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Probabilistic Assessment of Slope Stability Considering Uncertainties in Geotechnical Engineering

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RESUMO: Este estudo investiga a confiabilidade na estabilidade de taludes em solos predominantemente argilosos e arenosos, considerando alturas de 5 metros, 10 metros e 15 metros, com inclinação constante de 45 graus. A análise probabilística foi realizada com base no método do primeiro momento da segunda ordem, por meio do qual se determinou o índice de confiabilidade. Para a avaliação da estabilidade em abordagem determinística, utilizou-se o método de Morgenstern e Price, que atende integralmente às condições de equilíbrio estático. Os resultados indicam que o aumento da altura do talude está associado à redução progressiva dos valores do índice de confiabilidade, refletindo maior suscetibilidade à instabilidade. Taludes formados por solos granulares apresentaram índices mais elevados em comparação aos solos coesivos, especialmente nas maiores alturas. Observou-se, ainda, que a contribuição da coesão para a estabilidade torna-se menos significativa à medida que a altura do talude aumenta, sendo esse efeito mais pronunciado em solos arenosos. Os resultados obtidos reforçam a importância da consideração do tipo de solo e das características geométricas do talude em análises de estabilidade com enfoque probabilístico.

PALAVRAS-CHAVE: Estabilidade de Taludes, Parâmetros Geotécnicos, Índice de Confiabilidade, Solo Granular, Solo Coesivo

ABSTRACT: This study investigates the reliability of slope stability in predominantly clayey and sandy soils, considering heights of 5, 10, and 15 meters with a constant inclination of 45 degrees. The probabilistic analysis was performed using the first-order second-moment method, through which the reliability index was determined. For the deterministic assessment of stability, the Morgenstern and Price method was employed, as it fully satisfies the conditions of static equilibrium. The results indicate that increasing the slope height leads to a progressive reduction in the reliability index, reflecting a higher susceptibility to failure. Slopes composed of granular soils exhibited significantly higher reliability indices compared to cohesive soils, especially at greater heights. It was also observed that the contribution of cohesion to slope stability becomes less significant as the slope height increases, with this effect being more pronounced in sandy soils. These findings emphasize the importance of jointly considering soil type and slope geometry in reliability-based slope stability analyses.

KEYWORDS: Slope Stability, Geotechnical parameters, Reliability index, Granular soil, Cohesive soil

1 INTRODUCTION

The stabilization of inclined surfaces has always been a strongly present issue in geotechnics. According to Caputo (1988), any inclined surface that encompasses a mass, whether it's made of soil or rock, is called a slope. The stabilization of these slopes, in their various circumstances, can lead to similar hindrances that require quite distinct solutions (Guidicini and Nieble, 1976). According to Lumb (1966), among the hindrances present in stability assessments, we can highlight the variability of geotechnical parameters, where defining absolute values disregards the peculiarities of materials. This approach results in high safety factors that often conceal low reliability indices, justifying the failure in works considered stable (Falcão et al. 2020). Also, according to Gerscovich (2016), the investigation of slope stability is considered statistically undetermined, requiring the consideration of various initial hypotheses to reduce the number of variables existing in the problem, which vary according to the method used.

As an alternative to overcome these issues, nowadays we have the recourse of computational tools that, when associated with Limit Equilibrium methods, can bring considerable precision and representativeness to the behavior identified in the field. An example is the method of slices, developed by Fellenius in 1936, which is widely used for slope stability analysis due to its flexibility regarding homogeneity, geometry, and type of analysis. In general terms, the analysis by limit equilibrium using this method involves subdividing the slope into slices, where the equilibrium of forces is applied to each one, and then the equilibrium of the whole is calculated through moments relative to the semicircle (Gerscovich, 2016).

In addition to the method proposed by Fellenius and aligned with this approach, two other proposals stand out for investigating slope stability, each with its particularities in the criteria considered for determining parameters directly related to mass stability. The first of these is the Bishop method, proposed in 1955, which also uses the slice method, differing by disregarding the resultant of vertical forces between slices, thus reducing the number of unknowns but resulting in an overestimated solution (Abramson et al., 2002). Among the methods considered rigorous, we have the method of Morgenstern and Price, proposed in 1965, capable of statistically determining complex problems, satisfying all possible equilibrium conditions and proposed geometries, however, due to its complexity, it requires the use of computational resources.

