https://doi.org/10.20965/jdr.2021.p0512

Paper:

A Non-Linear, Time-Variant Approach to Simulate the Rainfall-Induced Slope Failure of an Unsaturated Soil Slope: A Case Study in Sapa, Vietnam

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[Received November 30, 2020; accepted March 19, 2021]

In this study, the Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Analysis (TRIGRS), v2.1 program, and module SLOPE/W in the Geostudio package were adopted for assessing rainfall-induced slope failure. TRIGRS was developed by the United States Geological Survey to determine the time-varying groundwater table at the regional scale under rainfall infiltration. The program employs partial differential equations represented by one-dimensional vertical flow in homogeneous materials for unsaturated conditions. With the application of a simple runoff routing scheme combined with the mass balance between rainfall, infiltration, and runoff over the study area, the distribution of the transient pore-water pressures within the entire landscape was simulated considering both the surface and subsurface flow. Additionally, compared to the traditional two-dimensional approach, the topographical conditions were also considered during the groundwater simulation. For conducting the slope stability analysis, a typical cross-section was constructed based on the site description. The predicted water-tables at the observed time of failure of the typical section were extracted and used in SLOPE/W to conduct the time-dependent modelling of rainfall-induced slope failures. In this study, the non-linear method was employed for simulating unsaturated soil shear strength, and the stability of the slope was evaluated using Bishop's simplified method. We applied the approach to the landslide event that occurred on August 5, 2019, in Sapa district, Lao Cai province, Vietnam. The event resulted in severe damage and blocked the road for days. The predicted results on the stability of the slope as the factor of safety were compared with the actual slope failure during the event. The results showed that, by inputting accurate data, the applied approach could provide valuable evidence about the time of the slope failure.

Keywords: TRIGRS, rainfall infiltration, SLOPE/W, slope failure, non-linear method

1. Introduction

Rainfall is recognized as one of the most common factors that trigger landslides and slope failures in tropical regions [1–4], particularly in Vietnam, a country that experiences heavy rainfall almost throughout the year. Landslides in steep residual soil slopes are a common problem [3, 5]. In slope stability assessment, it is crucial to estimate the shear strength of the soil during wetting processes since most slope failures are caused by rainfall that generally induces a wetting process in the soil [6, 7]. Basically, the infiltration of rainwater through the unsaturated zone above the groundwater table leads to an increase in moisture content, a rise in the groundwater table, and a reduction in matric suction [4, 8, 9]. This process subsequently decreases the shear strength of the soil. When the shear strength mobilized along the critical slip surface is not adequate to support the shear stress, slope failure will occur [10]. The mechanism of rainfall-induced slope failure, however, is still an unresolved issue since soil slippage is often controlled by various spatial and climatic factors [11–14].

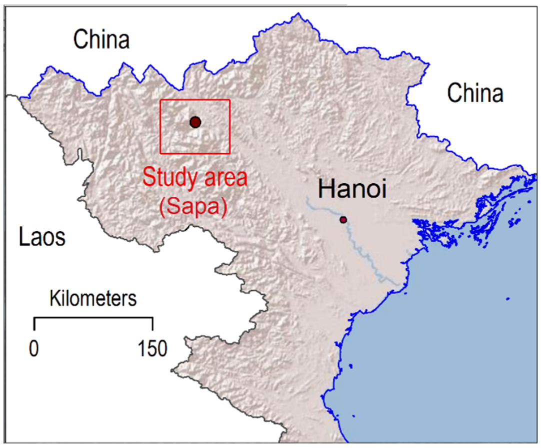
The significant difference between water flow in saturated and unsaturated soils is that the coefficient of permeability, which is usually assumed to be a constant in saturated soil, is a function of the matric suction in unsaturated soil [15]. Traditional slope stability analyses are commonly simulated assuming saturated conditions, where the influence of matric suction is often ignored [3]. The effect of rainfall infiltration is considered by assuming an increase in the groundwater table [16]. However, it is difficult for this kind of approach to explain the existence of slopes with very steep inclination and a deep groundwater table in nature when the existence of matric suction in unsaturated soil results in a considerable increase in the shear strength of the soil as well as the subsequent stability of soil slopes. Furthermore, the analysis using the unsaturated soil concept could consider more critical conditions to the slope [16], or it may help to conduct the back analysis of overly steepened slopes. Therefore, it is essential to develop theories related to unsaturated soils to understand the actual mechanism of rainfall-induced slope failure [17].

