Assessment of Geotechnical Parameter Uncertainty Using Probabilistic Methods in Slope Stability Analysis

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Abstract
This paper shows the results of an evaluation of geotechnical parameter uncertainty using probabilistic methods in slope stability analysis. These evaluations were conducted on a series of uniform soil slope profiles, considering both static and pseudo-static conditions. The obtained results were then compared to those derived from deterministic analyses applied to the same profiles. The analyses were conducted using limit equilibrium methods and the Mohr-Coulomb criterion, implemented through RocScience Slide v6.0 software. The simulations for each scenario focused on identifying circular slip surfaces, utilizing two widely employed methods in professional practice: the Spencer method and the Morgen-stern-Price method. In the probabilistic analyses, input parameters were modeled using a normal distribution. The reliability and probability of failure were deter-mined using the Latin Hypercube Sampling (LHS) and the First Order - Second Moment (FOSM) methods. Additionally, the methodology described here was applied to a real case. The results showed that not every slope considered stable, analyzed only from a deterministic approach, is safe, even when it meets the minimum safety factor (SF) requirement.

Keywords: Probabilistic analysis, Reliability, Slope Stability

1. Introduction

The stability of slopes consists of the resistance of natural or excavated inclinations against forces that may include collapses or slides. The evaluation of slope stability acquires significant importance due to its relevance in infrastructure planning and design, as well as in the management of geotechnical risks. Consequently, the identification and quantification of geotechnical parameters, such as cohesion and internal friction angle, become fundamental for carrying out a detailed stability analysis.

In professional engineering practice, uncertainty is an inherent element within most study systems, especially within the realm of geotechnical engineering and slope analysis. This element encompasses both geometric and geotechnical facets. The latter comprises the variability of soil properties, influenced by factors such as the location and timing of sample collection, the assessment of these properties through laboratory tests, where actual ground conditions may not be fully replicated, loading mechanisms, measurement inaccuracies, and more [1].

Likewise, many civil projects require the execution of temporary or permanent slopes, including the stabilization of natural slopes adjacent to the work areas, which could affect the work in question and, in addition, endanger many lives if the risks are not properly assessed. Hence the interest of adopting the probabilistic approach to slope stability assessment.

While it is true that it is necessary to comply with the minimum requirements related to standard safety factors, other equally important and complementary aspects, related to the evaluation of failure probability and reliability levels, can-not be disregarded. The safety factors alone do not allow the evaluation of the risk of failure, since slopes with equal FS can present different levels of risk related to the variability of soil properties [2].

In this sense, all this suggests that even when a deterministic analysis concludes that a slope is stable and meets minimum standards and requirements, it does not necessarily guarantee that it is safe and reliable. In this line, this work evaluates the uncertainty in the determination of geotechnical parameters through the study of the stability of synthetic slopes, and explores its effects on their behavior, through reliability analysis and the use of probabilistic tools that allow the sampling of data, the determination of the probability of failure and the reliability index associated to the safety factor of the observed models, and the description of an analysis methodology through the Slide v6.0 software, easy to apply.

2. Methodology

In this phase, slope profiles with simple geometry and geotechnical properties were designed, with reference to Bhattacharya [4], consisting of homogeneous soil, heights of 10, 20 and 30m, and H: V slopes of 1, 1.5 and 2. The selection of these heights and slopes is based on their practical relevance and their ability to address a variety of slope stability situations that may be encountered in civil engineering. These adjustments will provide a suitable framework for conducting a detailed analysis using limit equilibrium methods and the Mohr-Coulomb criterion, thus allowing exploration of a representative range of slope stability scenarios within the context of this research.

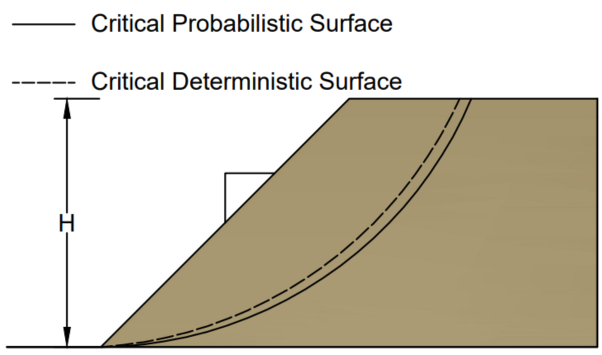

Fig. 1. Adapted reference sketch of slope profile [4]

2.2. Methods

Within the framework of this research, two fundamental approaches were employed to analyze slope stability: limit equilibrium methods and the Mohr-Coulomb criterion. These methods are pillars in geotechnical engineering and have been widely used in professional practice due to their effectiveness and reliability. The limit equilibrium method is based on comparing the acting forces and available resistances on a slope, thus determining the critical sliding surface.