To perform the stability analysis of the slopes studied in this work, the Slide 6.2 software from Rocscience was used. Slopes were simulated at three different heights, 5 m, 10 m, and 15 m, maintaining a 45° inclination. This was done for both granular and cohesive soils, in order to analyze the methods of Fellenius, Bishop, and Morgenstern and Price.

Aligned with this approach, this article aims to verify the influence of geotechnical parameters of materials with distinct characteristic behaviors on the behavior of a hypothetical slope. For this analysis, standard slope geometries were proposed, which were then replicated with two materials with characteristic behaviors, one cohesive soil and the other granular. With this, it became possible to verify the influence of geotechnical parameters on the overall stability of the structure, and its directly linked factors such as Safety Factor.

2 MATERIALS AND METHODS

2.1 Materials

For the proposed investigation, due to the analysis of hypothetical geometries, it was opted to select two materials of distinct compositions, one cohesive and the other granular, so that there would be significant differences in the input parameters for the analyses, thus making the influence of the materials' geotechnical characteristics on the slope behavior noticeable.

The material chosen to represent cohesive behavior was a Red Latosol, a material belonging to the Southern Plateau and collected at the Experimental Field of the University of Cruz Alta (UNICRUZ) located in the municipality of Cruz Alta, RS. The material underwent physical characterization and direct shear testing, a procedure carried out by Falcão (2021), who classified it as Silty-Sandy Clay. As for the material selected to represent granular behavior, it is a Clayey Sand, formed in the sedimentary terrains of Coastal Basin II, a material widely present along the coast of the state of Rio Grande do Sul. The material also underwent physical characterization and direct shear testing conducted by Bastos et al. (2008). Table 1 shows the geotechnical parameters identified through physical characterizations and direct shear tests for the two materials under study.

Table 1 – Material Index and Shear Strength properties.

Test/classification and regulatory standards		Cohesive	Granular
% gravel (2,0 – 4,0 mm)		8	0
% sand (0,06 – 2,0 mm)	Granulometric Analysis	27	72
% silt (2 µm – 0,06 mm)	NBR 7181 (ABNT, 2016)	16	2
% clay (%2 µm)		57	26
real specific gravity of grains (g/cm³)	NBR 6458 (ABNT, 2016)	2,72	2,63
Liquid Limit (%)	NBR 6459 (ABNT, 2016)	51	32
Plastic limit (%)	NBR 7180 (ABNT, 2016)	37	16
Plastic index (%)	-	14	16
Cohesion (KPa)	Direct Shear Test	13,4	9,8
Friction Angle (°)		29,4	37,4

2.2 Probabilistic

Considering the multiple uncertainties inherent in geotechnical projects, it is common to apply methods grounded in Reliability Theory. This enables the analysis of reliability index results (β), which is associated with the probability of failure (PF). The reliability index can be described as a parameter indicating how many standard deviations separate the mean Factor of Safety (μ_{FS}) from the critical FS (FS=1.0), where σ_{FS} is the standard deviation (Equation 1). It is emphasized that such an approach should only be used when employing the normal probabilistic distribution.

$$\beta = \frac{\mu FS - 1}{\sigma FS} \tag{1}$$

For the probabilistic approach, the FOSM (First Order Second Moment) method was employed for simulations. This method provides the primary advantage of requiring only the mean and standard deviation of the parameters, without necessitating knowledge of the probability distributions. Additionally, it allows for the quantification of the influence of parameters on the final model results. The U.S. Army Corps of Engineers (1977) established a relationship between β values and PF. The resulting quantification offers an estimate of the expected performance, as depicted in Table 2.

Table 2. Assessment of expected performance according to the classification of β and PF by USASCE.

