Development of an educational software for the assessment of natural slope stability

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Abstract. The analysis of natural slope stability is critical for reducing or mitigating potential catastrophic risks associated with landslides. This kind of disaster not only generates substantial economic and material losses but also creates significant threats to human safety. Landslides occur when forces acting downslope exceed the soil strength. In particular, critical factors such as the slope inclination and the thickness of the soil layer can increase such forces, making a slope prone to sliding. Another cause for landslides is rainfall infiltration because it can increase the soil weight and reduce the soil strength (such as the soil cohesion and friction angle), in particular under unsaturated conditions. Deterministic approaches based on numerical or limit equilibrium methods are used to check slope stability through the computation of the Factor of Safety (FOS). In this study, we introduce an educational software for the quick assessment of FOS in natural slopes. The application allows the analyses of FOS considering input data such as 3D declivity maps, soil thickness, soil properties and rainfall intensity. The application boasts user-friendly navigation and delivers real-time results, enabling sensitivity analyses of the FOS concerning parameters, alongside risk appraisal and prognostication of local condition changes following rainfall events.

Keywords: Educational software, Unsaturated soils, Slope stability.

1 Introduction

The study of natural slope stability is a critical discipline of geotechnical engineering risks posed by landslides. These events threaten both infrastructure and human safety. Addressing these occurrences requires a social approach and a comprehensive understanding of the factors contributing to slope instability, beyond technical considerations.

Key factors affecting slope stability include the increase in soil weight due to rainwater infiltration, which significantly alters soil geotechnical properties and compromises cohesion—a critical determinant of a slope's resistance to landslides. Other crucial variables include slope inclination, soil layer thickness, and resistance characteristics like cohesion and friction angle, all of which require thorough comprehension for accurate stability assessments. The Factor of Safety (FOS) calculation is pivotal in assessing a soil slope stability against landslide hazards, providing a quantitative measure that facilitates systematic evaluation and proactive measures. Soil saturation adds another degree of complexity, as excessive moisture can reduce cohesion and increase a slope's vulnerability to landslides.

In recent decades, extensive research has focused on rainfall-induced landslides due to their destructive impact and risks to infrastructure and lives. Significant contributions include the Antecedent Water Status Model for Wellington City, New Zealand, by Crozier [1], which predicts landslide initiation thresholds based on soil water status and local precipitation data. Studies in Hong Kong by Brand et al. [2] and Dai and Lee [3] emphasized the correlation between intense rainstorms and landslide occurrences, highlighting the intricate relationship between rainfall patterns and landslide dynamics.

Further advancements in slope stability analysis used analytical and numerical methods to assess the impact of pore water pressures and rainfall dynamics on slope stability [4, 5]. Chang and Chiang [6] integrated deterministic slope stability analysis with statistical methods to improve predictive accuracy for rainfall-triggered landslides. Recent studies by Rahardjo et al. [7] in Singapore evaluated regional slope stability under extreme rainfall scenarios, while Gu et al. [8] introduced a stochastic framework to estimate failure probabilities, emphasizing soil properties and rainfall characteristics' critical role in slope failure prediction. These research efforts have provided essential insights for effective landslide mitigation and emergency management strategies worldwide.

This study presents an innovative approach to slope stability analysis by integrating the detrimental effects of soil saturation on shear strength. Furthermore, this study introduces an educational application featuring a user-friendly interface conceived for the assessment of safety factors in natural slopes. This application makes easier the analysis of variations in slope susceptibility through parameter adjustments including cohesion, friction angle, precipitation, soil depth, and slope inclination. The educational software is being developed within the MATLAB environment and is currently in the development phase. Because of that, it is not yet available in any public repository.

2 Methodology

The application developed in this study aims to evaluate the FOS from a map of digital elevations along with soil and rainfall parameters. To efficiently perform this calculation and make it feasible for use over large areas represented by discretized maps, a predictive model is necessary. Initially, the mechanics of unsaturated soils are analyzed to understand how variations in total soil cohesion occur with changes in saturation. Following this, an approximate model for assessing rainwater infiltration is used to determine the depth of the water saturation front directly.

Subsequently, multiple models are generated, and their FOS are evaluated using a method based on limit equilibrium, resulting in a comprehensive database. With this database, a non-linear regression predictive model is trained and tested, which is then used to obtain faster FOS prediction in the engineering application.