On the other hand, the Mohr-Coulomb criterion establishes failure conditions based on the principal stresses and the soil's internal friction angle, allowing for the evaluation of slope stability through stress and deformation analysis.

These approaches provide a solid framework for slope stability studies and were successfully implemented through RocScience Slide v6.0 software in this research. Furthermore, to address reliability and failure probability, the Latin Hypercube Sampling (LHS) method was employed to efficiently select samples and ensure an equitable distribution of parameters. Additionally, the First Order - Second Moment (FOSM) method was used to analyze the propagation of uncertainty, identifying key variables. The combination of LHS and FOSM strengthens our ability to obtain robust and reliable results.

2.3. Statistics

This phase covers considerations on the application of statistical concepts in the treatment of sources of uncertainty, in this case those concerning soil properties (cohesion, angle of internal friction and unit weight), and the probabilistic methods used in the analysis of the stability of the designed slopes (LHS and FOSM), for the subsequent determination of FS, calculation of failure probability and reliability levels. To define the acceptable safety levels, the values proposed by USACE [5] were taken into account, which are shown in Table 1.

Table 1. Reliability indexes and failure probabilities [5]

Expected performance level	b	P[r]
High	5.0	$3.0x10^{-7}$
Good	4.0	$3.0x10^{-5}$
Above average	3.0	$1.0x10^{-3}$
Below average	2.5	$6.0x10^{-3}$

Poor	2.0	$2.3x10^{-2}$
Unsatisfactory	1.5	$7.0x10^{-2}$
Dangerous	1.0	$1.6x10^{-1}$

On the other hand, we considered what is referred to in the scientific literature on the typical values of coefficients of variation (CV) for the geotechnical parameters of interest. It is possible to use these values, in a preliminary way, when not enough test data are available, because they have low spatial and temporal sensitivity [6]

The CV value relates the standard deviation and the mean of the referred parameters. In the simulations, the slopes were analyzed by varying the CV (mini-mum and maximum values) for each parameter, and to establish comparisons of how the variability of the geotechnical properties affects slope stability and failure probability.

In addition, the pseudo-static stability analyses assumed a seismic acceleration factor in the vertical and horizontal directions of K_v=0 and K_h=0.225g, respectively [7, 8].

2.4. Parametric analysis

This section refers to the execution of slope stability analyses generated using Slide, starting from the definition of the simulation conditions (meshing, iterations and slip surfaces), input parameters, numerical methods (Spencer and Morgenstern-Price), sampling and processing of the data defined in the previous steps. The data used in this study are presented in Table 2.

Table 2. Summary of data for this study

Parameters		Units	Values
Geometrics	Height (h)	m	10, 20, 30
	Slope (H:V)	-	1, 1.5, 2
Geotechnical	Cohesion (c)	kN/m^2	18 (CV=20.0%)
	Specific weight (γ)	kN/m^3	18 (CV=3.00%)
	Friction angle (ϕ)	°	30 (CV=3.70%)

Table 3 and Figure 2 show the boundary conditions and their representation.

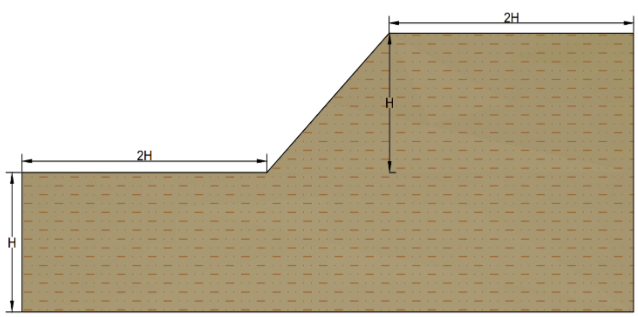

Fig. 2. Scheme of boundary conditions for synthetic slopes

Table 3. Boundary conditions on synthetic slopes

Description	Symbol	Values
Horizontal length at the slope foot (m)	2H	20,40,60
Vertical length at the foot of the slope (m)	H	10,20,30
Horizontal length at slope crest (m)	2H	20,40,60

3. Results

Due to the amount of data generated and the limited space available, the results corresponding only to the Morgenstern-Price method are presented, since no significant differences were found between the values obtained for this method and the Spencer method. In addition, it was decided to present some of the critical situations of the evaluated cases, both in static and pseudo-static conditions, for minimum and maximum CV values, in order to highlight the importance of the probabilistic approach and to establish some comparisons of interest.