Performance	β	*PF(%)*
High	5,0	0,0000003
Good	4,0	0,0003
Above Average	3,0	0,01
Below Average	2,5	0,006
Poor	2,0	0,023
Unsatisfactory	1,5	0,07
Dangerous	1,0	0,16

The FOSM is also a method that considers the first-order approximation of the Taylor Series expansion applied to the variance equation. The input values are the mean and standard deviation of the obtained geotechnical parameters. In summary, a small variation is imposed on one of the parameters while the others remain fixed. The number of simulations required by the method is equal to the number of independent values plus 1. Equation 2 presents this calculation, where the term $[FS]$ corresponds to the variance of the FS, $\delta FSii$

represents the variance of the FS when the study variables are varied by δXi, and $V[Xi]$ denotes the variance of each of the variables (Xi). In the FOSM method, the normal distribution was used in the calculations.

$$V[FS] = \sum_{i=1}^{n} \left(\frac{\delta FSii}{\delta Xi}\right)^2 V[Xi] \qquad (2)$$

Table 3 presents the values used in the computational stability analyses. It is noteworthy that the minimum, medium, and maximum standard deviations were compared, along with their impact on the calculations. For this purpose, the approach presented by Duncan (2000), Baecher (2003) and Sandroni and Sayão (1993) was utilized as a basis. Duncan (2000) further observes that, generally, the specific weight varies within the range of 3 to 7%, the friction angle between 2 and 13%, while cohesion falls within a range of variation between 20 and 80% (Baecher, 2003; Sandroni & Sayão, 1993).

Table 3 - Parameters Obtained from Direct Shear Test

Type of Soil	**Properties**	**Value**	**Standard Deviation**		
			Minimum	Average	Maximum
Granular Soil	Specific Weight (kN/m³)	19.20	0.58	0.96	1.54
	Cohesion (kPa)	9.80	0.98	1.96	2.94
	Friction Angle (°)	37.40	1.87	3.74	5.61
Clayed Soil	Specific Weight (kN/m³)	15.10	0.45	0.76	1.21
	Cohesion (kPa)	13.40	1.34	2.68	4.02
	Friction Angle (°)	29.00	1.45	2.90	4.35

3 RESULTS AND DISCUSSIONS

3.1 Analysis of the Reliability Index

Figure 1 presents the reliability index β results for the different evaluated heights, considering the FOSM method. It is important to note that the 45° slope inclination was maintained, even when their height varied. It was classified as predominantly granular soil when the largest particle size fraction was sand, and predominantly clayey soil when its particle size fraction was larger compared to the others (sand and silt).

Given the similar β results, as presented in Figure 1, for the limit equilibrium-based methods of Fellenius (F), Simplified Bishop (BS), and Morgenstern and Price (MP), the Morgenstern and Price method was selected for comparative analyses of this item. This decision was made because this method satisfies all static equilibrium equations. The criterion for evaluating expected performance was conducted using the classification proposed by the USASCE (1995). This criterion is based on the principle that the higher the β value, the better the performance of the evaluated slope, as it indicates a lower probability of failure. When the β value is low, for example, less than 1, the slope can be classified as risky.

In Figure 1 (a), the results of the soil with predominantly granular behavior are presented. In summary, this material exhibits a high percentage of the sand fraction, and its behavior is estimated to be governed by the friction angle. Assessing the slope with a height of 5m, it is observed that the β values decrease as the coefficient of variation (CV) imposed on the random variables increases. There is a reduction of approximately 50% in the β value compared to the minimum CV for the average CV. The variation between the average CV and the maximum CV is 33.51%. Evaluating the expected performance according to the USASCE (1995), it decreases with the increase in the CV, changing from high to above average to poor, respectively for minimum, average, and maximum CVs. The same proportion of reduction in β is observed for the slopes of 10 m and 15 m, that is, around 50% when comparing the minimum and average CVs, and 33% considering the average and maximum CVs. However, considering the 10 m slope, the expected performance goes from high to below average to unsatisfactory, respectively for minimum, average, and maximum CV values. Additionally, when evaluating the 15 m slope, the behavior changes from below average to unsatisfactory to dangerous, considering the minimum, average, and maximum CVs. In summary, the higher the slope's height, the greater its risk of instability.

