provides a comprehensive overview of geological risk zones, crucial information for identifying areas most susceptible to potential harm to the population and property. Figure 1c specifically highlights the regions at risk of landslides, characterized by steep slopes oriented towards the southeast.

In this area, at late January 2020, probably due to intense rainfall, the initiation of slope movement was observed (Figure 2), which developed to a mass movement in the following days. The rainy period between December 2019 and January 2020 was very intense, as shown by the rainfall records of Belo Horizonte (Figure 3). The most critical weeks of rainfall in the city occurred from 13/01/2020 to 15/02/2020 – the period that the slope came to failure and pathologies developed.

The initial landslide rapidly escalated, resulting in an extremely critical situation. Soil movement intensified, leading to even more concerning outcomes. The instability manifested itself alarmingly, with a significant increase in both intensity and extent of displacement, as documented. This swift progression of the landslide necessitated immediate action to mitigate the resulting damages and ensure the safety of the affected area.

Based on the technical investigations conducted, it was determined that the primary cause of this displacement was the sliding of the mass face, attributed to intense rainfall during the period. Initially, this instability was localized, resulting in a loss of confinement in preceding sections of the slope. This led to a widespread state of instability, triggering subsequent mass movements. The complete sequence is depicted in Figure 4, while Figure 5 provides a top view of the slope.

The cracks observed on the slope are a direct consequence of erosion, and it is imperative to conduct a comprehensive mapping of these cracks prior to commencing any excavation work. It has been noted that a substantial portion of the slopes exhibits pronounced erosive grooves (Figure 6).

3. Geotechnical investigation for underground exploration

Three Standard Penetration Test (SPT) boreholes were conducted on-site in March 2020 (Figure 7). In general terms, the three boreholes exhibit a surface layer of clayey soil with silt, followed by a layer of silty clay. In the first layer (3.5 to 6 meters thick), the standard penetration resistance (N_{SPT}) gradually increases, ranging from 9 to 19 blows. In the second layer, the N_{SPT} value also increases with depth, ranging from 22 to 41 blows towards the end of the boreholes, at approximately 9.5 to 13.5 meters deep. It is important to note

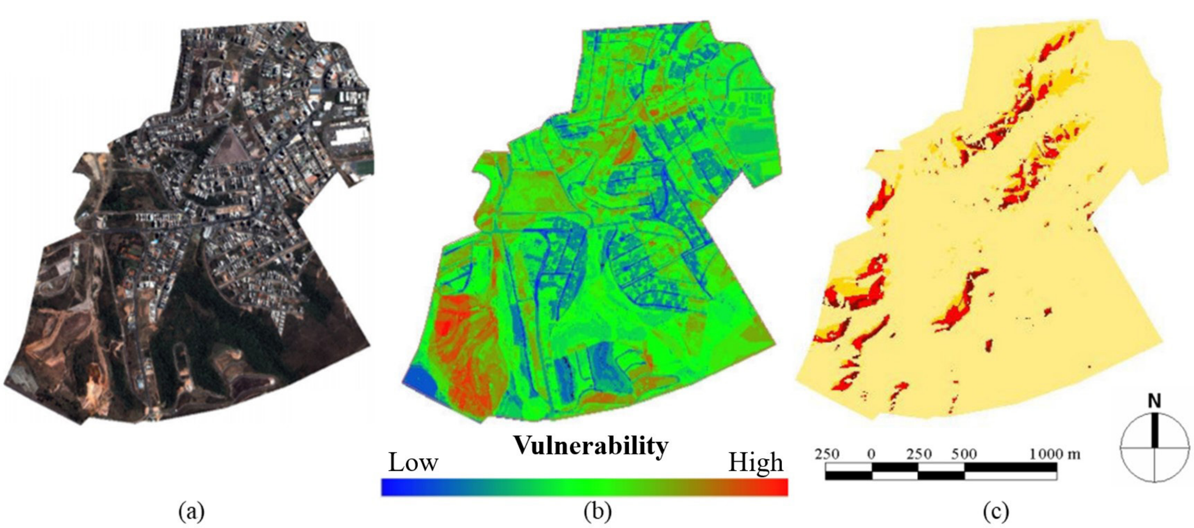

Figure 1. '*Buritis*' neighborhood study area: (a) infrastructure; (b) vulnerability map; (c) highlight of the steep slopes oriented towards the southeast. Source: Kux et al. (2007).

Figure 2. Soil Cracks in the surface indicating the initiation of mass movement.

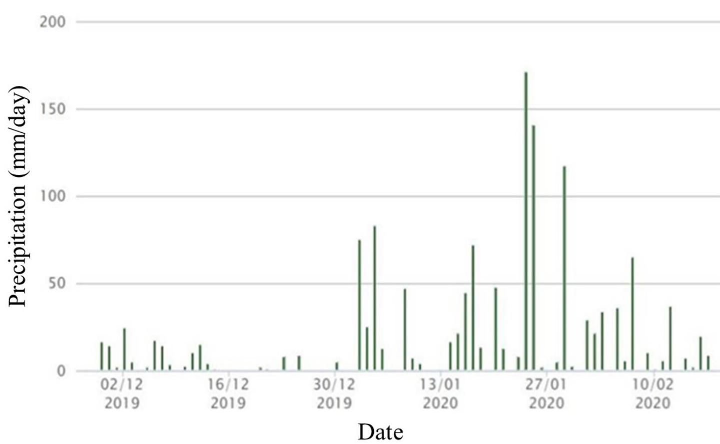

Figure 3. The most critical precipitation balance in Belo Horizonte during the years 2019 and 2021 accordingly to INMET (2021).

that the groundwater level was not encountered during the explorations. The three (3) SPT tests conducted in the area are represented by the yellow dots highlighted in Figure 7.

