EVALUATING CUT SLOPE STABILITY DURING RAINFALL EVENTS IN HA GIANG CITY, VIET NAM

Do Minh Hien(1)**, Quach Duc Tin**(1)
(1)*Viet Nam Institute of Geosciences and Mineral Resources*

Received: 01/8/2024; Accepted: 23/8/2024

Abstract: *The main objective of the present study is to investigate the mechanism of triggering slope failures during extreme rainfall events under the climatic and geological conditions of Ha Giang city, Viet Nam. For this purpose, the specific research objectives of this paper were based on the analytic results of the geotechnical properties of the soil samples. The pore water pressure distribution on a slope was changed by the influence of rainfall. In order to analyze the stability of the cut slopes, the two modules SEEP/W and SLOPE/W in the GEOSTUDIO 2012 software were employed and integrated. First, the initial steady seepage condition was used to assess the effect of extreme rainfall for a transient seepage. Second, the soil sample properties and some features were assigned in the slope stability model, such as unit weight, cohesion, internal friction angle, and hydraulic functions, and then the achieved transient pore water pressure regime was used as the input parameter to calculate the factor of safety (FS) on cut slopes. Finally, the relationship between the changing of the FS over time and the hourly rainfall intensity that resulted in slope failure were evaluated. In summary, the slopes in Ha Giang city can be stable under normal conditions, but their stability is always a dilemma for local authorities due to the influence of intense rainfall.*

Keywords: *Factor of safety, landslides, rainfall intensity, cut slope, SEEP/W-SLOPE/W.*

1. Introduction

In the last few years, huge damages were recorded because of the landslide disaster in Ha Giang city. Most of the landslides occurred on cut slopes along the traffic lines with small and medium scale ones, ranging from 50 m^3 to 1,000 m^3, with some exceeding 1,000 m^3 or even 10,000 m^3. One of the main factors that induced landslides in this region were extreme rainfall events [1]. Due to rainfall affecting pore water conditions in the slope material and because its influence requires interaction with other characteristics of the waste mantle, the influence of rainfall is considered an indirect impact on slope stability [2].

Any soil could become unstable in extreme rainfall conditions because it caused heavy rainfall with high intensity for long periods [1], [3]. The relationship between the antecedent and the triggering rainfall with slope instability has been investigated by some researchers, however, conclusions regarding this issue remain somewhat controversial [4]. Thus, the evaluation of rainfall-induced slope instability plays a critical role in the socio-economic development of the Hagiang city, where along the traffic roads, many landslides have occurred on the cut slopes and are going to occur in the future under the influence of extreme weather conditions. The main objective of this paper is to investigate the mechanism of triggering slope failures during extreme rainfall events under the climatic and geological conditions of the study area. For this purpose, the specific research works are as follows:

- Based on the analytic results of the geotechnical properties of the soil samples, a transient seepage analysis under the influence of extreme rainfalls was generated from the initial steady seepage condition.
- Based on the soil sample properties, some features were assigned in the slope stability

---

Corresponding author: Do Minh Hien
E-mail: hien_dm@yahoo.com

model, such as: Unit weight, cohesion, phi, and the hydraulic functions and then the achieved transient pore water pressure regime was used as the input parameter to calculate the factor of safety (FS) on cut slopes.

- Evaluation of the relationship between the changing FS over time and the hourly rainfall intensity that resulted in slope failure.