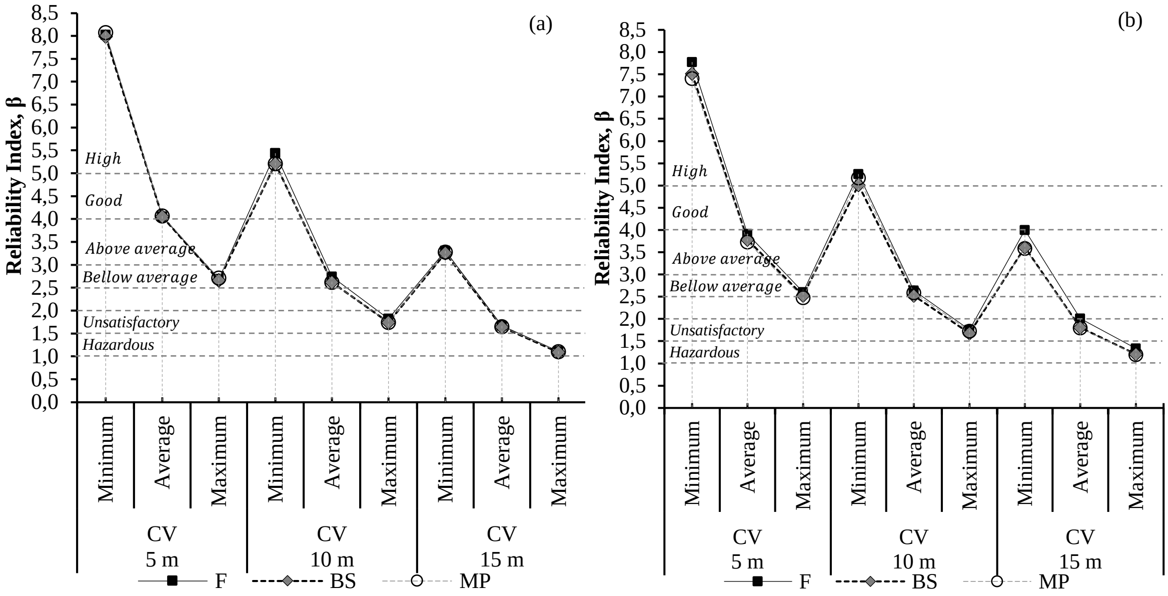

Figure 1: FOSM results (a) Granular behavior soil and (b) predominantly clayey soil.

In Figure 1 (b), the results of β for the predominantly clayey soil can be observed. The same proportion of reduction in β is observed for the slopes of 5 m, 10 m, and 15 m, that is, around 50% when comparing the minimum and average CVs, and 33% considering the average and maximum CVs. Regarding the performance index, the 5 m slope changes from high to good and below average; the 10 m slope changes from high to below average to dangerous; the 15 m slope changes from below average to unsatisfactory to dangerous. All conditions considering the variation of the minimum, average, and maximum CVs, respectively.

Figure 2 presents a comparison between heights, considering soil with predominantly granular and clayey characteristics. For this analysis, β values resulting from the average variation of random variables were considered. Additionally, the results from the Morgenstern and Price (MP) method were taken into account. When the slope has a height of 5 m, the predominantly clayey soil exhibits a higher β value than the granular soil. However, for 10 m, this variation is not observed, as both methods show analogous values. Regarding the 15 m height, the granular soil has higher β values than the cohesive soil. In summary, as the height of the slope increases, the granular soil exhibits a higher reliability index compared to the cohesive soil. However, it is noted that granular soil does possess some cohesion. Furthermore, each soil type should be analyzed separately, as the results obtained in the analyses may not correspond to other soil types with similar characteristics.

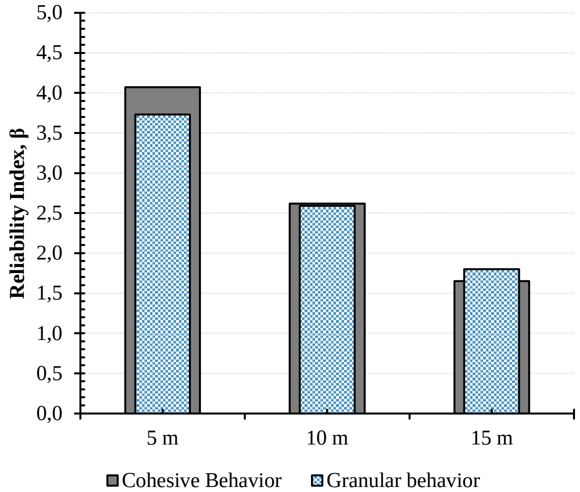

Figure 2. Results of the FOSM method for different soil types.