4. Geotechnical solution adopted

4.1. General aspects

The reinforcement used for stabilizing the breached slope consists of the technique known as Soil Nailing. For the specific project, upper, intermediate, and lower nails were installed with lengths of 12.0 m, 9.0 m, and 6.0 m, respectively, as shown in Figure 8. A total of 498 inclined sub-horizontal nails (15° angle) were used to stabilize the slope.

4.2. Slope stability analyses

Stability analyses were conducted using the computational tools Slide® and RS2. In addition to deterministic analysis, a probabilistic analysis was performed. The probabilistic approach allows for the incorporation of underlying uncertainties in the calculation. Consequently, the main advantage of reliability assessment lies in associating the Factor of Safety (*FoS*)

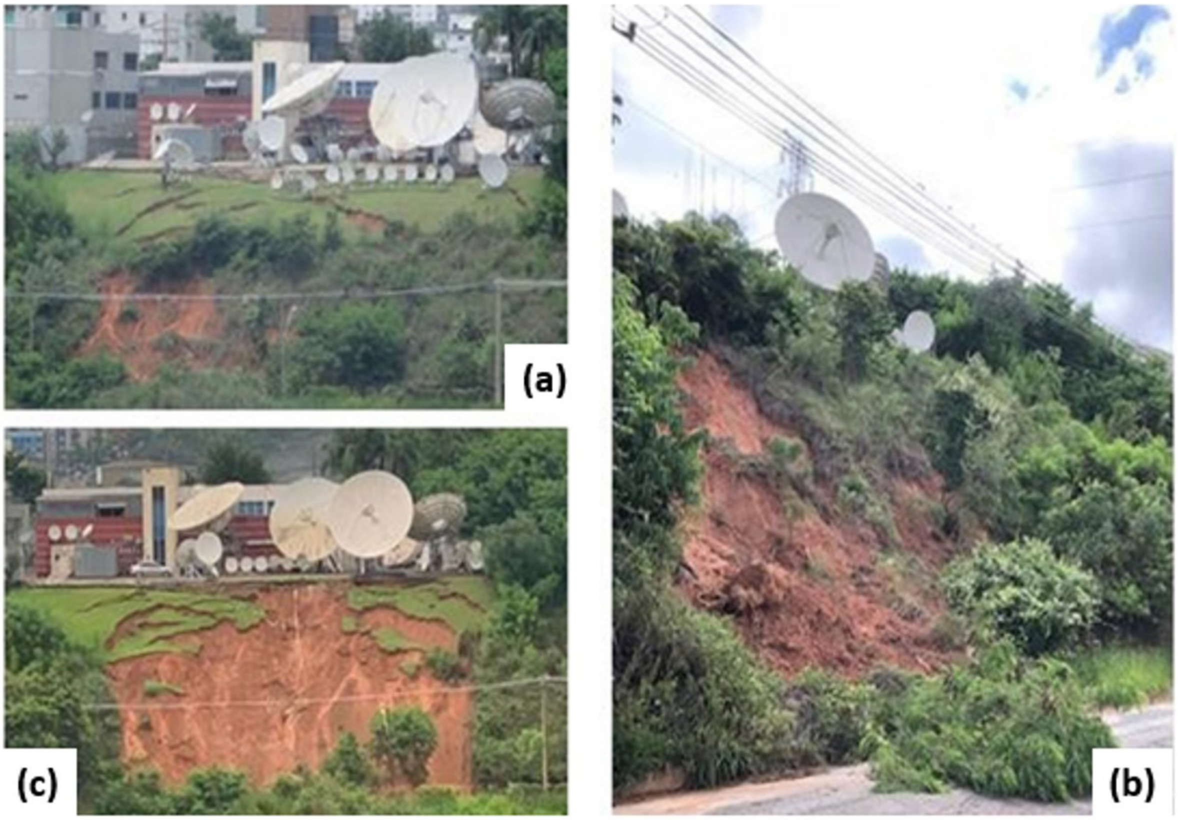

Figure 4. Slope failure occurred after the rains (a) Initiation of slope failure; (b) Continuity of mass movements; (c) Final condition of the failed mass.

Figure 5. Overview of the antennas situated at the top of the failed slope.

Figure 6. Erosion gullies identification alongside the slope surface.