The slope profiles were evaluated by varying heights, slopes, CV and seismic condition, equivalent to a total of 36 scenarios. Slide analysis was performed only for circular failure surfaces. Probabilistic sampling was performed using Latin Hypercube to obtain the FS, failure probability and reliability index. These results were compared with the FOSM method, which also allowed to identify the influence of geotechnical parameters on the variation of the FS. About 720,000 data were generated and processed through Microsoft Excel 2016 v1.0 software.

3.1. Factor of safety

In Figure 3 presents the contrast between the deterministic safety factors against the mean of the probabilistic factors obtained for the pseudo-static condition.

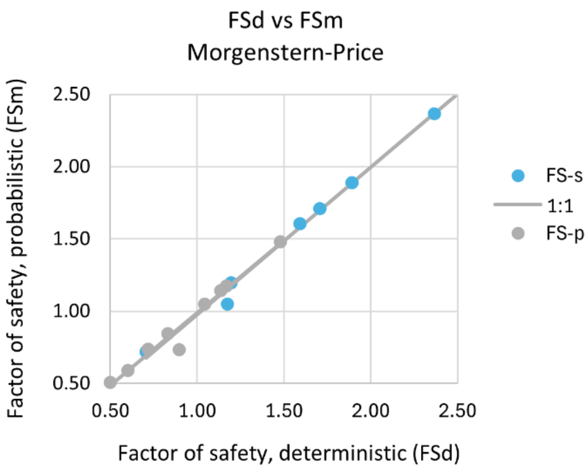

Fig. 3. Adapted reference sketch of slope profile [4]

It is possible to appreciate the linear relationship between both. That is, there are no significant differences between them for all the cases evaluated. The same trend occurs in the static condition.

In the scenarios evaluated in the static condition, the slopes are stable in most cases (14 scenarios, with a range between 1.056 and 2.363), except for slopes called 2C and 3C (4 scenarios, with a range between 0.721 and 0.850). while in the pseudostatic condition, 8 stable scenarios (range between 1,060 and 1,483) and 10 unstable (range between 0.525 and 0.909) were identified. It was also verified that the steeper the slope and the higher the height, the FS decreases. In addition, not all stable profiles met the minimum requirements of FS>1.5 for the static condition and FS>1.25 for the pseudostatic condition, according to the Peruvian standard CE.020 [9]. No significant differences were found between the FS when varying the CV.

3.2 Reliability and failure probability

Table 4 and Table 5 present the failure probability values, in static and pseudo-static conditions, respectively, of slope profiles with slope 1H:1V, for all heights and CV, obtained using Slide v6.0 software. There are no significant differences between the SFs when the CV is varied. However, when complementing this information with the values of the probability of failure, it was observed that increasing the CV increases the probability of failure in most cases.

In addition, it was verified that, in all the scenarios evaluated, as the slope height increases, the probability of failure increases, while the FS decreases. It is possible to However, it is convenient to work with the failure probability criterion, according to USACE [5]. In this sense, it is expected that the evaluated structures present a level of behavior above the average to be considered reliable, i.e., indices higher than 2.5, which is equivalent to a failure probability higher than 0.1%. In the static condition, most slopes are stable, unlike the pseudo-static condition.

Slope reliability was determined by applying the FOSM method. This method allowed measuring the contribution of the geotechnical parameters in the FS variance. Table 6 shows the results of one of the profiles analyzed.

Table 4. Probability of failure in 1H:1V slope profiles, static condition

Height (m)	FSp-CVmin	%	FSp-CVmax	%
10	1.602	0.00	1.609	1.250
20	1.210	1.26	1.215	11.59
30	1.055	22.18	1.060	34.08

Table 5. Probability of failure in 1H:1V slope profiles, pseudo-static condition

Height (m)	FSp-CVmin	%	FSp-CVmax	%
10	1.151	8.740	1.156	21.49
20	0.854	97.64	0.858	85.87
30	0.740	100.0	0.743	99.15

Table 6. FOSM method applied to a 30m profile, 1H:1V slope, static condition, CV_{max}

Parameter	Xi	ΔXi	FS(Xi+ ΔXi)	V(Xi)	Contribution
Cohesion	18	1.80	1.09	35.04	50.98
Friction angle	30	3.00	1.15	8.94	46.09
Specific weight	18	1.80	1.03	2.02	2.94
			Reliability	β	0.42
			Probability of failure	P_r (%)	35.22

