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INTEGRATING SOIL PROPERTY VARIABILITY IN SENSITIVITY AND PROBABILISTIC ANALYSIS OF UNSATURATED SLOPE: A CASE STUDY

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ABSTRACT: Slope failure poses a significant challenge in geotechnical engineering, with the spatial variability of soil properties emerging as a crucial factor influencing slope stability. This research paper introduces a method that integrates soil property variability into sensitivity and probabilistic analyses of slope failure. By means of sensitivity analysis, we identify the most influential soil properties that affect slope stability, while probabilistic analysis allows us to quantify the probability of slope failure. To exemplify this approach, we conducted a case study in Sapa, Vietnam. In this study, TRIGRS was employed to estimate the changes in groundwater induced by rainfall within the slope. Additionally, SLOPE/W, a widely used commercial computer program that leverages Monte Carlo simulation as its underlying methodology to estimate the probability of slope failure, was utilized in the next step. Our study underscores the significance of employing accurate and representative soil properties in slope stability analysis. By comparing the outcomes obtained through a deterministic approach with those derived from a probabilistic approach, we demonstrate that the latter provides a more realistic estimate of the probability of slope failure. Our findings unequivocally establish that soil property variability exerts a substantial impact on slope stability. Consequently, it is imperative to incorporate this variability into the analysis to effectively evaluate the risk of slope failure.

Keywords: Slope stability, Sensitivity analysis, Probabilistic analysis, TRIGRS, SLOPE/W.

1. INTRODUCTION

An accurate depiction of soil properties is crucial for reliable analysis as these properties significantly influence the stability of slopes [1, 2]. Traditionally, slope stability analysis has been performed using deterministic methods that assume fixed values for soil properties [1, 3-7]. As a result, these methods only provide a single estimate of a slope's factor of safety with conservative values. However, It may not be a reasonable approach to apply the same nominal safety factor value across conditions with considerably different levels of uncertainty [8]. The variability of soil properties persists spatially, even within layers that are ostensibly uniform, due to depositional and post-depositional processes that give rise to variations in soil characteristics [1]. Therefore, the inherent variability of soil properties impacting slope stability implies that slope stability is a probabilistic phenomenon rather than deterministic. Relying solely on deterministic methods may result in overestimating or underestimating the probability of slope failure, which can have serious safety and economic repercussions [4].

Sensitivity analyses are often performed to assess the influence of parameter variability on the predicted slope behavior [9-11]. It is thus valuable to understand which inputs are the most important for a slope stability analysis and where efforts should be focused with respect to field and laboratory investigations [10]. From the Sensitivity result, the authors can find the most significant parameters and choose to be random variable parameters [12]. Furthermore, uncertainties in soil properties, environmental conditions, and theoretical models are the reason for a lack of confidence in deterministic analyses [3, 13]. The probability approach offers a systematic way of treating uncertainty and quantifying the reliability of a design [14]. The use of probabilistic models can enable the exploration of alternative perspectives on risk and reliability, which fall beyond the purview of traditional deterministic models [15].

The reliability of slope design and performance assessment is frequently affected to a considerable extent by the presence of uncertainty [3, 8, 10, 16]. Multiple factors contribute to uncertainty in geotechnical analysis, including geological anomalies, the inherent spatial variability of soil properties, limited availability of representative data, fluctuating environmental conditions, unexpected failure mechanisms, simplifications and approximations employed in geotechnical models, and potential human errors during design and construction [17, 18]. Ignoring soil spatial variability "can be erroneous and misleading [16]. Therefore, to ensure a consistent risk level of slopes, it is not sufficient to specify a constant value of FS [19]. Probabilistic analyses provide a way to measure and integrate uncertainty in a logical manner within the design process [16].

In literature, there have been differences among probabilistic methods for analyzing slope stability in terms of their assumptions, ability to handle intricate problems, mathematical complexity, and limitations [3, 16, 20]. Monte Carlo simulation is a widely used probabilistic method that allows for the estimation of the probability of slope failure by considering the variability of soil properties and other relevant factors [3, 20, 21]. Monte Carlo Simulation is a technique that generates random points within the range of possible values that are involved in a calculation. This way, it covers the uncertainty and variability of the input parameters and produces a distribution of outcomes [22]. The direct Monte Carlo Simulation (MCS) technique has an advantage over other methods due to its easy computation and simple process [3].