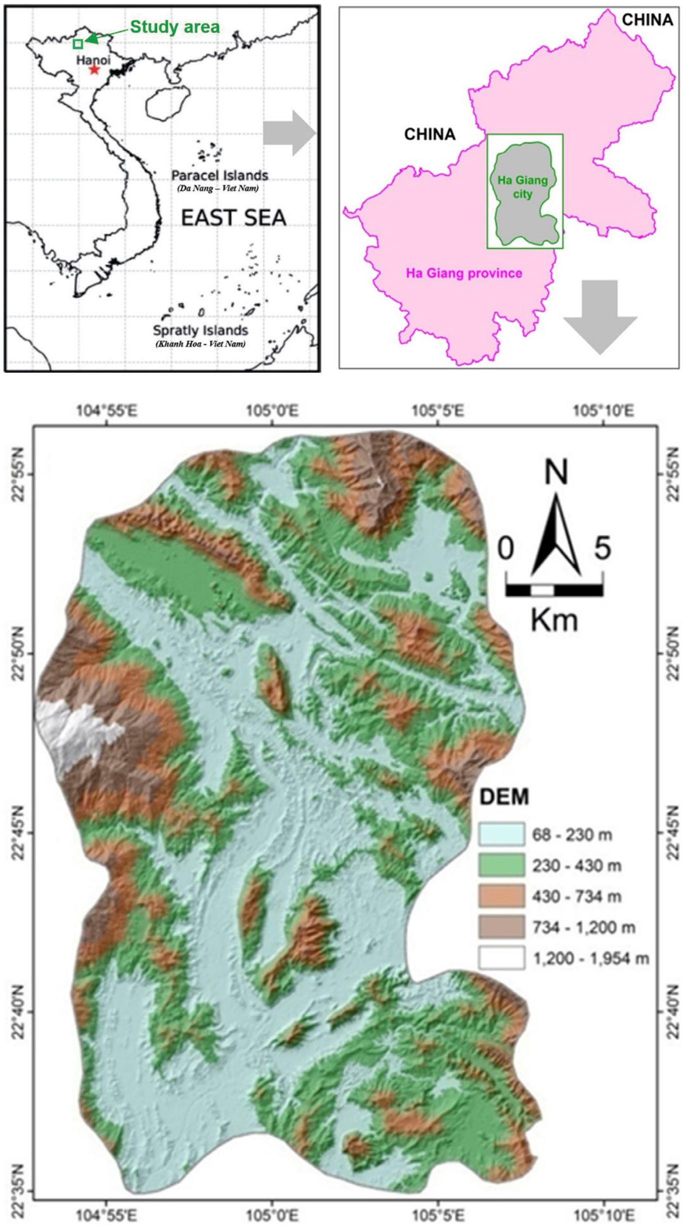

Figure 1. The study area

2. The study area

Ha Giang city and its surrounding areas (Figure 1) are located in the center of Ha Giang Province. The region is 40 km long and 15-25 km wide, with hills and mountains occupying more than 65% of the area. It covers an area of approximately 779 km^2 between the longitudes 104°52’E and 105°18’E and latitudes 22°34’N and 22°56’N. The altitude varies from 68 to 2,000 m above sea level, and the slopes are steep. There are some delta areas along some of the main rivers, and the North, South and East of the study area are distributed among these flat areas [5].

2.1. Geology

Geologically, the rock and soil components, which contain clay shale, carbonaceous shale, sericite-chlorite schist, mica schist, quartz-sericite sandstone, limestone, sandstone, greenschist, marl slate, etc,… are widely distributed in the study area. These rocks occupy most of the study area and they are divided into sedimentary rocks, metamorphic sediment rocks and Quaternary sediments [1], [5]. Grouping according to different geological properties is necessary because each geological unit has a different degree of sensitivity [6]. There are 28 geologic formations in the study area, the ages of rocks vary from the Proterozoic to Triassic and the lithological properties are summarized in Figure 2. According to [5], landslides mainly occurred on the area of 20 geological formations of the study area. Nearly 90% of the landslide locations occured on the Ha Giang, Khao Loc, Tong Ba, Chang Pung, Song Chay, Pia Phuong and Mia Le formations.