2.1 Shear strength of unsaturated soils

The fundamental principles governing the shear strength of saturated soils are applicable to unsaturated soils as well. In the context of unsaturated soils, these stress conditions can be characterized by net normal stresses and matric suction. Theoretical frameworks for shear strength in unsaturated soils have been developed as extensions of established concepts and mathematical formulations used in shear strength theories for saturated soils, such as the Mohr-Coulomb, Modified Cam-Clay Model [9], and HSM model [10].

For example, Fredlund et al. [11] expanded the Mohr-Coulomb failure criteria to encompass unsaturated soils as follows:

$$\tau = c' + (\sigma_n - u_a)\tan(\phi') + (u_a - u_w)\chi\tan(\phi') \tag{1}$$

where:

- τ is the shear strength;
- c' is the effective cohesion;
- σ_n total normal stress on the failure plane at failure;
- u_a pore-air pressure;
- u_w pore-water pressure;
- ϕ' is the effective friction angle;
- χ characterizes the relationship between the matric suction and cohesion defined by Bishop et al. [12]. In this work χ is assumed to be equal to the effective water content ($\chi = \theta_e$).

Moreover, the matric suction component $s = (u_a - u_w)\chi\tan(\phi')$ has been combined with the effective cohesion c' to obtain the total cohesion of the soil c defined as:

$$c = c' + (u_a - u_w)\chi\tan(\phi') \implies c = c' + s \tag{2}$$

The soil suction has been related to the water content through different relationships in the literature. According to Van Genuchten [13], the suction is obtained as follows:

$$s(\theta_i) = \gamma_w \left[\frac{1 - \left(\dfrac{\theta_i - \theta_r}{\theta_s - \theta_r}\right)^{1/m}}{\alpha^n \left(\dfrac{\theta_i - \theta_r}{\theta_s - \theta_r}\right)^{1/m}} \right]^{1/n} \implies c(\theta_i) = c' + \gamma_w \left[\frac{1 - \left(\dfrac{\theta_i - \theta_r}{\theta_s - \theta_r}\right)^{1/m}}{\alpha^n \left(\dfrac{\theta_i - \theta_r}{\theta_s - \theta_r}\right)^{1/m}} \right]^{1/n} \chi\text{tg}(\phi') \tag{3}$$

where γ_w is the water specific weight, θ_i, θ_r and θ_s are the initial, residual and saturated water content, α, n and m are the van Genuchten parameters that define the characteristic curve of the soil, and their values are specific to the material under consideration.

2.2 Rain water infiltration

The Green and Ampt equation [14] is widely used to describe the temporal evolution of cumulative infiltration depth of water in homogeneous soils caused by intense rainfall events. This model is renowned for its straightforward implementation and theoretical foundation, which derives from the application of Darcy's law using finite-difference methods.

Serrano [15] introduced a simplified formulation for both cumulative infiltration depth and infiltration rate, which is employed in this study. These formulations provide an explicit solution to the Green and Ampt infiltration equation through a systematic series decomposition approach. The mathematical expression is outlined below:

$$h_w(t) = h_{w0}(t) + a\ln\left[\frac{h_{w0}(t)+a}{h_{wp}+a}\right]\left[\frac{h_{w0}(t)+a}{h_{w0}(t)}\right] \tag{4}$$

$$h_{w0}(t) = k(t-t_p) + h_{wp}; \qquad a = |\Psi_f|(\theta_s - \theta_i); \qquad h_{wp} = h_w(t_p); \qquad t_p = \frac{ka}{p(p-k)} \tag{5}$$

where:

- $h_w(t)$ is the saturation front depth;
- t is the time of evaluation;
- t_p is the ponding time;
- p is the precipitation;
- k is the saturated hydraulic conductivity;
- Ψ_f is the pressure head at the wetting front.

2.3 Database generation and predictive model

Several parameters were utilized as design variables to encompass a broad spectrum of soils and slopes in a generic model. These parameters include the soil layer thickness (h), the depth of the saturation front (h_w), slope inclination (β), as well as various soil parameters such as effective cohesion (c'), friction angle (ϕ'), and initial water content (θ_i). The model is depicted in Figure 1, where γ_{nat} and γ_{sat} are the natural and saturated specific weights, respectively.

To ensure the robustness of the dataset, 1000 distinct models were generated using the Latin Hypercube Sampling (LHS) technique. This procedure was conducted across five different types of soil: Coarse, Medium, Medium Fine, Fine, and Very Fine, as defined by the classification of soils provided by Wösten et al. [16]. The lower and upper bounds of parameters are detailed in Table 1. It should be noted that initial water content bounds differ for each soil type. The lower initial water content is taken as the value that makes the soil achieve a matric suction of 500 kPa, according to eq.(3) and the upper value is the saturated water content. The van Genuchten parameters for each type of soil are detailed in Table 2.