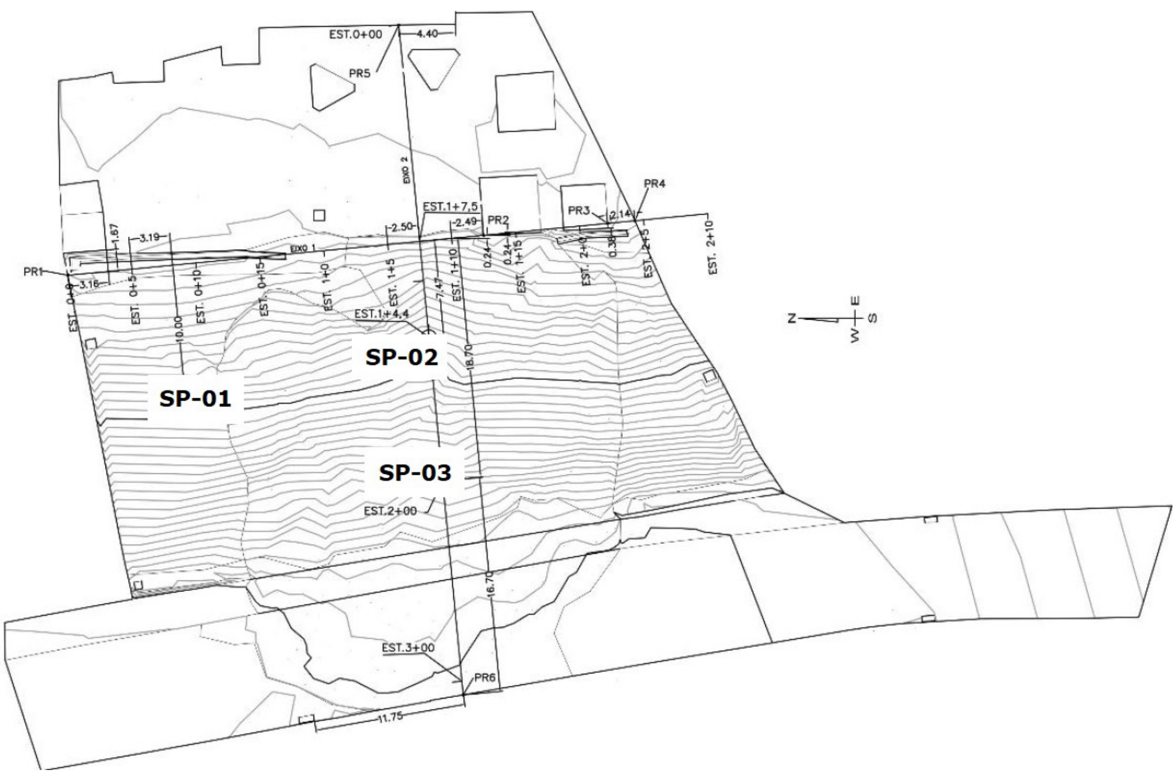

Figure 7. Borehole location for standard penetration tests in the studied area.

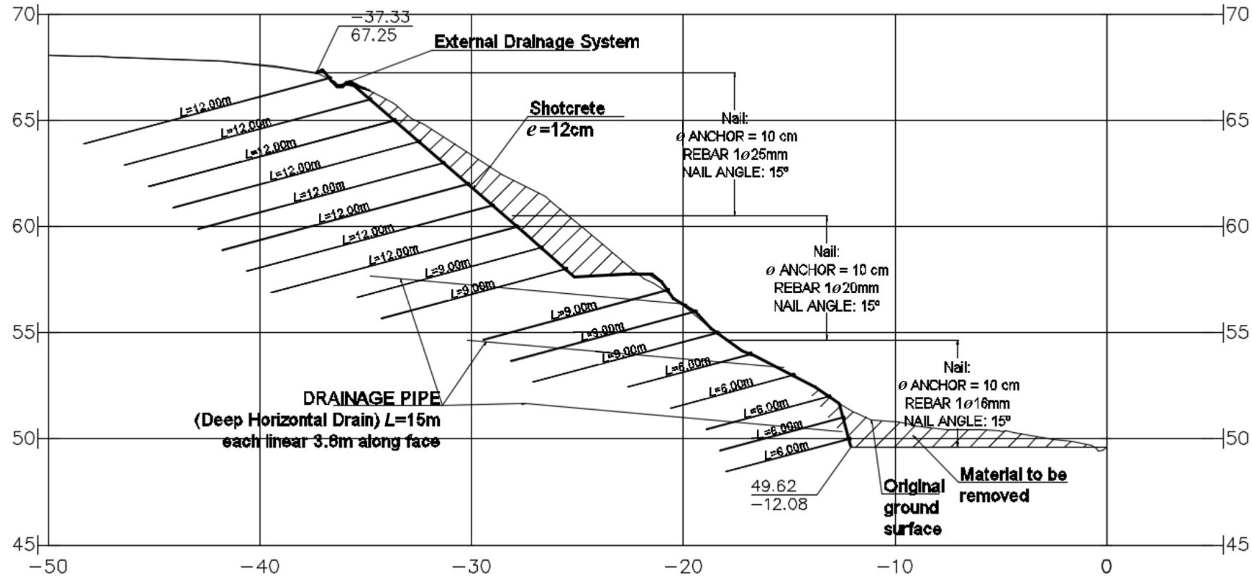

Figure 8. Cross section of soil nailing wall.