Recently, with the development of computer programs, the theory of unsaturated soil mechanics is being applied to manage transient seepage analyses. Using such programs, the stability of a slope can be assessed at some times during or after the rainstorm event. The role of soil suction in the increasing shear strength of unsaturated soils, and hence, the safety factor (Fs) of the slope, has been acknowledged widely [18, 19]. However, the actual mechanism of this relationship is still unclear. While the literature reports several experimental studies on unsaturated soils, which are usually expensive and time-consuming, it also presents two widely-accepted theoretical equations that define the shear strength of unsaturated soil. These equations comprise the linear and non-linear approaches. The former proposes a linear relationship using two stress state variables, namely, the net normal stress and matric suction [20]. In the latter, Vanapalli et al. [8] suggested a non-linear shear strength equation that involves the normalization of the volumetric water content function. According to this approach, the shear strength of unsaturated soil increases approximately proportionally with the matric suction until the air entry value is reached. This approach is consistent with various experimental studies reported in [6, 18].

In the present study, we used the Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Analysis (TRIGRS), v2.1 [21] to simulate the time-varying water-table within the slope in response to the vertical rainfall infiltration. Using a simple runoff routing scheme in combination with the mass balance between rainfall, infiltration, and runoff over the studied domain, the transient pore-water pressures within the slope were simulated considering both the surface and subsurface flow. The predicted water-table at a specific time in the typical cross-section was then used in SLOPE/W [22] with the non-linear approach to conduct the time-dependent modelling of rainfall-induced slope failures. This approach was applied to a case study in Sapa, Vietnam, for validation.

2. The Study Area

Lao Cai is a mountainous province located about 260 km from Hanoi, the capital of Vietnam (**Fig. 1(a)**). The study area is located along Provincial Road No. 152, at Km9 + 100 (**Fig. 1(a)**), which lies at the border between the Hau Thao, Ta Van, and Su Pan communes of Sapa District, Lao Cai Province. On August 5, 2019, at around 09:00 (local time), about 300 m^3 of loose soil and rock fell, resulting in the death of one person and road blockages for days (**Fig. 1(b)**). The incident was the consequence of heavy rains that lasted for several days across the whole area. **Fig. 1** presents an illustration of the location of the study area and the observed sliding scar, taken by Google Earth.



(a)

(b)

Fig. 1. (a) Location of the study area, (b) landslide site, the dotted line shows the sliding scar.

According to Bui et al. [23] and Nguyen and Tran [24], the study site has very complex geological conditions comprising debris deposits of granite with many large and small tectonic faults cut through. The large cleavage and distribution of geological formations having different ages and origins, and are directly related to the tectonic faults [24]. Most of the slopes in the area comprise landslide landforms and are highly weathered. Therefore, as evident from **Fig. 1(b)**, in the study area, landslides often occur on the boundary between the impervious hard layer and the cover residual soil layer. The soil on the slip surface is loose and in the saturated state (**Fig. 2**).

Lao Cai Province experiences tropical monsoon with abundant rainfall throughout the year. **Fig. 3** illustrates the relationship between rainfall intensity versus duration and the cumulative rainfall that lasted from 04:00 on August 3, 2019, to 13:00 on August 5, 2019, in Sapa. This rain was the main reason that caused the failure of the slope.