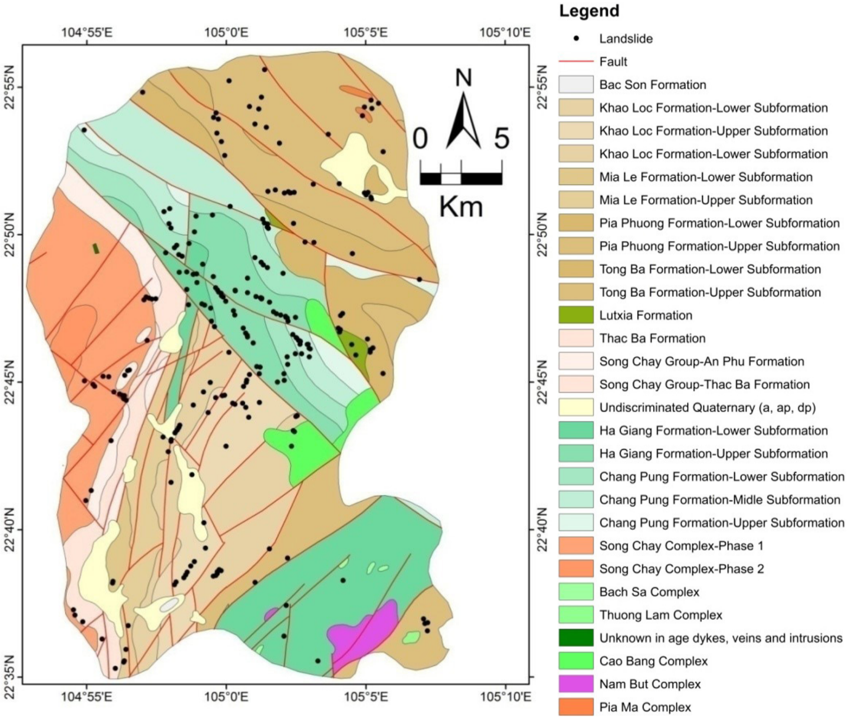

Figure 2. Geologic map of the study area

2.2. Rainfall events and slope failures in 2013

Ha Giang city is one of the highest rainfall intensity areas in Viet Nam and the rainfall is always concentrated from May to October and the months with highest amount of rainfall are often July and August. The daily rainfall and hourly rainfall data were used to calculate the rainfall thresholds and the computed values of the conditional landslide probability [1]. Based on the analyses, the relationship between rainfall and landslide occurrence in the region was indicated. The landslide initiation was estimated based on the relationship between the rainfall events and the historical landslide records in July of 2013 (the four landslide events had occurred on the days of 1st, 2nd, 5th, and 18th which were considered in this paper). The hourly rainfall intensity in July, 2013 was used to estimate the changes in pore water pressure that could impact the stability of cut slopes. The slope stability safety factor, FS, would be calculated to analyze slope instability caused by an external factor and rainwater intrusion.

According to the hourly rainfall data in 2013, July was recorded as the highest month of rainfall with a total rainfall of 1,068.6 mm. There were seven days with rainfall intensity recorded greater than 60 mm per day. Based on the hourly rainfall data in July of 2013 (rainfall intensities ranged between 0.1 mm/h and 35.5 mm/h, with a maximum of about 108.7 mm in 7 hours) (Figure 3), landslide phenomena had occurred on the days of 1st, 2nd, 5th, and 18th with rainfall intensity of 127.4, 100.7, 65.8, and 60.6 mm, respectively. Besides, the hourly rainfall data in June 2013 (rainfall intensities ranged between 0.1 mm/h and 46.2 mm/h, with a maximum of about 48.4 mm in 3 hours) was also used to assist in assessing the relationship between antecedent rainfall and the day that slope failure occurred (Figure 3).

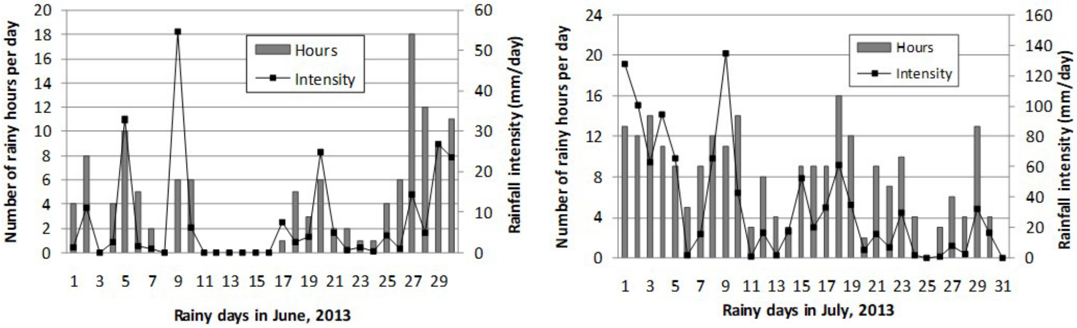

Figure 3. The rainfall intensity and duration in June (left) and July (right), 2013

3. Characteristics of cutting slopes in the study area

The lithological units are strongly weathered, the weathered layers often have an average thickness of 3 to 5 meters and the most thicknest layer is 25 meters, as observed in the cut slopes along the transportation routes [1]. The field works shown that the bedrock in Ha Giang city has a high clay content, which contains weathering productions of clay shale, sericite-chlorite schist, mica schist, greenschist, carbonaceous shale, etc,… The weathered crust is formed from clay, silt, sand and softly weathered rock particles with weak resistance, and the cohesion of soils is low, crumbly, and susceptible to landslide when the cut slopes are saturated. Hence, the thickness of the weathering crust is proportional to the severity of the sliding process and the easy creation of large sliding bodies [7].