Sapa, Vietnam, is known for its hilly terrain and steep slopes [5, 6, 23]. It is situated in a high rainfall zone and frequently experiences intense precipitation during the monsoon season (the average annual rainfall reaches 1,800 - 2,200mm) [5]. These kinds of conditions make the area vulnerable to landslide occurrences [5, 6]. Furthermore, the uncontrolled urbanization and deforestation in the region have resulted in the removal of vegetation cover that stabilizes soil and protects slopes. This loss of vegetation cover, combined with increased human activity and infrastructure development, increases the likelihood of landslides. Therefore, it is essential to implement effective landslide mitigation measures and improve land-use planning in Sapa to minimize the impact of such events.

This study introduces a methodology to integrate the variability of soil properties in sensitivity and probabilistic analyses of slope failure. The analysis was carried out on a sliding site in Sapa, Vietnam, and involved two main steps. Firstly, the hydrological conditions triggered by intense rainfall were simulated utilizing TRIGRS [24], a widely used tool for grid-based regional slope-stability modeling and transient rainfall infiltration. Secondly, the hydraulic response to rainfall conditions, as predicted by TRIGRS, can be readily integrated into SLOPE/W [25] for conducting sensitivity and probability analysis. The simulation was performed during the time step corresponding to the observed time of the landslide.

2. RESEARCH SIGNIFICANCE

The outcomes of this study underscore the profound influence of soil property variability on slope stability and emphasize the necessity of incorporating such variability in the analytical framework to achieve an accurate assessment of the risk associated with slope failure. These findings have far-reaching implications for slope stability analysis and management, thereby highlighting the imperative of employing a probabilistic approach that accommodates soil property variability in order to accurately evaluate the risk of slope failure.

3. METHODOLOGY

The study encompassed two principal stages: firstly, the implementation of TRIGRS, a widely recognized computational tool renowned for its capacity to model regional slope stability and transient rainfall infiltration on a grid-based framework, with the objective of simulating the hydrological conditions triggered by intense precipitation at a regional scale during the time frame when the landslide event occurred. Subsequently, the application of SLOPE/W facilitated the execution of sensitivity and probability analyses on a representative cross-section that bisected the landslide mass. The sensitivity analysis aimed to discern the parameter exerting the most pronounced influence on slope stability analysis, while the probability analysis was conducted to ascertain the likelihood of slope failure by leveraging statistical distributions characterizing the influential soil properties. The estimation of failure probability was achieved by calculating the probability associated with the safety factor falling below unity, employing Bishop's simplified method in conjunction with Monte Carlo simulation.

3.1 Prediction of The Hydraulic Conditions Within the Slope in Response to Heavy Rain

TRIGRS was employed to simulate the temporal variation of hydraulic conditions within the slope arising from intense precipitation. The program utilizes the solution of the one-dimensional Richards' equation, a simplified runoff routing scheme, and an exponential soil-water retention relationship to calculate the transient response of pore-water pressures resulting from rainfall infiltration in unsaturated soil. The underlying principle of the program is predicated on the observation that an increase in the groundwater table occurs when the volume of vertically infiltrating water surpasses the maximum capacity that can be drained by gravity [26]. TRIGRS advanced the analysis presented by Iverson [27] by adopting a two-layer soil system consisting of a saturated zone with a capillary fringe above the water table and an unsaturated zone extending to the ground surface (Fig. 1). The infiltration at the ground surface and vertical flow through the unsaturated zone can be effectively modeled as follows [26]:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial Z}\left[K(\psi)\left(\frac{1}{cos^2\delta}\frac{\partial\psi}{\partial Z} - 1\right)\right] \quad (1)$$

in Eq. (1), ψ is the ground-water pressure head; t is time; Z is the vertical coordinate direction (positive downward) and depth below the ground surface; δ – is the slope angle (Fig. 1); $K(\psi)$ is the dependence of hydraulic conductivity; θ is the volumetric water content.