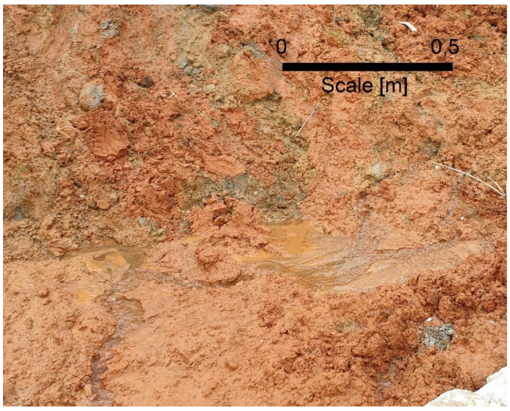


Fig. 2. Conditions of the surface of rupture of the selected landslide site.

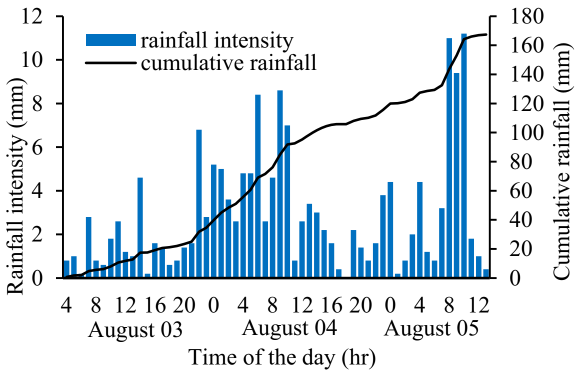


Fig. 3. Relationship between rainfall intensity versus duration and the cumulative rainfall lasting from 04:00 on August 3, 2019, to 13:00 on August 5, 2019, in Sapa. The landslide occurred on August 5, 2019, at around 09:00.

3. Use of the TRIGRS for Simulating Rainfall-Induced Pore Pressure Change

It is still a challenge to measure the actual infiltration pattern [25] as in nature; this pattern is affected by the temporal and spatial variations in subsoil conditions as well as the depth of the surface flow. The infiltration rate varies with time since the infiltration capacity is a time-dependent process. The surface flow depth performs like an additional pressure head to the ground surface, which in turn affects the soil's infiltration capacity [26]. Huat et al. [27] concluded that water infiltration established the connection between surface and subsurface hydrology. Zhang et al. [28] reported that the depth of surface water and the interaction between infiltration and runoff had large effects on the rainfall infiltration process. Wallach et al. [29] also suggested that ignoring the interaction between the overland flow depth and the infiltration rate may lead to errors in predicting the surface runoff. Thus, advanced slope stability analyses should consider time-varying surface and subsurface water amounts during a landslide event [30].

With the adoption of a simple runoff routing scheme combined with the mass balance between rainfall, infiltration, and runoff across the selected digital terrain, TRIGRS is a powerful tool that can consider both the surface and subsurface flow while simulating groundwater table changes at a regional scale. Furthermore, by considering the topographical conditions during the groundwater simulation, the program is rendered substantially superior to traditional two-dimensional (2D) methods for simulating rainfall-induced groundwater table changes.

3.1. Runoff Routing Scheme

TRIGRS uses a simple method (D8 method) for routing surface runoff from raster cells that have excess surface water to adjacent downslope where it can either infiltrate or flow further downslope [31]. Specifically, the program employs the mass balance between rainfall, infiltration, and runoff over the study area by allowing excess water from one cell to flow to downslope cells. Excess precipitation that cannot infiltrate at the cell of origin can infiltrate at some places downslope, or all water applied as input is accounted for as either infiltration or runoff [32]. This function helps prevent the loss of excess precipitation that cannot infiltrate into the cell of origin [33].

3.2. Simulation of the Variation in Groundwater Table Rise Caused by a Rainstorm in TRIGRS

Stability analysis of unsaturated soil slopes requires an extensive and detailed seepage analysis because such slopes' failure is closely related to heavy rainfall and infiltration [2]. However, modelling infiltration in unsaturated soil remains difficult as the process depends on numerous factors [9]. TRIGRS was developed to predict the distribution and timing of rainfall-induced shallow landslides [21, 32]. The program can compute the transient pore-water pressure's response to rainfall infiltration into saturated or unsaturated soil by considering the solution of the one-dimensional Richards' equation, a simple runoff routing scheme, and a simplifying exponential soil-water retention relationship [34].