Based on the characteristics of the rock and soil components and the descriptive scheme for grading the degree of weathering for the study area [7] and, according to the field survey data, the typical slope cross-section was illustrated in Figure 4. Due to the lack of information on engineering geology features at the seven cross-sections, the profile of each cut slope where soil samples were taken not depicted. In which, the top soil layers have a thickness of 0.3 to 0.9 meters. The thickness of a completely weathered layer is usually about 3 to 5 meters, but in some locations, the maximum thickness varies from 10 to 15 meters. The moderately weathered layers and weakly weathered layers were very rarely observed in geological sections, their thickness usually ranges from one to several meters.

3.1. Collecting the soil samples

The weathered rock and soil components of the two layers, residual and completely weathered soil layers are the main objects for slope stability assessment due to the fact that most cut slope failures usually occurred in these layers in the study area.

The soil samples were collected in the completely weathered layers of the lithological units with highest landslides frequency. Sample collection was carried out in the field surveys in September 2010. Soil sampling was done for soil classification and measurement of shear strength parameters in the laboratory. All sampling locations were performed at the scarps of the landslide points. To get the highest accuracy, cylindrical steel tubes with a diameter of 12 cm and a length of 25 cm were used to collect undisturbed soil samples. Then, these samples were sealed to avoid evapotranspiration before performing mechanical tests (Figure 5). The sampling depth at the landslide's scarps varies from 1.5 to 3 meters. In Figure 5, the dashed yellow lines in the top two photos and those the lower left photo show the sampling locations and the bottom right photo show the sample that was preserved after collection.

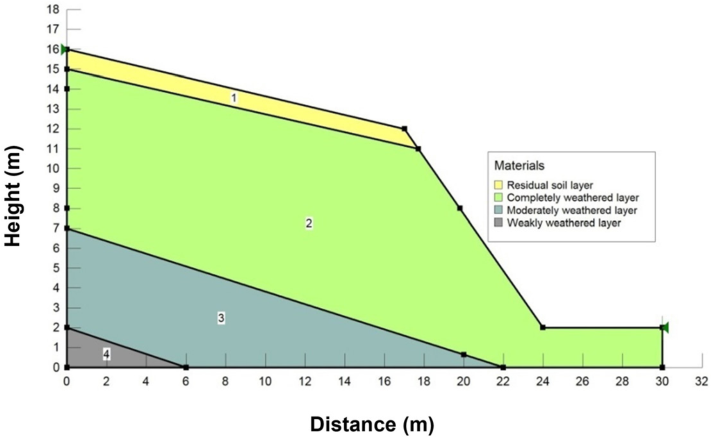

Figure 4. Typical cross-section of cut slopes in Ha Giang city

Figure 5. Taking the soil samples at the scarps of landslide locations (a, b, c) and the undisturbed soil sample was preserved in a pvc tube with plastic wrap (inside the yellow dashed line in photo d)

The relationship of slope-forming materials with the rainfall intensity that caused the change in the factor of safety was assessed using the analysis results of the geotechnical properties of the seven cut slope sites in the study area.

In this study, the soil sample locations of the seven failed slopes (A, B, C, D, E, F and G) are shown in Figure 6 and their mechanical properties were also considered for seepage and instability analysis. The lithology map was reclassified into fifteen lithological groups (Figure 6) based on the twenty-eight geologic formations mentioned in Figure 2. The features of clay composition, degree of weathering and estimated strength and density were the main important features to reclassify in relation to the geological formation divisions [8].

3.2. Physical properties of slope materials

Based on the results of laboratory investigation and Viet Nam's soil classification standard (TCXD 45-78), seven soil samples were classified into half-hard state clay, hard state clay, hardened clay with grit, hard plastic clay and semi-clay with the hard plastic state. The laboratory testing results on the hydro-mechanical parameters of seven failure sites are listed in Table 1. Figure 7 shows the particle size distribution plots of the soil samples in the study area.

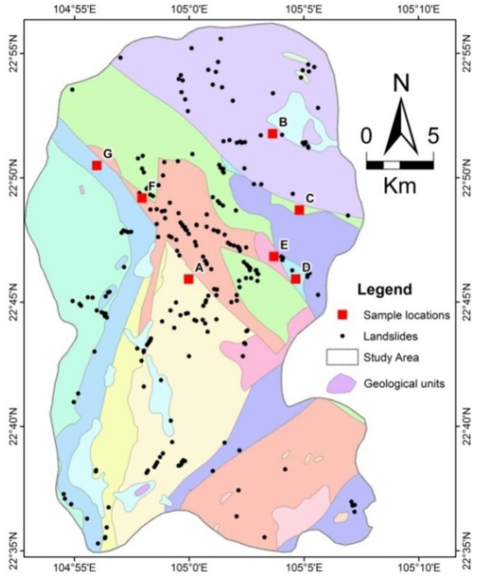

Figure 6. The locations collected the soil samples in the study area

Table 1. Some geotechnical properties at seven sampling locations in the study area