According to Srivastava and Yeh [28], Equation (1) can be linearized by the exponential hydraulic parameter model proposed by Gardner [29] to provide an analytic solution for transient infiltration through the unsaturated zone. The relationship between the pressure head, the hydraulic conductivity K(ψ), and the volumetric water content (θ) in the Richards equation is determined by the following formulas [28, 29]:

$$K(\psi) = K_s exp(\alpha\psi^*) \quad (2)$$

$$\theta = \theta_r + (\theta_s - \theta_r)exp(\alpha\psi^*) \quad (3)$$

In Eq. 2 and Eq. 3, $\psi^* = \psi + 1/\alpha$, where 1/α represents the vertical height of the capillary fringe above the water table, K_s is the saturated hydraulic conductivity, θ_r is the residual water content, and θ_s is the water content at saturation.

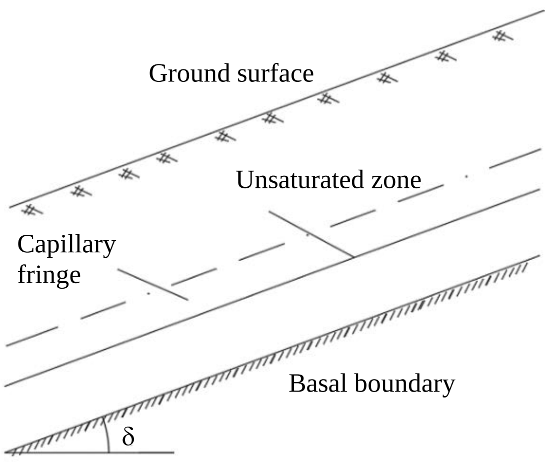

Fig.1 Schematic cross sections showing boundary conditions assumed in deriving the infiltration formulas in TRIGRS.

3.2 Sensitivity and Probability Analysis of Slope Failure

3.2.1 Slope stability analysis of unsaturated soil

In this study, Bishop's simplified method was employed to estimate the factor of safety (FS) associated with the slope. It is noteworthy that this method has been demonstrated to yield comparable accuracy to more rigorous approaches [25]. The stability analysis of the slope relies on the fundamental definition of the factor of safety (FS), which represents the ratio of the ultimate shear strength ($\boldsymbol{\tau_f}$) to the mobilized shear strength (τ) when the slope is on the brink of failure.

$$FoS = \frac{\tau_f}{\tau} \quad (4)$$

To incorporate the alteration in soil shear strength resulting from the evolution of suction, the approach proposed by Vanapalli, Fredlund [30] was implemented. In accordance with this methodology, the estimation of the overall non-linear function can be accomplished by utilizing a soil-water characteristic curve in conjunction with the saturated shear strength parameters of the soil [30].

$$\tau = c' + (\sigma_n - u_a)tan\phi' + (u_a - u_w)\left\{\left(\frac{\theta_w - \theta_r}{\theta_s - \theta_r}\right)tan\phi'\right\} \quad (5)$$

where, c' is the effective cohesion; σ_n is total normal stress; u_a is pore air pressure; u_w is pore water pressure, ϕ' is effective friction angle, θ_w – the volumetric water content, θ_s is the saturated volumetric water content, θ_r – the residual volumetric water content, (u_a - u_w) represents soil matric suction, (σ_n - u_a) is net normal stress.

3.2.2 Sensitivity and probability analysis

A sensitivity analysis shares certain similarities with a probabilistic analysis; however, it distinguishes itself by employing a different approach to selecting variable parameters [25]. Unlike the random selection employed in probabilistic analysis, sensitivity analysis employs an orderly selection of parameters utilizing a uniform probability distribution function. By utilizing this approach, sensitivity analysis provides insights into which input parameters are critical for the accurate assessment of slope stability [9]. On the other hand, the Monte Carlo Simulation technique entails the iterative computation of a deterministic model using randomly generated input values derived from sets of random numbers [25].