Water-table rise is caused in response to the vertical infiltration that occurs when the amount of infiltrating water reaching the water table exceeds the maximum amount that can be drained by gravity [32]. TRIGRS extends the analysis conducted by Iverson [35] by treating the soil as a two-layer system comprising a saturated zone with a capillary fringe above the water table overlain by an unsaturated zone extending to the ground surface (**Fig. 4**).

The pressure head can be simulated as a function of the depth below the ground surface (Z) and time (t), considering the effects of the sloping ground surface using the coordinate transformation proposed by Iverson [35]:

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

where ψ is the ground-water pressure head; θ is the volumetric water content; t is the time; $Z = z/\cos\delta$ is the vertical coordinate direction (positive downward) and depth

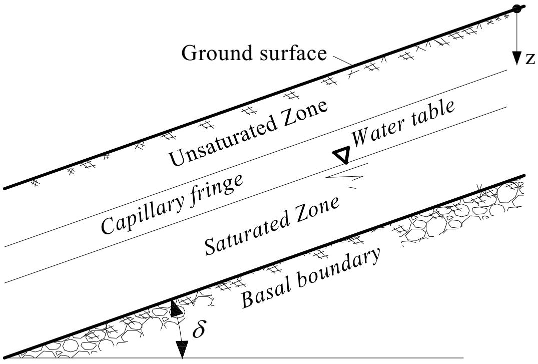


Fig. 4. Conceptual sketch of the hydrological model in the TRIGRS (modified from Baum et al. [32]).

below the ground surface, where z is the slope-normal coordinate direction (also positive downward); δ is the slope angle.

The above equation can be linearized using the exponential hydraulic parameter model suggested by Gardner [34], where the dependence of hydraulic conductivity, $K(\psi)$, and volumetric water content, θ, on the pore water pressure head in the Richards' equation is given by the following formulae:

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

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

where $\psi^* = \psi - \psi_o$, with $\psi_o = -1/\alpha$ is a constant, and K_s is the saturated hydraulic conductivity. Parameter α denotes the soil pore-size distribution, which represents the rate of reduction in hydraulic conductivity or moisture content as ψ becomes more negative. α is estimated by fitting Eq. (3) to the characteristic curve for the soil. $\psi_o = -1/\alpha$ indicates the height of the capillary fringe above the water table, θ is the volumetric water content, θ_r is the residual volumetric moisture content or the water content that causes the soil suction strength to becomes zero, and θ_s is the saturated volumetric water content.

3.3. Input Data for the Temporal Simulation of Rainfall-Induced Pore Pressure Change

The stability of a slope is controlled by the interaction of three-dimensional variations in gravitational stress, strength, and pore water pressure. Required data for the temporal simulation of rainfall-induced groundwater table change is the spatial distribution of the topographical conditions, the slope angle, hydraulic conductivity, initial infiltration rate, and initial depth of the groundwater table. For the topographical conditions, we used the AW3D 1.0 m DEM, which was calculated by an image matching process that employed a stereo pair of optical images taken using the Digital Globe satellite constellation (**Fig. 5**).

For the spatial distribution of soil depth, a field survey showed that the soil profile could be represented by two

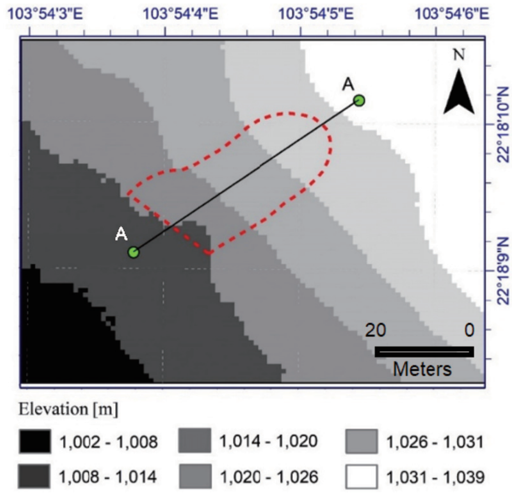


Fig. 5. Digital elevation model of the study area; the dotted line represents the actual landslide scar, A-A represents the typical cross-section cut through the actual landslide body.