3.2 Analysis of the Influence of Random Variables

Figure 3 illustrate the influence of random variables on predominantly clayey soil. The variation between the minimum, medium, and maximum coefficient of variation is not significant. However, as expected for soil with a high clay content, cohesion demonstrates greater significance in the factor of safety analyses. For a 5 m slope, cohesion contributes approximately 78 to 80%, followed by the friction angle, which accounts for 16%. On a 10 m slope, cohesion contributes within the range of 63 to 64%, while the friction angle accounts for 32 to 33%. Similarly, for a 15 m slope, cohesion contributes within the range of 51 to 52%, with the friction angle accounting for 45%. Throughout all analyses, the significance of the specific weight remains below 10%.

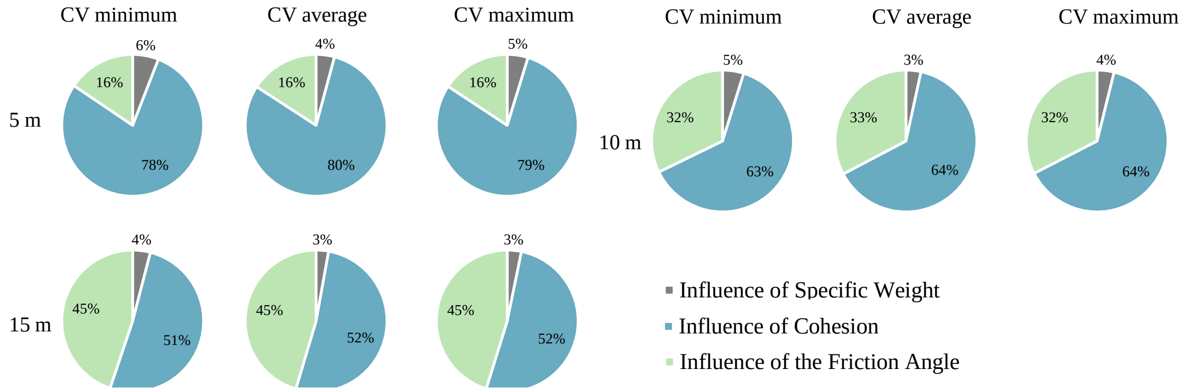

Figure 3. Influence of random variables: predominantly clayey soil.

In Figure 4, the influence of random variables on the calculation of FS for varying heights is depicted. It is observed that, as the height varies, there is a decrease in the percentage of cohesion's impact on FS calculations, with a reduction of approximately 66%. Moreover, there is a notable increase in the influence of the friction angle on the calculations. In summary, for a 5 m slope, the friction angle's influence was 16%, for a 10 m slope it rose to 32%, and for a 15 m slope it reached 45%. Thus, it is evident that as the slope's height increases, so does the impact of the friction angle.

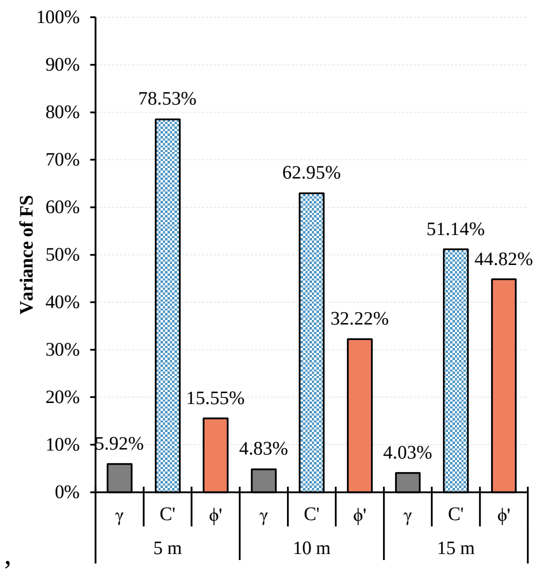

Figure 4. Variance of FS: predominantly granular soil.