The probability of failure is defined as the likelihood of obtaining a factor of safety (FS) value less than 1.0. In order to determine the probability of failure, the number of safety factors below 1.0 is counted, and this count is expressed as a percentage of the total number of Monte Carlo trials that have successfully converged [25]. The probability of failure (P_f) can be calculated using Monte Carlo Simulation as the ratio between the number of cases in which FS is less than 1 and the total number of trials (denoted as n, with n = 3000 in this case):

$$P_f = \frac{cases\ with\ F_s < 1}{n} \quad (6)$$

Natural datasets and random variable measurements frequently exhibit a bell-shaped distribution that closely approximates a normal probability density function, a pattern that is also observed in numerous material properties within the field of geotechnical engineering [25]. The normal probability density function employed in SLOPE/W is expressed as follows:

$$f(x) = \frac{e^{-(x-u)^2/2\sigma^2}}{\sigma\sqrt{2\pi}} \quad (7)$$

where x is the variable of interest, in this study, soil cohesion, friction angle, and soil unit weight were selected as random variables; u is the mean; and σ is the standard deviation.

3.2.3 Definition of the potential slip surface

Upon the identification and observation of the landslide body, the “Entry and Exit” technique was judiciously chosen as an appropriate methodology. This technique serves the purpose of designating specific sections of the ground surface that facilitate the entry and exit of the potential slip surface within the defined domain [25]. Simultaneously, optimization Settings were meticulously employed to harness the advanced capabilities of SLOPE/W. These settings offer a potent functionality that enables the generation of slip surfaces featuring reduced factor of safety (FS) values and more realistic geometries, achieved by disregarding the original geometric parameters utilized to define the initial trial slip surfaces. To elaborate further, the optimization process initiates by dividing the critical slip surface into linear segments. Subsequently, the termination points of these linear segments are systematically adjusted to ascertain the potential for attaining a decreased FS. The slip surface undergoes iterative adjustments along the ground surface, oscillating randomly in both backward and forward directions until the minimum FS is obtained. This iterative process is repeated for all points along the slip surface, comprehensively exploring the entire critical slip surface.

4. STUDY AREA AND INPUT DATA

The study area is situated at Km9+100 on provincial road No. 152, within Sapa District (Fig. 2). On August 04, 2019, at around 09:00 local time, a landslide occurred, involving loose soil and rock with an estimated volume of about 300 m^3. This event resulted in the blockage of the road for several days. The landslide was triggered by persistent heavy rainfall spanning multiple days across the entire region. The precise location of the study area, along with the delineation of the sliding scar, is shown in Fig. 2. Fig. 3 presents the relationship between rainfall intensity and duration during the rainfall event that precipitated the landslide within the study area. To facilitate simulation, soil samples were collected from five distinct locations in the vicinity of the landslide mass. Table 1 presents descriptive statistics summarizing the laboratory test results of the major soil parameters.

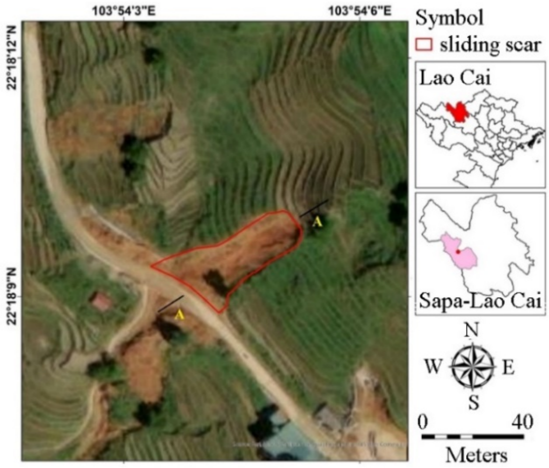

Fig.2 Location of the study area in Sapa town, Lao Cai province. Section A-A represents the center line cutting through the landslide body.