Table 1. Hydraulic parameter of the cover soil layer.

Parameters	Symbol	Value range	Selected value
Hydraulic conductivity [m/s]	K_{sat}	1.0×10^{-6} – 1.0×10^{-7}	8.0×10^{-7}
Saturated volumetric moisture content	θ_s	0.45	0.45
Residual volumetric moisture content	θ_r	0.15	0.15

layers: the residual soil and the bedrock layer. The former was about 4.0 m thick at the deepest part. Therefore, for conservative reasons, a uniform 4.0 m thickness of the cover residual soil layer was utilized. Similarly, as the data related to the initial conditions of the groundwater table were not available, the initial groundwater table is assumed to coincide with the bottom of the cover soil layer.

The hydraulic properties of the cover soil layer were determined using laboratory tests, including the constant head test for hydraulic conductivity, and the pressure plate extractor and filter paper approach for the residual and saturated volumetric water content, respectively. The results of these tests have been presented in **Table 1**.

4. Use of the SLOPE/W in the Stability Analysis of Unsaturated Slopes

TRIGRS is also a promising tool for the prediction of rainfall-induced landslides [36–38]. However, the slope-stability model employed in this program is only based on an infinite model that provides the worst Fs variations with respect to the slope susceptibility map. Such an approach may be too conservative and it may not reflect the actual situation. In the present study, the SLOPE/W, a well-known module in the Geostudio package, was used to identify the 2D Fs of the slope under the transient water pressure condition calculated by TRIGRS. The Bishop's method was used for the slope stability analysis because it offers a simple and effective solution to a wide range of practical problems [36, 39].

4.1. Linear and Non-Linear Approach for Simulating Unsaturated Soil Shear Strength

The shear strength of the soil is an important parameter that has a vital impact on numerous geotechnical issues such as bearing capacity, earth pressure, and slope stability. Traditional methods often use the linear approach to estimate the unsaturated shear strength of the soil, where ϕ^b is the angle linking the increased rate in shear strength with the increasing matric suction. The use of ϕ^b is simple and it provides a rough estimation because of the increase in shear strength as a function of soil suction [22]. However, the drawback of using ϕ^b is that the unsaturated strength envelope is assumed to increase linearly with soil suction, which tends to overestimate the unsaturated shear strength, particularly when the soil suction is very high [22]. In the present study, the non-linear approach was used [8], which involves a normalization of the volumetric water content function to estimate the shear strength of unsaturated soil. According to Geoslope International Ltd. [22], the non-linear strength equation provides a better representation of unsaturated soil behavior. Following this method, the unsaturated shear strength of soil can be estimated based on the soil-water characteristic curve and the saturated shear strength parameters of a soil, as follows:

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)S_e \tan\phi', \quad . \quad (4)$$

where τ is the shear strength of the soil, c' is the effective cohesion, $(\sigma_n - u_a)$ is the net normal stress on the failure plane, σ_n is the total normal stress, u_a is the pore-air pressure, u_w is the pore-water pressure, $(u_a - u_w)$ is the matric suction, ϕ' is the friction angle, and S_e is the effective degree of saturation given. The literature demonstrates that the unsaturated shear strength can be related to the volumetric water content function [8].

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}. \quad . \quad (5)$$

4.2. Method and Data Used for the Slope Stability Analysis when the Groundwater Table is Available

In this study, the SLOPE/W was used to simulate the stability of a slope based on a two-dimensional (2D) Bishop's simplified method; therefore, a typical cross-section representing the actual landslide site was used. The cut was made through Section A-A (**Fig. 5**). The typical cross-section has been presented in **Fig. 6**. The figure also shows the groundwater table's location simulated