3.3. Historical case

With the probabilistic approach [3], the proposal to stabilize the Maria Reiche slope was analyzed. Located in the Miraflores district, province of Lima, department of Lima, with UTM coordinates East 277012 and North 8659722 using the WGS 84 system according to INGEMMET [11]. The critical need for a geotechnical study on the Maria Reiche Slope is due to the intrinsic complexity of slope stability in the region. The interaction of factors such as the topography of the Costa Verde and the presence of weakness planes demands a detailed evaluation. The resulting assessment guides the implementation of effective mitigation measures, ensuring the long-term stability of infrastructures such as the María Reiche Bridge. Therefore, this geotechnical study is not only academic but essential for civil engineering, guaranteeing the safety of structures and the protection of those who transit through the Costa Verde. Slide software was used for modeling. Figure 3 and Figure 4 show the profile and the model, respectively. Table 6 presents the results.

Fig. 4. Maria Reiche slope [10]

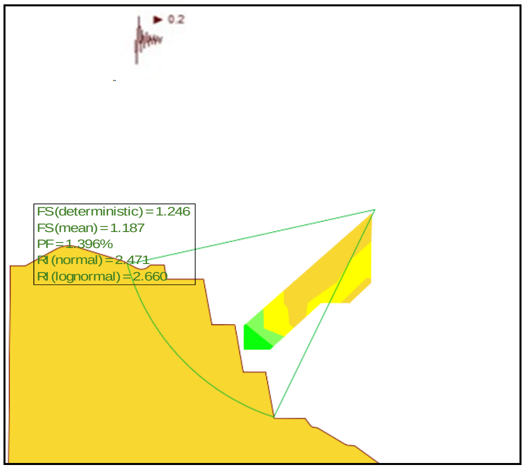

Fig.5 Slope profile modeling in Slide

Table 6. Geotechnical parameters of Maria Reiche Slope

Parameter	Symbol	COV(%)$_{min}$	COV(%)$_{max}$	Unit	Middle value
Cohesion	**c’**	20.00	33.33	kN/m^2	55.00
Specific weight	**γ’**	3.00	8.00	kN/m^3	21.00
Friction angle	**φ’**	3.70	10.10	-	40°

Table 7. Seismic slope parameters Maria Reiche

Parameter	Symbol	Condition	
		Static	Pseudostatic
Horizontal seismic coefficient	K_h	0.00	0.20
Vertical seismic coefficient	K_v	0.00	0.00

Table 8. Comparison of methods using Morgenstern-Price solution

Methods		CV$_{min}$	CV$_{max}$
	FS$_{st}$	FS$_{pst}$	FS$_{pst}$
Mendoza (2016)	1.55	1.22	-
Slide (deterministic)	-	1.25	1.25
Slide (probabilistic, LHS)	-	1.19	1.22
FOSM	-	1.19	1.22

4. Conclusions

The design of synthetic slopes, and the complementary study of a real case, allowed us to fulfill the main objective of the research, referring to the evaluation of the uncertainty of geotechnical parameters, through probabilistic methods, in the analysis of stability. The results, in the different scenarios and conditions evaluated, provided useful information about the behavior of the slopes, and in that sense, in relation to the general hypothesis formulated at the beginning, it was possible to establish the following conclusions.

There are no significant differences between the deterministic and probabilistic safety factors, so it is impossible to notice the effect of uncertainty if the information provided by probabilistic analysis approaches is ignored. The results of the slope analysis allowed us to identify cases where it is verified that they meet the stability criteria, but do not meet the reliability criteria. This means that, although in these cases the slopes are stable, they are not reliable. It was determined that the parameters with the greatest influence on slope stability are cohesion, the angle of internal friction and the weight of soil, in that order of relevance. However, this order is altered in scenarios of uncertainty and earthquakes, where the angle of internal friction dominates the influence. Reliability analyzes applied to slope evaluation do not guarantee that the designs proposed based on the results will never fail, but it does provide a broader panorama in the formulation of better solution proposals. In the historical case, it was shown that, despite considering that it is a stable slope, the probabilistic approach allowed identifying a range of failure probability varying between 1.39% and 12.01%. This can be interpreted as meaning that, for a 100m long slope, up to 12m could fail in the most critical scenario.

Slope analysis encompasses a wide range of research in geotechnical engineering, allowing the addressing of instability problems from multiple approaches and methodologies. In this research, analyses can be complemented by incorporating boundary conditions and additional approaches, such as more complex geometries, heterogeneous slopes, additional numerical methods, and considerations of multiple loads, as well as variations in calculation conditions, such as adjusting the number of iterations, types of complex failure surfaces, force models, and even three-dimensional evaluations. Additionally, procedures can be adjusted to analyze rocky soils and other types of structures, such as dams and reinforced soils.

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