Table 1. Mean value variation of the random variables adopted in the study.

Variable	Mean Value (μ)	Standard deviation (σ)	Mean + variation
SiAg1 - unit weight (kN/m^3)	19	0.95	20.9
SiAg1 - Cohesion (kPa)	26	7.8	28.6
SiAg1 - Friction angle (°)	22	2.2	24.2
SiAg2 - Unit weight (kN/m^3)	20	1	22
SiAg2 - Friction angle (°)	25	2.5	27.5
SiAg1- Cohesion (kPa)	40	12	44
Nailing 1 (kPa)	128	38.4	140.8
Nailing 2 (kPa)	79	23.7	86.9
Nailing 3 (kPa)	41	12.3	45.1

with the probability of failure to manage the risk to which a specific project may be exposed. In this article, the reliability index was evaluated using the Method of Moments (MMC), Hughston's Limit State Method (MHL), First Order Second Moment (FOSM), and the Finite Element Method (FEM) to obtain the *FoS* values. The probabilistic evaluation of the reliability index followed the same assumptions described by Souza et al. (2023), where a numerical analysis was conducted to assess the excavation stability at the base of a natural slope for the implementation of a trunk collector for effluent disposal.

One must be aware that, in Brazil, the prevailing approach to geotechnical design is the utilization of semi-empirical equations to establish the geotechnical parameters. Once the client was reluctant to conduct laboratory and field tests, the soil strength parameters were determined (according to the Mohr-Coulomb constitutive model) based on semi-empirical equations and mainly on the authors' experience with projects and geotechnical consultancy in the area. Thus, Table 1 summarizes the values used in the simulations. It is important to emphasize the difference between the coefficient of variation (*CoV*) and the standard deviation (σ). The latter is a measure of dispersion, indicating how far the values in a data set are from the mean, while the coefficient of variation (*CoV*) is a relative measure of dispersion, indicating the variability of the data relative to the mean.

4.2.1. Deterministic and probabilistic assessment

In order to assess the shear strength of the slope soil, a back-analysis of the landslide was conducted as no strength tests had been carried out previously. Soil parameters corresponding to the periods of heavy rainfall when the failures occurred were adopted. The second phase of the study involved evaluating the optimal approach for slope recovery and stabilization, utilizing the Slide® software (by Rocscience) for all computational analyses.

The calculations incorporated a minimum surcharge of 20 kPa for the Soil Nail. The geotechnical parameters used were previously presented (Table 1), taking into account the conducted investigations, existing literature, the technical team's expertise, and the back-analyses of the current conditions. These considerations encompassed the reported failures of the slope face during intense rainfall events common in the region, as well as the presence of cracks on the road surface indicating instability of the downstream slope.

The analysis methods used the Mohr-Coulomb criterion based on cohesion (c), friction angle (ϕ), deformability modulus (E), unit weight (γ), and Poisson's ratio (v). To determine the values for unit weight (γ), Poisson's ratio (v), and deformability modulus (E), data presented by Teixeira & Godoy (1996) were used. The adhesive stresses between the grout and the soil or rock mass were estimated according to the recommendations of NBR 5629 (ABNT, 2018), GeoRio manual, and existing literature.

The First Order Second Moment (FOSM) method is a widely discussed probabilistic approach in geotechnical literature. The methodology of this method involves determining the variance of the factor of safety based on variations in the mean values of the independent random variables. Using this information, along with the variances of the variables, it becomes possible to calculate the total variance and, subsequently, the percentage contribution of each variable to the overall variance. As noted by Farias & Assis (1998), the simulation of the mean variations of these variables should range between 5% and 10% of their actual values. In this particular study, a variation of 10% was adopted. Table 1 summarizes the values used in the simulations.

It is important to note that the number of iterations in the First Order Second Moment (FOSM) method is equal to the number of random variables involved (n) plus one unity (1), which means n+1. In the specific case discussed, each analysis considers a set of eight random variables, resulting in nine interactions.

Within the context of these analyses, one analysis is performed deterministically for the section using the mean values of the geotechnical parameters. In each simulation, one variable is adjusted to the mean value plus a 10% variation, while the other variables are held fixed at their respective mean values. For a clearer understanding of the calculation procedures employed, Table 2 provides a detailed evaluation.

Stability analyses using the limit equilibrium method were conducted using the Slide® software (version 5.0). For the evaluation of the soil nailing, the results of these analyses with deterministic calculations and the reliability index using the MMC and MHL methods are presented in Figures 9 and 10, respectively, showing an overall factor of safety that exceeds the requirements of the standard.

The studies illustrated the results of the slope stability analysis using Slide®, showing that the factor of safety is above the specified standard and the reliability index is above 3.0. British Columbia Hydro, as cited by Flores (2008), considers a probability of failure (rupture, failure, or collapse) below 10^{-4} or higher than 3.72 as acceptable. The US Army Corps of Engineers, as cited by Flores (2008), proposes acceptability levels based on the reliability index, with a satisfactory β higher than 2.5 typically adopted.