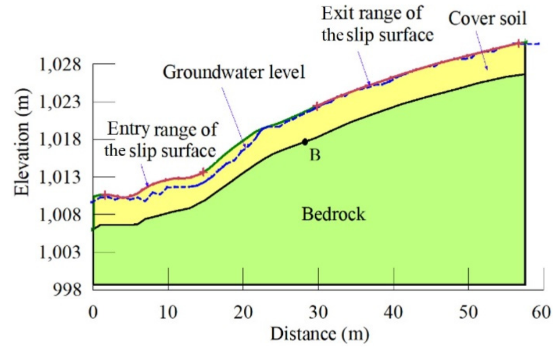


Fig. 6. Typical cross-section of the stability analysis using the SLOPE/W. The groundwater level predicted by the TRIGRS at the time of failure has also been illustrated.

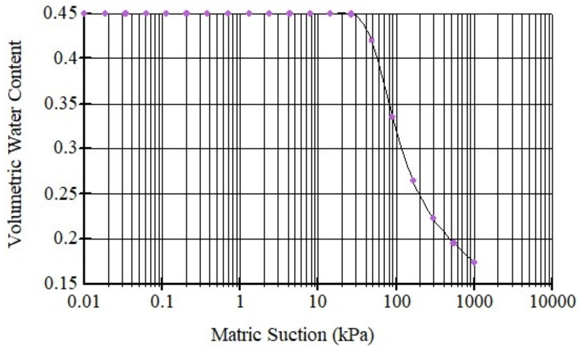


Fig. 7. Estimated SWCC using the SLOPE/W.

at 09:00 on August 5, 2019, by TRIGRS. Additionally, the slip surface's entry and exit range shows the potential entry and exit locations of the potential slip surface. These ranges were defined based on the observed landslide dimensions.

For the unsaturated soil parameters, the soil-water characteristic curve (SWCC) was estimated based on parameters related to the grain size data, liquid limit, and saturated volumetric moisture content. The predicted SWCC has been presented in **Fig. 7**. The unsaturated unit weight is calculated based on the pore-water pressures and associated volumetric water content described by the SWCC. Finally, the saturated shear strength parameters of the soil were defined using direct shear tests. **Table 2** presents all the parameters used in the SLOPE/W for the stability analysis. The most critical value was used for the simulation for conservation reasons.

5. Results and Analyses

The study applied the TRIGRS to simulate the transient groundwater condition within the slope in response to the vertical infiltration caused by the rain. The predicted groundwater table at all time steps was subsequently used in Module SLOPE/W for conducting the time-dependent modeling of rainfall-induced slope failures. We employed this approach to the August 5, 2019 landslide event that

Table 2. Soil parameters used in the SLOPE/W.

Soil parameter	Value range	Selected value
Diameter at 10% passing D_{10} [mm]	0.001–0.005	0.002
Diameter at 60% passing D_{60} [mm]	1.1–1.8	1.3
Liquid limit [%]	51.0–60.0	55.0
Porosity	0.42–0.50	0.45
Cohesion [kPa]	11.1–13	11.1
Friction angle [°]	15.0–16.5	15.0
Saturated unit weight [kN/m^3]	18.3–19.0	19.0

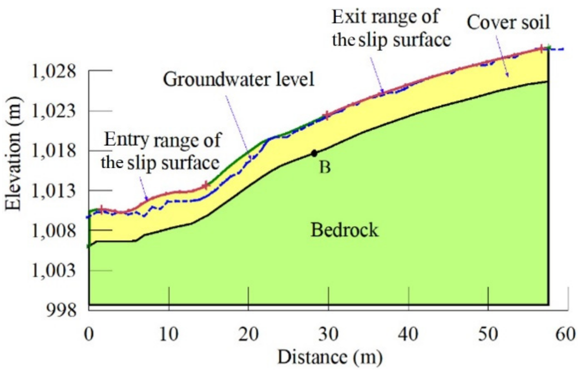


Fig. 8. Variation of the groundwater table with time during rain within the typical cross-section.