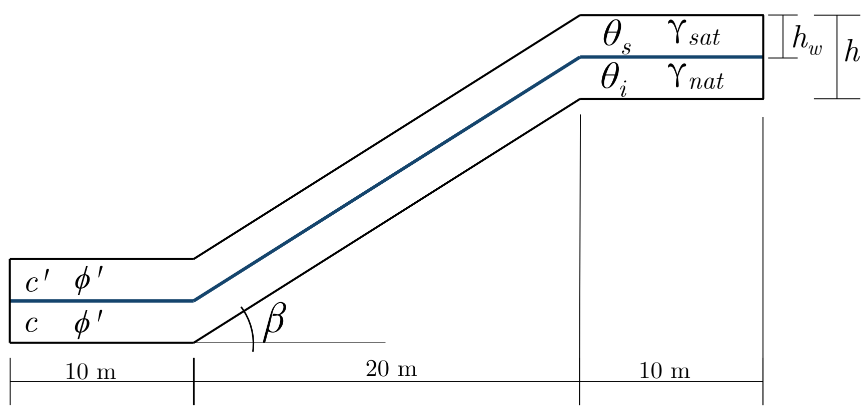


Figure 1. Generic slope model used to create the database.

Table 1. Model parameters lower and upper bounds.

Parameters	Symbol	Lower bound	Upper bound	Unit
Height of soil on slope	h	1	5	m
Height of saturated soil	h_w	0.1	4.5	m
Slope inclination	β	15	45	degree
Cohesion	c'	0	20	kPa
Friction angle	ϕ'	15	45	degree
Initial water content (Coarse)	θ_i	0.046	0.365	m^3/m^3
Initial water content (Medium)	θ_i	0.179	0.392	m^3/m^3
Initial water content (Medium Fine)	θ_i	0.188	0.412	m^3/m^3
Initial water content (Fine)	θ_i	0.327	0.481	m^3/m^3
Initial water content (Very Fine)	θ_i	0.392	0.538	m^3/m^3

Table 2. Mualem-van Genuchten parameters for available soil textures [16].

Soil Texture	θ_r	θ_s	α [m^{-1}]	n	m	k [m/day]
Coarse	0.025	0.366	4.30	1.521	0.342	0.600
Medium	0.010	0.392	2.49	1.169	0.145	0.121
Medium Fine	0.010	0.412	0.82	1.218	0.179	0.023
Fine	0.010	0.481	1.98	1.086	0.079	0.248
Very Fine	0.010	0.538	1.68	1.073	0.068	0.150

Limit equilibrium methods are employed to assess the FOS of slopes, assuming simplifying hypotheses such as the presence of a single failure surface and uniform soil properties. These simplifications make them well-suited for expedient evaluations in slope stability analyses. In this study, the Morgenstern–Price method [17] was utilized. For FOS assessment the software HYRCAN® was applied.

Then, a predictive model based on polynomial regression was trained, aiming to predict a model represented by the function $f(h, h_w, \beta, c', \phi', \theta_i)$. Initially, a data processing procedure was conducted for each population of 1000 models of each soil type. During this process, a filter was applied to remove outliers, defining an outlier as any model presenting an FOS greater than the mean plus twice the standard deviation. After outlier removal, the data population was divided into 85% for the training set and 15% for the test set.

The training population was utilized to optimize the parameters of a polynomial regression, with the objective of minimizing error relative to the value evaluated by the Morgenstern-Price method. In total, five distinct functions were defined, one for each soil type. The regression problem metrics are detailed in Table 3.

Table 3. Regression metrics results.

Soil Sample	Number of Terms	R^2	$RMSE$	$MAPE$
Coarse - Train	26	0,97	0,15	5.04%
Coarse - Test	26	0,99	0,11	4.17%
Medium - Train	31	0,94	0,29	8,09%
Medium - Test	31	0,88	0,45	9,17%
Medium Fine - Train	28	0,91	0,41	9,56%
Medium Fine - Test	28	0,89	0,44	9,66%
Fine - Train	27	0,89	0,46	9,65%
Fine - Test	27	0,85	0,53	10,55%
Very Fine - Train	23	0,84	0,62	13,49%
Very Fine - Test	23	0,87	0,61	13,07%

3 Graphical user interface

The application developed in this study designed for educational purposes features an intuitive and user-friendly graphical interface. The interface supports interactivity, allowing users to adjust variable parameters via sliders and observe real-time updates of the susceptibility map.

The interface is structured into six distinct panels, that composes the graphical user interface (GUI) as it is shown in Figure 2.