In Figure 5, it is observed that there is no significant variation in the geotechnical parameter calculations when considering different coefficients of variation. In Figure 6, the relevance of geotechnical properties in stability analyses is observed for a slope with a vertical to horizontal inclination ratio of 1:1. In Figure 6 (a), despite the 39° friction angle, cohesion predominates in the calculations (52%) for a 5 m slope. Conversely, the friction angle influences within the range of 44 to 45% at this height. However, as the slope height increases, cohesion's influence decreases to around 31%, while the friction angle rises to 67%. Furthermore, with a slope height increase to 15 m, cohesion's influence decreases by 75% compared to the 5 m slope. In Figure 6 (b), the results of the analyses on the two types of soil are depicted. It's evident that both soils exhibit a cohesion value of 13.4 kPa for the clayey soil and 9.8 kPa for the predominantly sandy soil. For the 5 m slope height, cohesion shows significance in the calculations for both soils compared to other geotechnical parameters (friction angle and specific weight). However, it's noteworthy that the granular soil has a friction angle of 37.8°, whereas the clayey soil has 29.4°. This disparity justifies the greater influence of the friction angle in the calculations for the granular soil, approximately 45%, while for the clayey soil, it was 16%. In both scenarios, the friction angle became increasingly influential in the FS variance as the slope height increased. Nonetheless, for the clayey soil, cohesion continued to predominate in the calculations for the highest evaluated height, whereas for the granular soil, it was the friction angle.

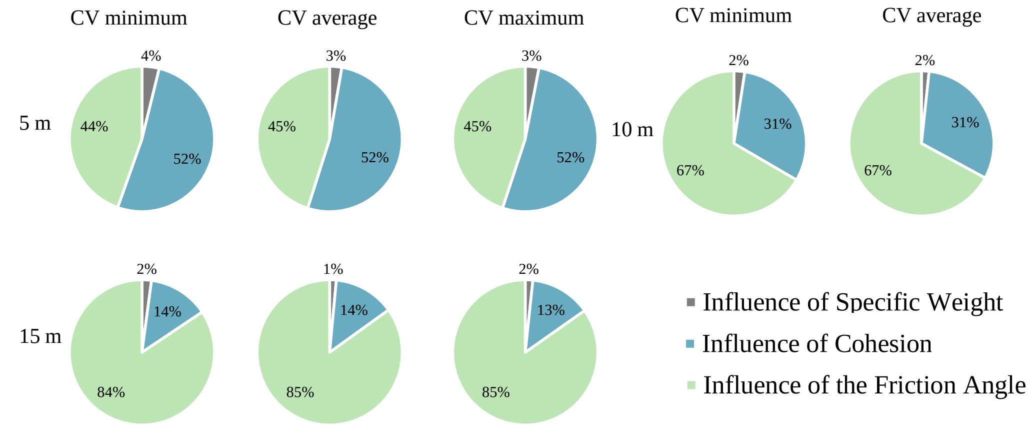

Figure 5. Influence of random variables: predominantly granular soil.

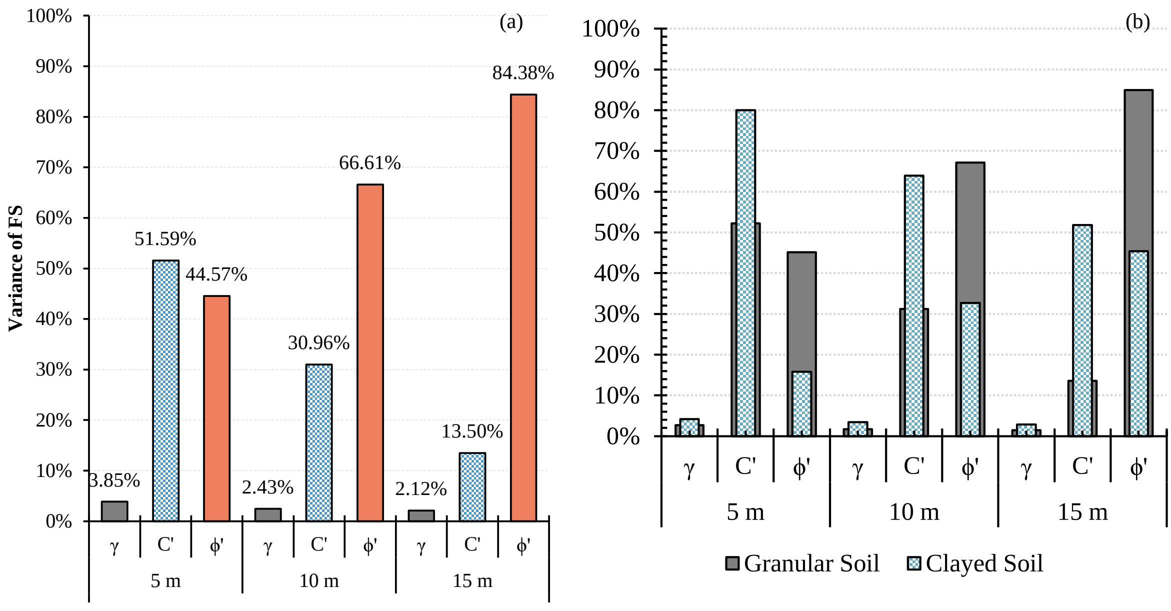

Figure 6. (a) Variance of FS: predominantly granular soil and (b) Comparison of results between soils.