ID	Unit weight	Saturated volumetric water content	Internal friction angle	Effective cohesion	Hydraulic conductivity	Vietnam's soil classification standard
	γ (kN/m^3)	n	φ (^{0})	c (kN/m^2)	k (cm/s)	(TCXD 45-78)
A	17.85	0.530	20	29.42	$4.0\text{x}10^{-5}$	half hard state clay
B	16.63	0.431	22	27.03	$5.3\text{x}10^{-5}$	hardened clay with grit
C	17.55	0.512	20	32.36	$4.0\text{x}10^{-5}$	hardened clay with grit
D	16.67	0.601	18	27.46	$8.1\text{x}10^{-5}$	hard plastic clay
E	17.65	0.568	20	27.46	$4.1\text{x}10^{-5}$	hard plastic clay
F	17.24	0.483	24	30.26	$4.3\text{x}10^{-5}$	semi-clay with hard plastic state
G	17.46	0.515	24	41.19	$6.3\text{x}10^{-6}$	hard state clay

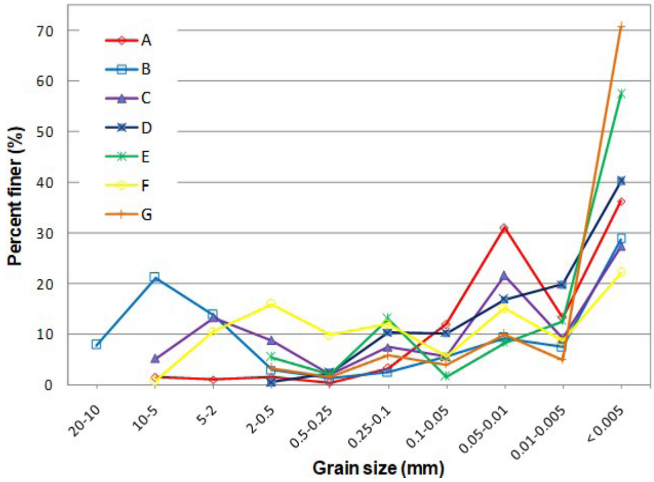

Figure 7. Grain-size distribution of the soil samples (A, B, C, D, E, F, G) collected from failed slopes

The testing was carried out by Power Engineering Consulting Joint Stock Company 1 (PECC1) of Viet Nam. All of these parameters were used in the seepage and slope stability modeling as detailed in sections 4.1 and 4.2.

4. Slope stability analysis

The topic of rainfall-induced slope failures had been studied by many scientists, most previous research was focused on the analyses of saturated materials [9], [10]. Moreover, some geotechnical researchers believed that the negative pore-water pressure (PWP) can be ignored or heavy rainfall will lead to the elimination of all the negative PWPs [11]. The main reasons for reducing the slope stability of elongated slopes were related to the changes in the groundwater table [12]. However, [13] argue that in some cases, these assumptions are impractical because they depend on the infiltration properties of the soil that has the zones of water near the slope surface (with an unsaturated profile below) and therefore would not be accurately analyzed by traditional methods.

Soil infiltration can be predicted from a transient seepage analysis or numerical models and equations [14].

To evaluate the stability of the cut slopes, and to investigate the potentiality of failure during rainfall, coupled SEEP/W-SLOPE/W ([15], [16]) models were used in the GEOSTUDIO 2012 software [4], [17-22].

Three steps were carried out to assess the stability of cut slopes:

(1) Drawing and assigning the parameters that relate to the features of the cut slopes (materials, the number of the layers in a typical cross-section, some main properties of soil sample used for slope stability calculation in the study area);

(2) Using SEEP/W model to simulate the PWPs in both static (steady-state analysis) and transient (rainfall infiltration, duration, boundary conditions and hydraulic functions were assigned) conditions;

(3) Using SLOPE/W to find the slip surface and to calculate the FS with the transient PWP conditions generated by SEEP/W in the previous step. Morgenstern-Price's analysis type was selected for the stability analysis.