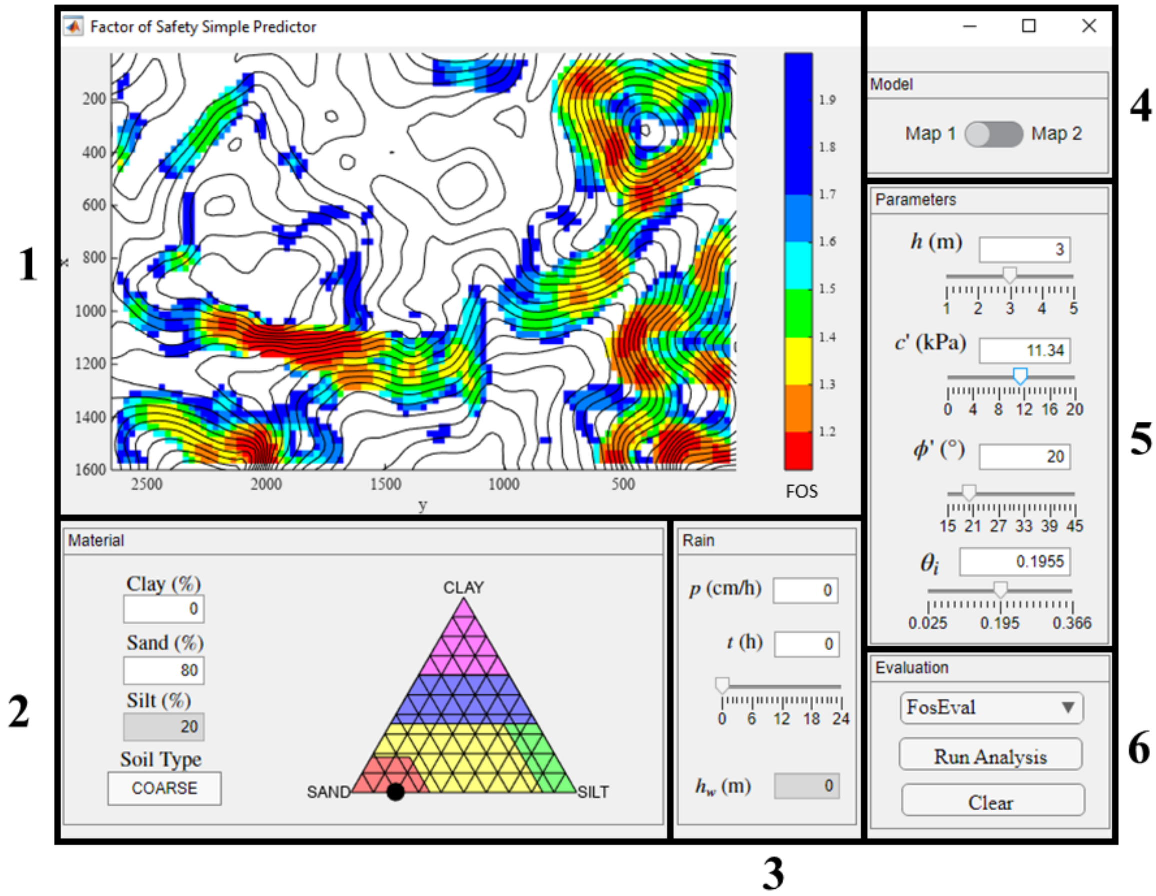


Figure 2. Graphical User Interface (GUI).

The name and function of the six panels are:

(**1**) *Visualization Axis*: A visualization axis is employed to depict the predicted FOS results, alongside a digital elevation model represented by contour lines. Positioned on the right-hand side of the panel is a colorbar, which delineates hazard gaps through a spectrum of distinct colors;

(**2**) *Soil Type Panel*: The characterization of soil type is presented. The user is asked to furnish a percentage value denoting the proportion of clay and sand constituents in the soil. These provided values are used to define the soil type in five distinct categories, marked by the position of a point within the texture triangle. Furthermore, the derivation of all Van Genutchten parameters is based upon the soil type classification obtained as defined on Table 2.