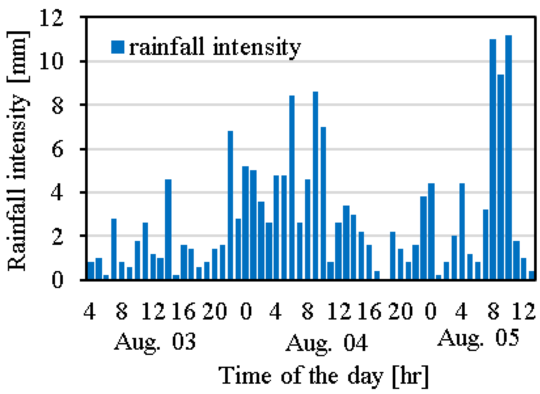

Fig.3 Relationship between rainfall intensity and time. The landslide was observed to occur at around 09:00 am on August 05, 2019.

To evaluate the significant parameters of unsaturated soil, the soil water characteristic curve (SWCC) was constructed. This curve represents the soil's water storage capacity at different levels of matric suction [31]. The SWCC was established through standard laboratory tests. The resulting SWCC for the covered soil layer is shown in Fig. 4.

Table 1 Soil parameters used for simulation.

Soil parameter	Max	Min	Mean	Standard deviation
Hydraulic conductivity (m/s)			10^{-7}	
Saturated unit weight (kN/m^3)	19.0	18	18.44	0.439
Cohesion (kN/m^2)	14.0	11.1	12.62	1.26
Internal friction	16.5	14.5	15.34	0.832

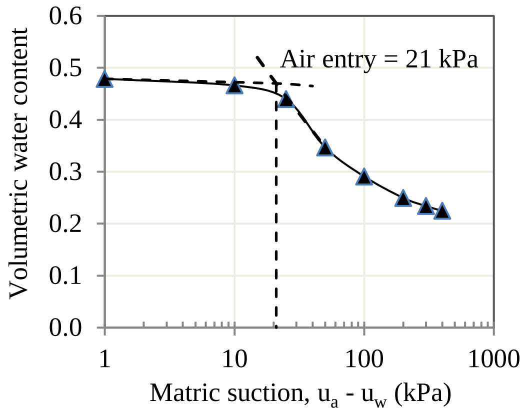

Fig.4 Results of the SWCC curve.

Regarding the spatial distribution of soil depth, the findings of the field survey indicate that the soil profile can be conceptually divided into two distinct layers: the residual soil layer and the bedrock layer. Specifically, the residual soil layer was determined to possess a thickness of approximately 4.0 m at its deepest point [6]. Considering this, for the sake of caution, a uniform depth of 4.0 m for the covering residual soil layer was adopted in the current investigation. Fig. 5 illustrates the typical cross-section of the landslide following section A-A as presented in Fig. 2.

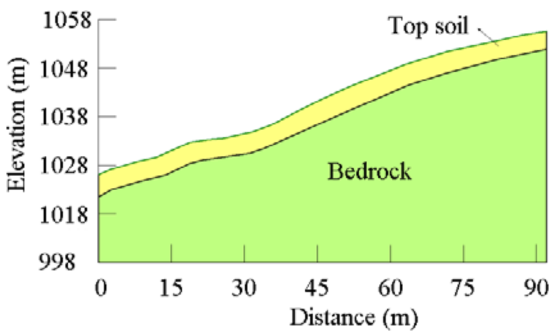

Fig.5 Typical cross-section of the landslide following section A-A.

5. STUDY AREA AND INPUT DATA

5.1 Hydraulic Conditions within the Slope in Response to Heavy Rain

The simulation of hydraulic conditions within the slope in response to rainfall was conducted under the assumption that initially, the groundwater table coincided with the underlying interface between the cover soil layer and the low permeability bedrock surface. Using TRIGRS, the hydraulic conditions within the slope were simulated at the specific time of failure, based on the recorded rainfall data as depicted in Fig. 3. Fig. 6 displays the predicted spatial distribution of groundwater elevation observed at the time when the landslide occurred. Additionally, Fig. 7 illustrates the distribution of the groundwater table within the typical cross-section (section A-A, as shown in Fig. 2). These simulated hydraulic conditions will be imported into Slope/W for sensitivity and probability analysis.