Based on the data provided on Tables 1 and 2, it was possible to calculate the variance of the factor of safety (*FoS*) using the FOSM method. These results are presented in detail in Figure 11, highlighting the variation of the factor of safety and its respective distributions.

Through Figure 12, trends and patterns related to the variation of the factor of safety can be identified, contributing to a more comprehensive assessment of geotechnical stability and facilitating informed decision-making regarding associated risks. This information is crucial for the success of a project or endeavor, as it enables the identification and mitigation of potential stability and safety issues within the analyzed geotechnical system. This approach fosters a deeper understanding of the uncertainty associated with the factor of safety and the variations that can occur in different scenarios. It is important to note that the analysis using the FOSM method considers not only the mean values of the geotechnical parameters but also their respective variations, providing a more complete and accurate view of the results.

Table 2. Simulation considering the mean value variation of the random variables adopted in the study with their respective factor of safety (*FoS*) obtained.

Material	Deterministic analysis	1	2	3	4	5	6	7	8	9
SiAg1 - unit weight (kN/m³)	19	**20.9**	19	19	19	19	19	19	19	19
SiAg1 - Cohesion (kPa)	26	26	**28.6**	26	26	26	26	26	26	26
SiAg1 - Friction angle (°)	22	22	22	**24.2**	22	22	22	22	22	22
SiAg2 - Unit weight (kN/m³)	20	20	20	20	**22**	20	20	20	20	20
SiAg1- Cohesion (kPa)	40	40	40	40	40	**44**	40	40	40	40
SiAg2 - Friction angle (°)	25	25	25	25	25	25	**27.5**	40	27.5	27.5
Nailing 1 (kPa)	128	128	128	128	128	128	128	**140.8**	128	128
Nailing 2 (kPa)	79	79	79	79	79	79	79	79	**86.9**	**79**
Nailing 3 (kPa)	41	41	41	41	41	41	41	41	41	45.1
FoS	**1.632**	**1.587**	**1.652**	**1.645**	**1.6**	**1.686**	**1.714**	**1.632**	**1.632**	**1.634**

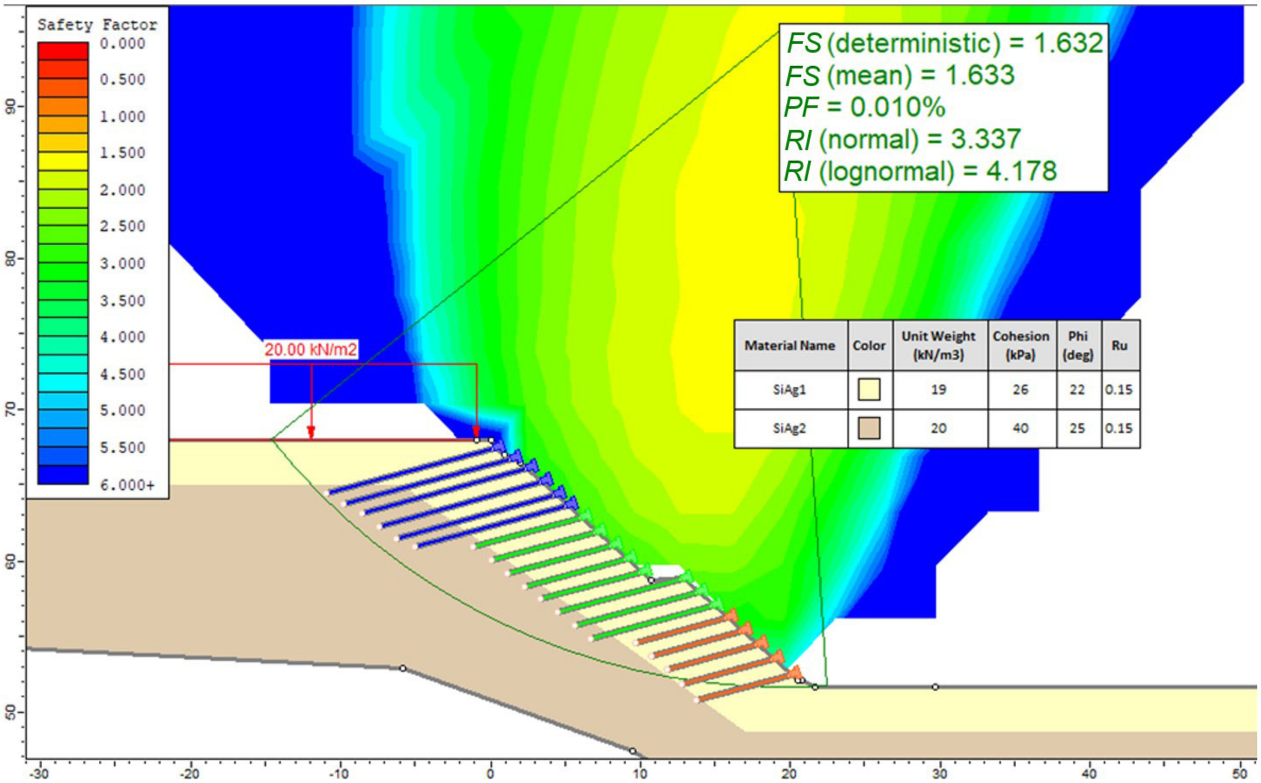

Figure 9. General stability of the slope – Nailed soil – *FoS* equal to 1.63 and probability of failure equal to 0,010% (Beta >3.0 using the Method of Moments; MMC).