4.1. Seepage modeling

SEEP/W is a finite element-based program in GeoStudio 2012 that simulates the flow of water through the soil with a numerical model to analyze seepage problems in natural slopes. The main input parameters that play a critical role in this step were the soil-water characteristic curve (SWCC) function and the soil permeability curve (SPC) function. The SWCC function (Figure 8, left) was created from GeoStudio 12 software based on the parameters in table 1. Whereas the SPC function (Figure 8, right) was estimated from SWCC using Van Genuchten method. For the Van Genuchten criterion, the input parameters of residual soil layers, such as the hydraulic conductivity and water content, were assumed. Due to the material properties in this layer having weak resistance and soil cohesion, they can be easily saturated, so the coefficients were assigned to be larger than those in the completely weathered layer. The SWCC function and the SPC function were integrated with other parameters in Table 1 to simulate the changes in PWP conditions and to calculate the FS values. The initial water table was ignored. The days of failure in the study area were 1, 2, 5, and 18 July 2013 with the rainfall intensity being 127.4, 100.7, 65.8, and 60.6 mm/day, respectively. But it is difficult to describe the initial seepage condition in the slope before the rainfall events since most of the days of July had considerable rainfall and no data were available for pore water variation. So, to simulate the relationship between rainfall duration and the changes in PWP, the rainfall event of 1 July 2013 is assumed to last for 3 days (72 hours of continuous rainfall) with the rainfall intensity of 127.4 mm/day, or 5.3 mm/hour.

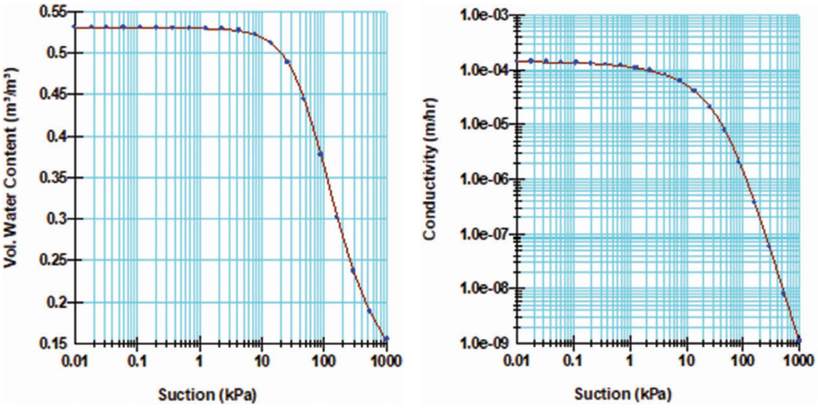

Figure 8. SWCC function (left) used in seepage modeling and SPC function (right) used in seepage modeling which was estimated from Van Genuchten method (using the input parameters of soil sample A)

All rainfall infiltrates into the soil during the initial period of many rainfall events. In the early stages of infiltration, when the rainfall intensity is greater than the minimum infiltration capacity but does not exceed the soil infiltration capacity, all the precipitation infiltrates the soil until this infiltration capacity is less than the rainfall intensity [23]. When the rainfall intensity is greater than the infiltration capacity, water begins to accumulate on the soil surface [14], [23]. To evaluate the relationship among the rainfall intensity (I), saturated conductivity (k) and infiltration capacity (fc), the second case of infiltration ($k < I \leq fc$) is applied instead of three stages of infiltration to assign computational parameters [23] in the seepage modeling. Table 2 shows information about the values of I, k, and fc that are used in the model calculation.

To assess the slope instability in the study area, soil was assigned to be the same as the hourly rainfall intensity of 1 July 2013. The K values of residual soil layers (Table 2) at the slopes A, B, C, D, E, F, and G were assumed to be greater than those in completely weathered layers, and using the same estimation method, Van Genuchten in hydraulic functions tool of GeoStudio 12 software.

Other parameters declared in the transient analysis part of seepage modeling are shown in Table 3. Due to the lack of soil samples in residual soil layers, saturated water content parameters (Table 3) at 7 locations (A, B, C, D, E, F, G) were also assigned to be greater than those in completely weathered layers in the calculating process. The potential seepage face was considered so that the excess water, which is generated when $q > k$, could drain away from the slope.

Module SEEP/W used to calculate the transient seepage and the distribution of PWP after 72 h of the extreme rainfall event with a constant hourly rainfall intensity of 1 July 2013 that assumed to last 3 days, from 1-3 July 2013. To simulate the changes in PWP, the information about the geotechnical parameters of the soil sample and the rainfall intensity was assigned in module SEEP/W to calculate the PWP values.