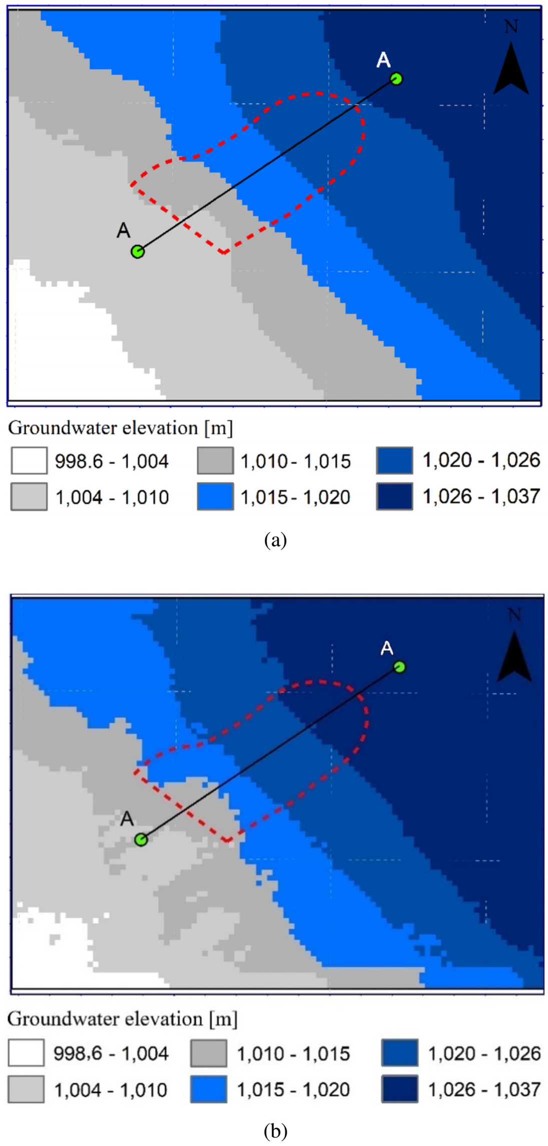


Fig. 9. Spatial distribution of groundwater elevation at (a) the initial stage and (b) at 09:00 on August 5, 2019, when the slope was observed to fail.

occurred in Sapa, Lao Cai, Vietnam, and compared the predicted results with the actual slope failure in the timing of the occurrence for validating the simulated results.

5.1. Time-Varying Groundwater Table Within the Study Area Simulated by the TRIGRS

The infiltrating water that accumulates at the base of the unsaturated zone will raise the groundwater table. Using all the necessary input data, TRIGRS would simulate the impact of rainfall infiltration on the variation in the groundwater table within the study area over time during the rain. The expected results are maps showing the spatial variation in the groundwater table at different times.

Figure 6 presents the groundwater table within Cross-section A-A at the time of the failure, while **Fig. 8** shows the variation in the water tables at different times during the rain. **Fig. 9** presents the spatial distribution of the groundwater elevation at the initial stage at 09:00 when the slope was observed to fail.

As evident from **Figs. 6** and **8**, the rain played a critical role in raising the groundwater table and increasing the pore water pressure head (**Figs. 6**, **8**, and **9**). The groundwater table almost reached the soil surface layer at the time of the failure (**Fig. 9**). Moreover, the groundwater level at the lower part of the slope was lower than that at the upper part of the slope. It does not rise parallel to the surface at the upper part, as often observed in traditional two-dimensional simulations. This observation could be explained by the fact that the rise in the groundwater table depends not only on the properties of the rainfall and subsurface soil but also on the topographical conditions of the surrounding sliding site.