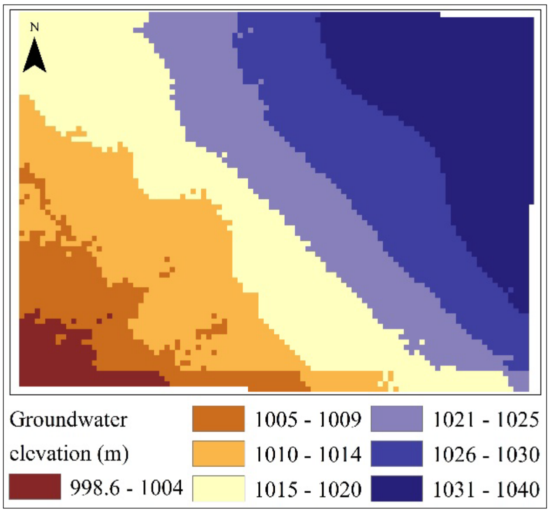

Fig.6 Result of the spatial distribution of the groundwater table at the time when the landslide was observed to occur.

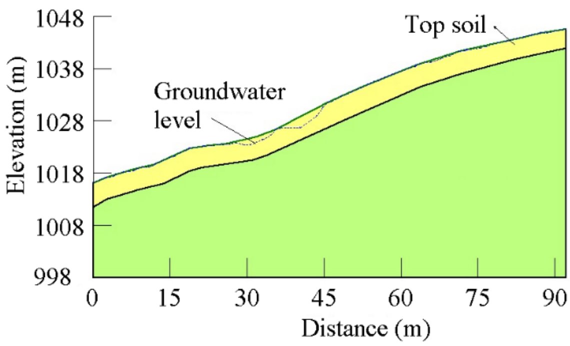

Fig.7 Distribution of the groundwater table within section A – A.

5.2 Sensitivity Analysis

A sensitivity analysis indicates which input parameters may be critical for assessing slope stability and which parameters are less significant [9, 32]. Sensitivity analysis involves varying individual variables within their minimum and maximum values. It examines one variable at a time, unlike probabilistic analysis which considers all random variables [25]. In the case of conducting sensitivity analysis using SLOPE/W, a sensitivity graph (Fig. 8) is provided, depicting the computed factor of safety at different parameter values for the time-step corresponding to the observed time of the landslide.

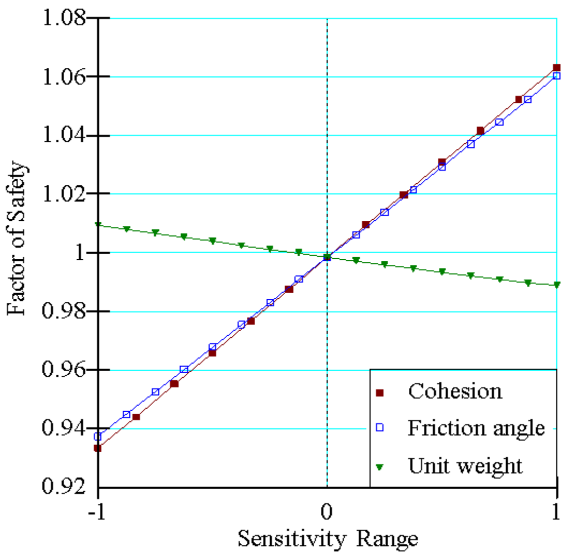

Fig.8 Sensitivity plot of the computed FS versus the range of the cohesion, friction angle, and unit weight of the topsoil layer.

Fig. 8 illustrates the crossing point that corresponds to the factor of safety obtained when using the mean value of all parameters (FS = 0.995). Fig. 9 is the corresponding slip surface defined using the entry and exit method.