4 CONCLUSIONS

In this section, we outline the primary conclusions drawn from our findings. It's important to highlight that our main aim was to evaluate how variations in geotechnical parameters affect FS calculations. To accomplish this, we examined two types of soil: one predominantly sandy and the other clayey. Among the limit equilibrium-based methods utilized, namely Fellenius, Simplified Bishop, and Morgenstern and Price, similar β values were observed, with the latter selected for comparative analyses. As the slope height increased, β values decreased, indicating a heightened risk of instability. Notably, granular soil demonstrated a higher reliability index compared to cohesive soil, especially with increasing slope height. Additionally, the influence of cohesion diminished as the slope height increased, a trend particularly pronounced in granular soil.

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REFERENCES

Abramson, Lee W., Lee, Thomas S., Sharma, Sunil, Boyce, Glenn M. 2002. Slope stability concepts. *In Slope Stability and Stabilization Methods*, 364-367, John Wiley & Sons, New York.

Baecher, G. (2003). *Reliability and Statistics in Geotechnical Engineering*. Available at: https://www.researchgate.net/publication/247385445. Accessed on: July 8, 2025.

Bastos, C. A. B., Schimitt, L. A., Vasconcellos, S. M., Rabassa, C. M., Souza, E. W. 2008. Geotechnical properties of a lateritic fine sandy soil of coastal barrier in the South Coastal Plain of Rio Grande do Sul. *Teoria e Prática na Engenharia Civil*, n.12, Rio Grande.

Brazilian Association of Technical Standards. 2016. NBR 6458: *Gravel grains retained on the 4.8 mm sieve - Determination of specific gravity, apparent specific gravity and water absorption*. Rio de Janeiro.

Brazilian Association of Technical Standards. 2016. NBR 6459: *Soil: determination of liquid limit.* Rio de Janeiro.

Brazilian Association of Technical Standards. 2016. NBR 7180: *Soil: determination of plasticity limit.* Rio de Janeiro.

Brazilian Association of Technical Standards. 2016. NBR 7181: *Soil: granulometric analysis.* Rio de Janeiro.

Caputo, H.P. 1988. *Soil Mechanics and its Applications. Fundamentals.* 6th edition, Rio de Janeiro: Technical and Scientific Books Publisher.

Duncan, J. M. (2000). Factors Of Safety and Reliability in Geotechnical Engineering. *Journal Of Geotechnical and Geoenvironmental Engineering*, 307.

Falcão, P. R. 2021. *Evaluation of the Impact of Flooding on the Strength and Deformability of a Lateritic and Collapsible Soil: Experimental and Numerical Study.* Dissertation (Master's in Geotechnical Engineering) - Federal University of Santa Maria.

Falcão, P. R., Fagundes, D. F., Alves, M. L. 2020. Probabilistic Analysis of Embankments on Soft Soils. *Vetor, Rio Grande*, vol. 30, no. 1, 38–48.

Gerscovich, D.M.S. 2016. *Slope Stability.* 2nd Edition, São Paulo: Oficina de Textos, 192.

Guidicini, G. and Nieble C.M. 1976. *Stability of Natural and Excavation Slopes*, 170.

Lumb, P. 1966. The variability of natural soils. *Canadian Geotechnical Journal*, vol. 3, no. 2, 74-97.

Sandroni, S. S., & Sayão, A. S. F. ,. (1993). The Use of Relative Probability of Failure in the Design of Open Pit Mine Slopes. In: *Innovative Mine Design for the 21st Century*, 21–24.

U.S. Army Corps of Engineers. (1997). *Engineering and Design Introduction to Probability and Reliability Methods for use in Geotechnical Engineering.* Distribution Restriction Statement.