5.2. Stability Assessment of the Slope Using the SLOPE/W

Figure 10 shows the potential slip surface predicted at 09:00 am on August 5, 2019, for the typical cross-section cut through Section A-A using Bishop's simplified method. The general size and geometry of the slip surface were based on the observed landslide by defining the entry and exit of the slip surface (**Fig. 6**). Additionally, the simulation also applied the optimization technique in the SLOPE/W that ignores the original geometric parameters used to determine the trial slip surface and result in a

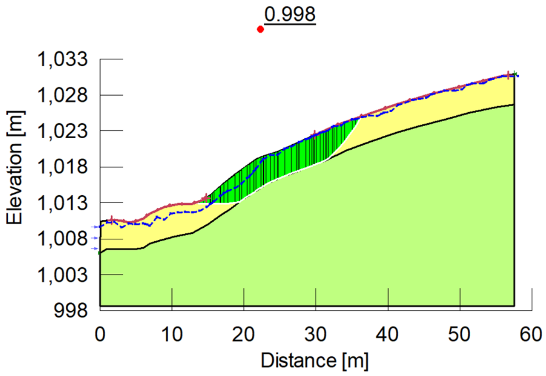


Fig. 10. Fs value predicted by the SLOPE/W with Bishop's simplified method and optimization process at 09:00 am, August 5, 2019.

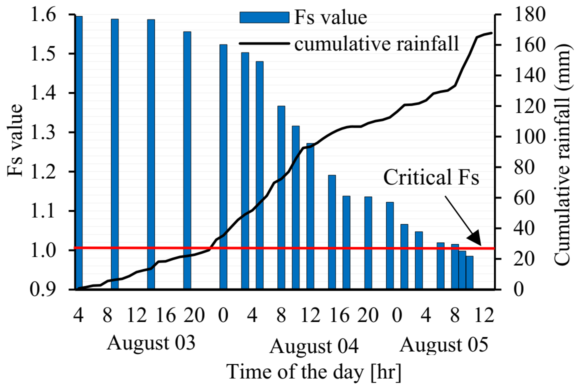


Fig. 11. Variation in the Fs and cumulative rainfall over time.

more realistic slip surface shape [22]. In **Fig. 10**, the factor of safety $Fs = 0.988 < 1.0$ means that the slope was theoretically unstable, as observed in the actual situation.

For the illustration of the variation in the Fs value of the slope, the Fs values of the slope at various time steps during the rain was simulated. The corresponding results have been presented in **Fig. 11**. Evidently, the Fs values reduced over time during the rain. Initially, the reduction was small since the groundwater level was still located deep below the ground surface and its influence on the stability of the slope was minor. However, as time progressed, the Fs values reduced significantly, and they reached the critical value of $Fs = 1$ at around 09.00 am on August 5, 2019. This was the actual time of the landslide.

6. Conclusion

The study used the TRIGRS v2.1 and Module SLOPE/W from the Geostudio Package for predicting rainfall-induced slope failures. Among these two, TRIGRS was employed to determine the transient pore-pressure changes under rainfall infiltration, considering both the surface and subsurface flow. Subsequently, the predicted water-table at specific time steps (every hour) were used in the SLOPE/W for conducting the time-dependent modelling of rainfall-induced slope failures. From the simulated results, several conclusions could be drawn:

- The approach was applied to the August 5, 2019 landslide event in Sapa, Lao Cai, Vietnam. The result showed that, with the input of reliable and quality data, the applied approach provided crucial evidence about the failure time of the slope, indicating that this is an appropriate tool for predicting rainfall-induced landslides in unsaturated soil slopes.
- Like other physical-based models, the predicted results were highly dependent on the reliability of the initial groundwater conditions, spatial distribution of the soil thickness, and physical properties of the soil, such as the shear strength (soil cohesion and friction angle), hydraulic conductivity, and unit weight. Therefore, these data could be improved for future work.
- Since the spatial distribution of the groundwater table is known, it is possible to evaluate the stability of the slope in any designed direction within the actual sliding mass. However, in this study, the role of the seepage force in slope stability assessment was ignored. The inflow and outflow were considered only to simulate the variation in the groundwater table using TRIGRS.
  The current study utilized the most critical value of soil shear strength for a conservative reason. Future studies should focus on integrating the proposed model with the Monte Carlo simulation to automatically search for the critical slip surface and predict the probability of slope failure.
- In the future, studies should assess the influence of the slip direction of the sliding body in 2D slope stability analyses. Additionally, the stability of the slopes in a fully three-dimensional form in both spatial and temporal aspects should be considered.

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