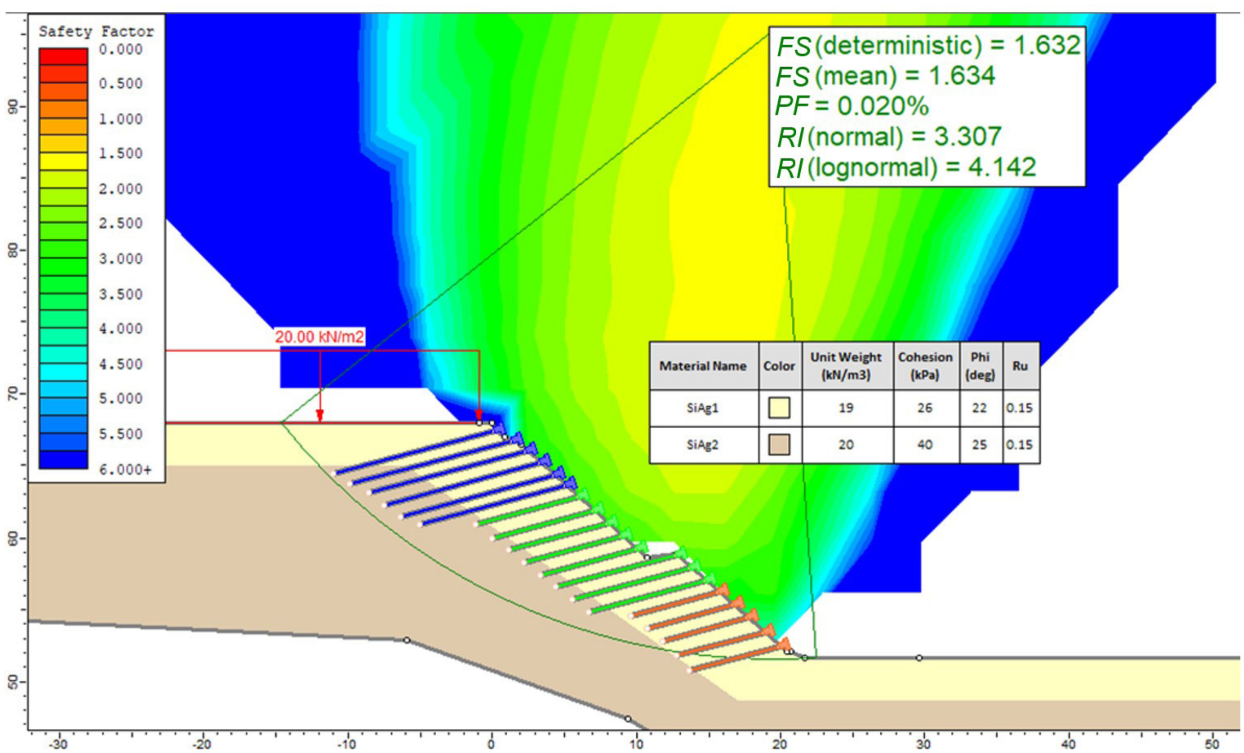

Figure 10. General stability of the slope – Nailed soil – *FoS* equal to 1.63 and probability of failure (p_f) equal to 0,020% (Beta >3.0 using the Limit State Method; LHS (Latin Hypercube Sampling)).

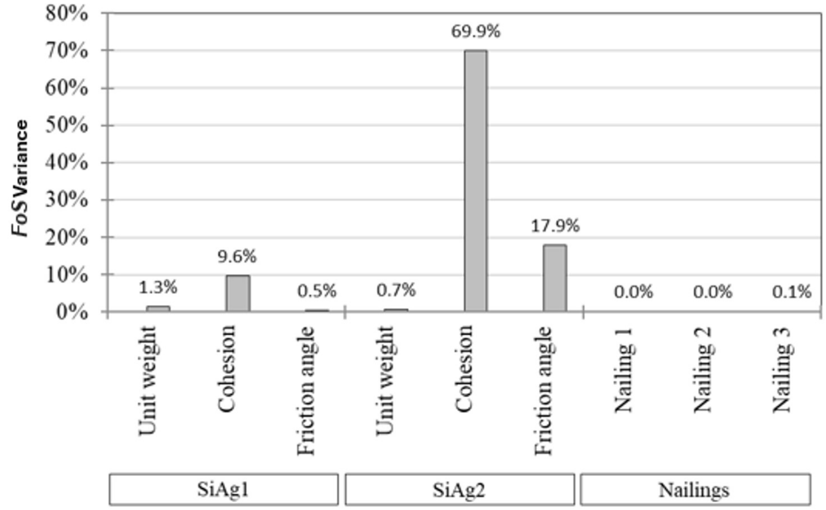

Figure 11. Factor of safety (*FoS*) variance versus soil and Nailing parameters.