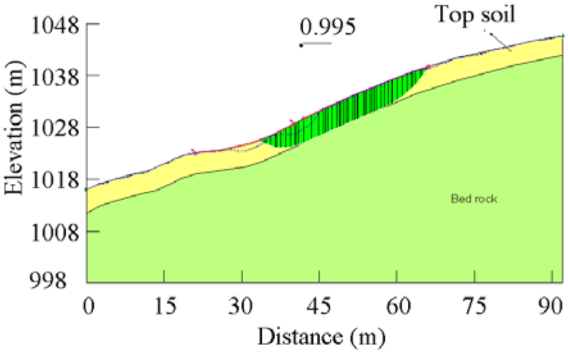

Fig.9 Slip surface defined using the entry and exit method and mean value of all parameters.

As can be seen in Fig. 8, the factor of safety exhibits the highest sensitivity to the cohesion values of the embankment, while being the least sensitive to the material unit weight. Consequently, the variability of cohesion has the most significant impact compared to other parameters in almost all the conditions considered and is chosen as a random variable for the probability analysis of slope failure. Furthermore, the sensitivity graph (Fig. 8) reveals a noteworthy range of Factor of Safety, which spans from 0.93 for an effective cohesion value of 11.1 kN/m^2 to 1.061 when the cohesion is 14.0 kN/m^2. This range signifies a substantial margin of safety, guarding against potential failures. Additionally, it elucidates the underlying cause behind the observed instability of the slope in practical circumstances.

5.3 Probability Analysis

SLOPE/W offers simultaneous deterministic and probabilistic analyses. Given that cohesion is the most critical parameter, it was selected as the random variable for probability analysis. In each trial of the Monte Carlo simulation, the soil properties for the entire soil layer were sampled just once and then uniformly assigned to all the slices within that layer. Consequently, the resulting probability of failure was determined based on this approach. The factors of safety were computed by Bishop's Simplified method with Monte Carlo simulation. After performing 3000 Monte Carlo trials in SLOPE/W in this study, the probability distribution output of the factor of safety value is illustrated in Fig. 10.

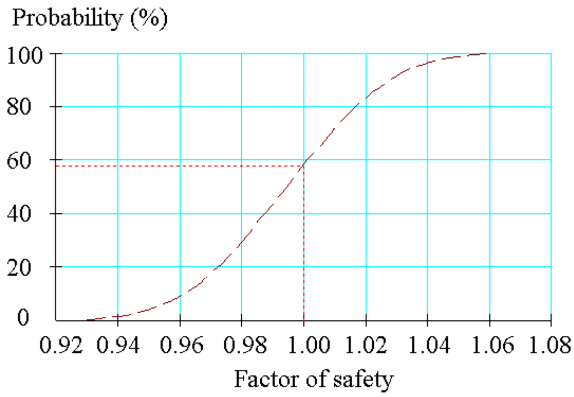

Fig.10 Probability distribution function of the 3000 Monte Carlo FS illustrates the likelihood of encountering failure.

As can be seen, it is evident that for a factor of safety of 1, there is a 57.733 percent probability of failure for all material parameter variability tried in the analysis. The descriptive statistics of the simulated FS values are presented in Table 2. From the general point of view, this result reflects the actual condition of the slope in reality.

Table 2. Descriptive statistics of the simulated FS values.

Mean	P failure (%)	Stand. dev.	Min FS	Max FS
0.995	57.733	0.0253	0.93	1.061

Note: Stand. dev. = standard deviation, P = probability

6. CONCLUSION

The suggested approach presented in this study offers a comprehensive solution for evaluating slope stability by considering the spatial variability of soil properties. This method proves invaluable in designing secure and reliable slope structures by providing a more practical estimation of the probability of slope failure.

The sensitivity analysis conducted in this study revealed that cohesion is the most critical input distribution when analyzing a slope for a circular failure surface, closely followed by internal friction. These findings confirm the expected significance of each input parameter.

The results obtained from the proposed approach indicate that it provides a more realistic assessment of slope failure risk when compared to traditional deterministic methods. However, it should be noted that conducting additional field investigations and soil testing can further enhance the accuracy of estimating the probability of failure.

7. ACKNOWLEDGMENTS

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