Table 2. The input parameters were assigned in hydraulic conductivity functions

Hydraulic conductivity functions				
Slope failure spot	**Estimation method**	**Saturated k (m/hr)**		**Rainfall intensity (m/hr)**
		Residual soil	Completely weathered	
A	Van Genuchten	0.0002	0.00014	0.0053
B		0.00025	0.00019	
C		0.0002	0.00014	
D		0.00035	0.00029	
E		0.0002	0.00015	
F		0.0002	0.00015	
G		0.00003	0.00002	

Table 3. The input parameters were assigned in water content functions

Vol. Water Content Functions					
Slope failure spot	**Estimation method**	**Saturated WC (m^3/m^3)**		**Sample material**	
		Residual soil	Completely weathered	Residual soil	Completely weathered
A	Sample functions	0.61	0.53	Silt	Clay
B		0.511	0.431	Silt	Silty clay
C		0.612	0.512	Silt	Silty clay
D		0.651	0.601	Silty clay	Clay
E		0.618	0.568	Silt	Silty clay
F		0.533	0.483	Silt	Silty clay
G		0.565	0.515	Silt	Silty clay

4.2. Slope stability modeling

SLOPE/W allows limited equilibrium analysis of soil slope. It uses various analysis types to compute factors of safety such as Ordinary, Janbu, Bishop, Sarma (vertical slices only), Janbu Generalized, Lowe-Karafiath, Corps of Engineers #1, Corps of Engineers #2, Spencer and Morgenstern-Price methods. Also, soil strength models such as SEEP/W, SIGMA/W, QUAKE/W or VADOSE/W can be selected to perform slope stability analyses.

Due to SLOPE/W lacking the dynamic hydrological modeling of PWP, simulated seepage information from SEEP/W is directly linked to SLOPE/W. In this study, Morgenstern-Price method with half-sine user-specified interslice force function was used to compute the factor of safety. The Morgenstern-Price method considers both shear and normal interslice forces, satisfies both moment and force equilibrium and allows for a variety of user-selected interslice force functions [16]. The entry and exit function is used to find the slip center and the potential failure surface.

In this research, the Mohr-Coulomb soil strength model which also includes shear strength variation due to matric suction in unsaturated soil was used in the slope stability analysis. The equation for this model is given below:

$$\tau = c + (\sigma_n - u_a)\tan\varphi + (u_a - u_w)\tan\varphi' \qquad (1)$$

Where τ is the shear strength of unsaturated soil; c is the effective cohesion; $(\sigma_n - u_a)$ is the net normal stress; σn is the total normal stress; $(u_a - u_w)$ is the matric suction; u_w is the pore-water pressure; φ is the angle of shearing resistance; and φ' is the angle expressing the rate of increase in shear strength relative to the matric suction [22].

In the analysis of slope stability, the FS value will provide information about the stability or instability of a slope. Therefore, the FS coefficient evaluation table was referenced as suggested by [24] in Table 4.

There are different ways to express the safety of a slope. [25] expressed the safety factor FS as follows:

$$FS = \frac{c' + (\gamma.zcos^2\beta - u_w)tan\varphi'}{\gamma.zsin\beta cos\beta} \qquad (2)$$

Groundwater conditions in the above equation are accounted for by calculating pore water pressure u_w described as:

$$u_w = \gamma_w h_w \cos^2 \beta \qquad (3)$$

Where c' and φ' are the effective strength parameters of cohesion and the angle of internal friction, respectively; γ is the unit weight of soil; γ_w is the unit weight of water, β is the slope angle, z is the thickness of soil above the slip surface, and h_w is the height of groundwater level above the slip surface.

The results illustrated that the FS value decreases over time and all 7 sampling locations had FS values < 1 after 72 hours of rain. Results of slope stability modeling of 7 sites in the study area are shown in Figure 9.

Figure 10 (A, B, C, D, E, F, G) indicated the FS values obtained from analyzing the slope stability over time corresponding to the rainfall event in July 2013.

To assess the relationship between rainfall intensity and duration and the safety factor, the average hourly rainfall intensity of 1 July 2013 was assumed to last for 72 hours in the calculated model. However, it is difficult to confirm that with the daily rainfall intensity of 127 mm/day, it takes 2.5 consecutive days of rain with such rainfall intensity for the landslide phenomenon to appear.