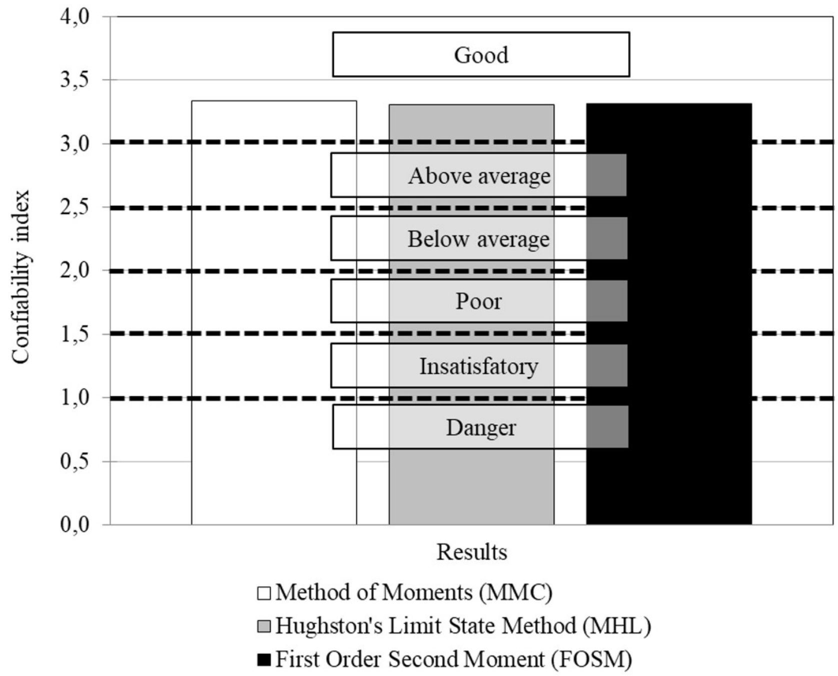

Figure 12. Results from the probabilistic methods.

4.2.2. Finite element method (FEM) analysis

Finite element analysis assumes a paramount role in slope evaluation, yielding invaluable information regarding their stability and allowing for the implementation of effective mitigation measures to ensure the safety of structures and individuals involved. For the finite element numerical modelling, Phase 2 (version 6.0) software was used, as depicted in the mesh presented in Figure 13. This triangular finite element mesh consisted of 2,553 elements and 5,278 nodes.

Regarding the finite element analysis, several significant advantages can be highlighted. Firstly, the utilization of numerical models through finite element analysis allows for a more accurate representation of the physical and geotechnical characteristics of the slope, taking into consideration the complexity of soil behavior. Additionally, numerical models enable the graphical visualization of

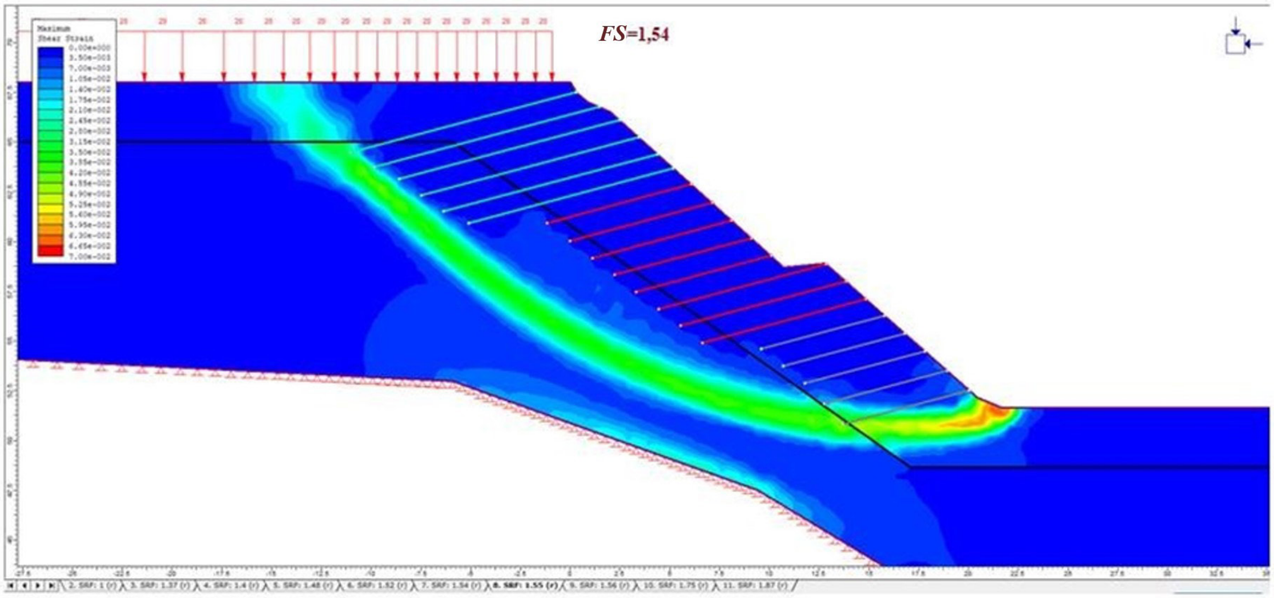

Figure 13. Numeric modelling of soil nailing using finite element method – *FoS* = 1.54.