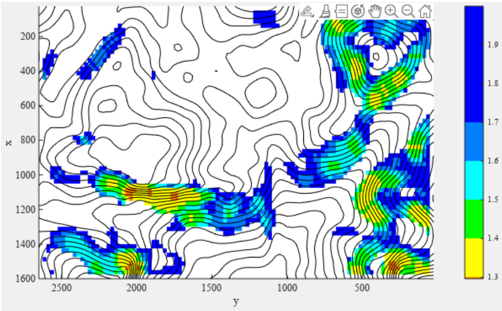
(**3**) *Rainfall Parameters Panel*; Users are prompted to input precipitation intensity and time parameters, used for the assessment of the of front saturation depth (h_w) through the Green-Ampt equation. Additionally, a slider is incorporated, allowing users the option to dynamically adjust the temporal input, thereby facilitating an exploration of the resultant variations in FOS relative to rainfall duration;

(**4**) *Model Panel*: Interface through which users specify their preference regarding the digital elevation model for analysis. This initial version provides access to two digital elevation models for analysis;

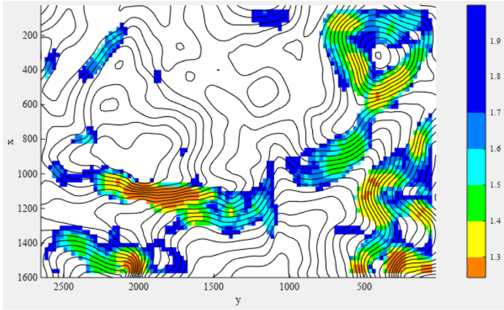
(**5**) *Parameters Panel*: Locus for user input concerning variables essential to the prediction of the FOS. The required variables encompass soil depth (h), effective cohesion (c'), friction angle (ϕ'), and initial water content condition (θ_i). It is important to emphasize that saturation front depth (h_w) and slope inclination (β) constitute indispensable parameters for FOS evaluation; however, their values are derived respectively from the digital elevation model and the rainfall parameters panel.

(**6**) *Evaluation Panel*: Users have the option to select the function to be applied for FOS prediction. Additionally, there are features available to initiate the analysis and to reset the model.

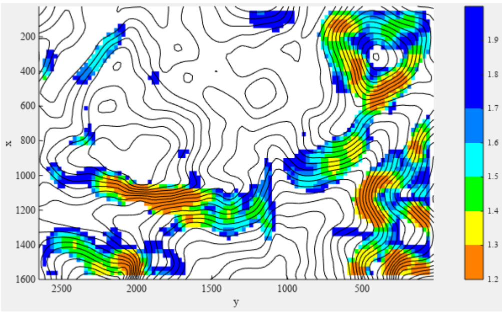
Figure 3 illustrates an example of the variation of the FOS with time of rain, it is noteworthy that the saturation depth front changes as the time passes, according to eq. (4).



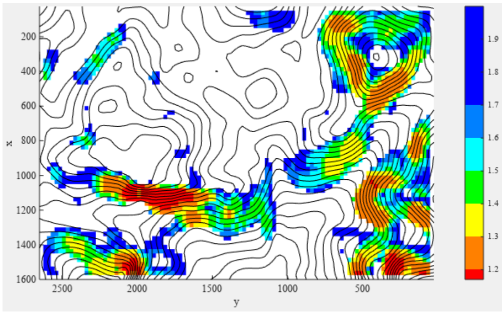
(a) $t = 0$ h, $h_w = 0$ m;



(b) $t = 6$ h, $h_w = 0.56$ m;



(c) $t = 12$ h, $h_w = 1.03$ m;



(d) $t = 18$ h, $h_w = 1.35$ m;

Figure 3. Variation of the FOS with the time of rainfall.

4 Conclusions

This study comprehensively investigates the stability of natural slopes, a critical concern not only due to economic and environmental damages but also due to the profound social consequences associated with landslides. The research primarily aims to identify and understand the multiple factors influencing slope stability, particularly in the context of the heavy rainfall patterns exacerbated by climate change. Key variables examined include soil saturation, depth of soil layers, slope inclination, and resistance parameters such as cohesion and friction angle. Through rigorous theoretical and numerical analyses, this study provides a detailed and systematic assessment of the safety conditions of these natural formations.

Beyond theoretical exploration, this research extends its scope to the development of an innovative application featuring an intuitive graphical interface, initially designed with an educational emphasis. This application not only makes easier real-time visualization and comprehension of landslide risks but also motivate users to simulate various scenarios and manipulate parameters to personalize assessments of slope stability. This tool proves invaluable for educational purposes, enabling detailed studies on the sensitivity of FOS to parameter variations, as well as investigations into the impacts of intense precipitation events on soil strength degradation and subsequent contribution to landslide risks.

Furthermore, the application's capability to generate susceptibility and risk maps represents a significant advancement. Future versions hold promise for broader application in geotechnical disaster management, offering decision-makers and local communities enhanced tools to implement more effective preventive measures.

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