Figure 14. Phases of soil nailing execution: (a) partial Excavation; (b) Drill nail hole; (c) execution of permanent cover (including shotcrete, bearing plate and washer).

stresses, deformations, and factors of safety, facilitating the interpretation of results and the understanding of potential failure mechanisms.

Although the factors of safety are satisfactory, a detailed instrumentation of the Soil nailing was recommended in the consultancy. As described by Souza & Querelli (2022), numerical predictions should be considered as theoretical references for monitoring, as the calculations underlying these predictions require various simplifications. These simplifications, along with the variability of mass and structural properties, result in differences compared to the values actually measured on-site.

4.3. Construction phases

The facing of the Soil nailing was constructed using shotcrete with a thickness of 12 cm, reinforced with double ribbed welded wire mesh with Q238 (inner side) and Q196 (outer side) wire diameters. Initially, a plate and nut connection between the anchors and the facing was planned, but during execution, this approach was changed to a simple connection by bending the anchor bar. Figure 14 shows the execution steps of the work.

The filling of the hole with binding material was done in an ascending manner. In other words, an auxiliary tube was inserted to the bottom of the borehole, and then the binding material was pumped until it overflowed from the borehole. Pumping was continued until the overflowed binding material was visually free of drilling residues. Filling the sheath was mandatory for all anchors, and pull-out tests were performed. The pull-out tests were conducted satisfactorily, following all the precautions and assumptions established by the standard (Figure 15). The tests were performed according to NBR 16920-2 (ABNT, 2021).

Figure 15. Performance of nailing's tensile test.

Figure 16. Completion of drain system.

The soil nailing solution in the '*Buritis*' neighborhood was completed in 2021, and the obtained results are extremely positive. In addition to its functionality and effectiveness, the soil nailing solution also stands out for its aesthetics. The authors noticed that the intervention harmonized perfectly with the surrounding environment, preserving the landscape and the region's aesthetics. They were able to evaluate both technical and aesthetic aspects of the implemented solution (Figures 16, 17 and 18). The work is concluded, as indicated in the figures 16 and 17.

Figure 17. Front view of Soil nail technique.

Figure 18. General view of soil nail technique and ‘*Buritis*’ neighborhood.

5. Conclusion

This study presented an effective solution for the recovery and stabilization of a failed slope in Belo Horizonte through the use of a Soil Nailing structure. It was evident that the failure did not have a single cause but rather a combination of geological and hydrological factors that contributed to the mass movement.

The study also addressed a systematic methodology for selecting the solution, considering technical, execution, and financial aspects. The importance of drainage in slope stabilization was emphasized, demonstrating its effectiveness in the work.

In terms of the challenges encountered and the project's distinctive features, the rapid conceptualization is noteworthy, particularly given that the action took place shortly before the onset of the rainy season. Furthermore, a comparative assessment was undertaken between the finite element solution and the limit equilibrium method. This was an important aspect of the project.

A notable outcome was the considerable minimization of the impact of the anchors on buried structures, achieved through the integration of the geotechnical and structural elements via BIM modelling.

Two other engineering companies presented alternative designs, one using tie-back walls and the other using reinforced soil embankment in front of the slope. After a thorough analysis, it was found that our Soil Nailing solution was more cost-effective compared to the tie-back wall solution and more suitable in terms of safety since the reinforced soil embankment did not meet the required factors of safety, especially in temporary phases. Based on all the assessments of technical, execution, and financial feasibility, our solution was chosen and is currently undergoing performance verification with the installation of instrumentation equipment.

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Declaration of interest

This manuscript has not been published and is not under consideration for publication elsewhere. The authors have no conflicts of interest to disclose.

Authors' contributions

Tiago de Jesus Souza: conceptualization, formal analysis, visualization, project administration, resources, software, writing – review & editing. André Querelli: project administration, conceptualization, investigation, methodology, supervision, validation, writing – review & editing.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

Declaration of use of generative artificial intelligence

This work was not prepared with the assistance of Generative Artificial Intelligence (GenAI).

List of symbols and abbreviations

c	Cohesion (kPa)
n	Random variables involved (dimensionless)
p_f	Probability of failure (dimensionless)
ABNT	Associação Brasileira de Normas Técnicas
CoV	Coefficient of variation
E	Deformability modulus (MPa)
FEM	Finite Element Method
FoS	Factor of safety (dimensionless)
$FOSM$	First Order Second Moment
LHS	Latin Hypercube Sampling
MEL	Limit Equilibrium Method
MMC	Method of Moments
MG	Minas Gerais
MHL	Hughston's Limit State Method
NBR	Brazilian Technical Standard
N_{SPT}	Standard penetration resistance (dimensionless)
SPT	Standard Penetration Test
β	Reliability index (dimensionless)
γ	Unit weight (kN/m^3)
ϕ	Friction angle (°)
μ	Mean value (property dependent)
v	Poisson's ratio (dimensionless)
σ	Standard deviation (property dependent)

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