The days of landslides in the study area are July 1, 2, 5 and 18, 2013, and according to the hourly rainfall data of these days, the average hourly rainfall intensity is not high, about 2.5 mm/h to 5.3 m/h. However, in these days, the rainfall was mainly concentrated in the first 7 hours and the last 4 hours of the day. Specifically, on day 1, 2, and 5, the rainfall concentration in the first 7 hours of the day were 69.5, 76.9 and 61.4 mm, respectively; and days 1 and 2 had rainfall concentrated in the last 4 hours of the day (50.7 and 23.7 mm, respectively). On the 18th day, the rainfall mainly concentrated in the first 15 hours, with a rainfall of 59.1 mm. It is sometimes complicated to assess the relationship between the rainfall intensity and duration and the factor of safety, and the antecedent rainfall of the landslide event should also be taken into account. For a more multidimensional view, the average rainfall intensity for the first 7 hours of July 1 (about 10 mm/h) is also assumed to last for 48 consecutive hours to calculate the change of the FS value of site A. The results showed that, FS values changed rapidly after the first 24 hours of the rainfall event and it was less than 1 at 28 hours of continuous rain at 7 sites. Figure 11 shows the changes of FS values over time at site A with the rainfall intensity of 0.01 m/h.

Table 4. Landslide susceptibility classification based on the factor of safety [24]

Factor of safety (FS)	Slope stability class
0 < FS < 0.5	Very unstable slope
0.5 < FS < 1.0	Unstable slope
1 < FS < 1.25	Quasi-stable slope
1.25 < FS < 1.5	Moderately stable slope
FS > 1.5	Stable slope

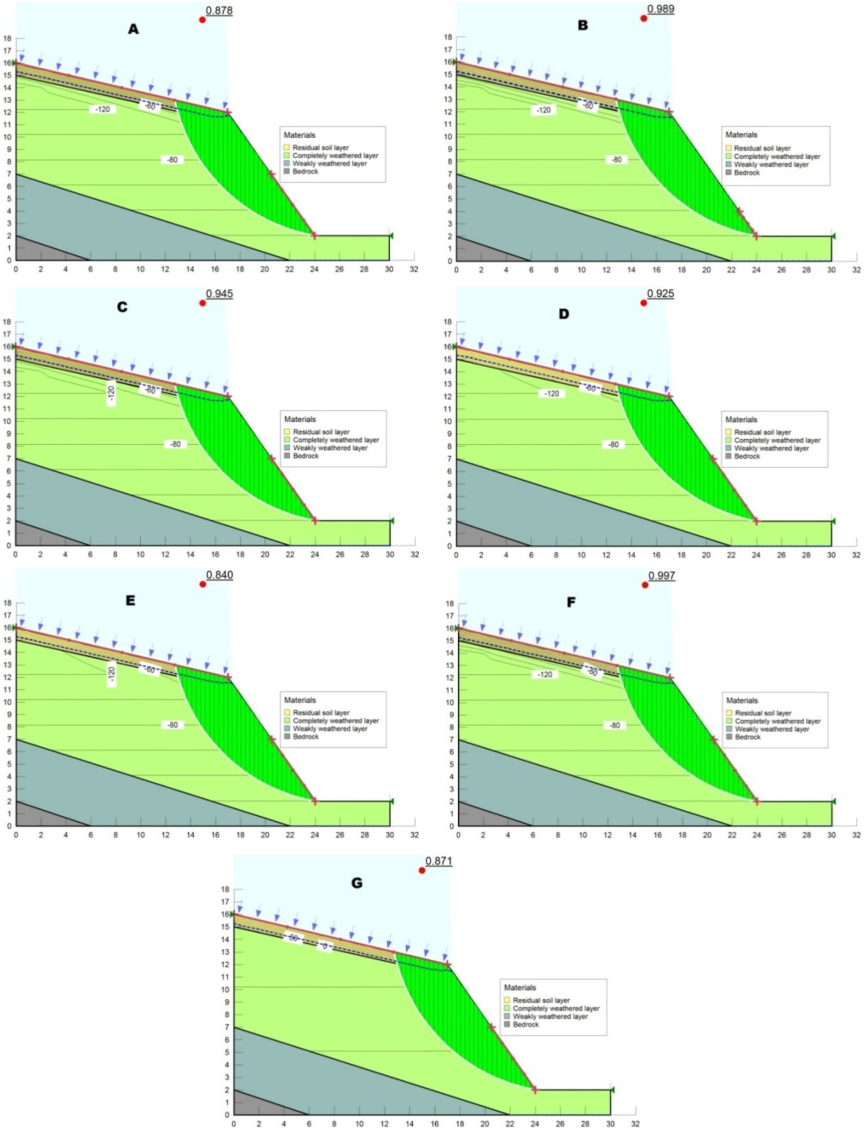

Figure 9. Using two modules SEEP/W and SLOPE/W to simulate sliding masses and their FS values (the values are displaying on the red points) at 7 locations (A, B, C, D, E, F, G) in the study area

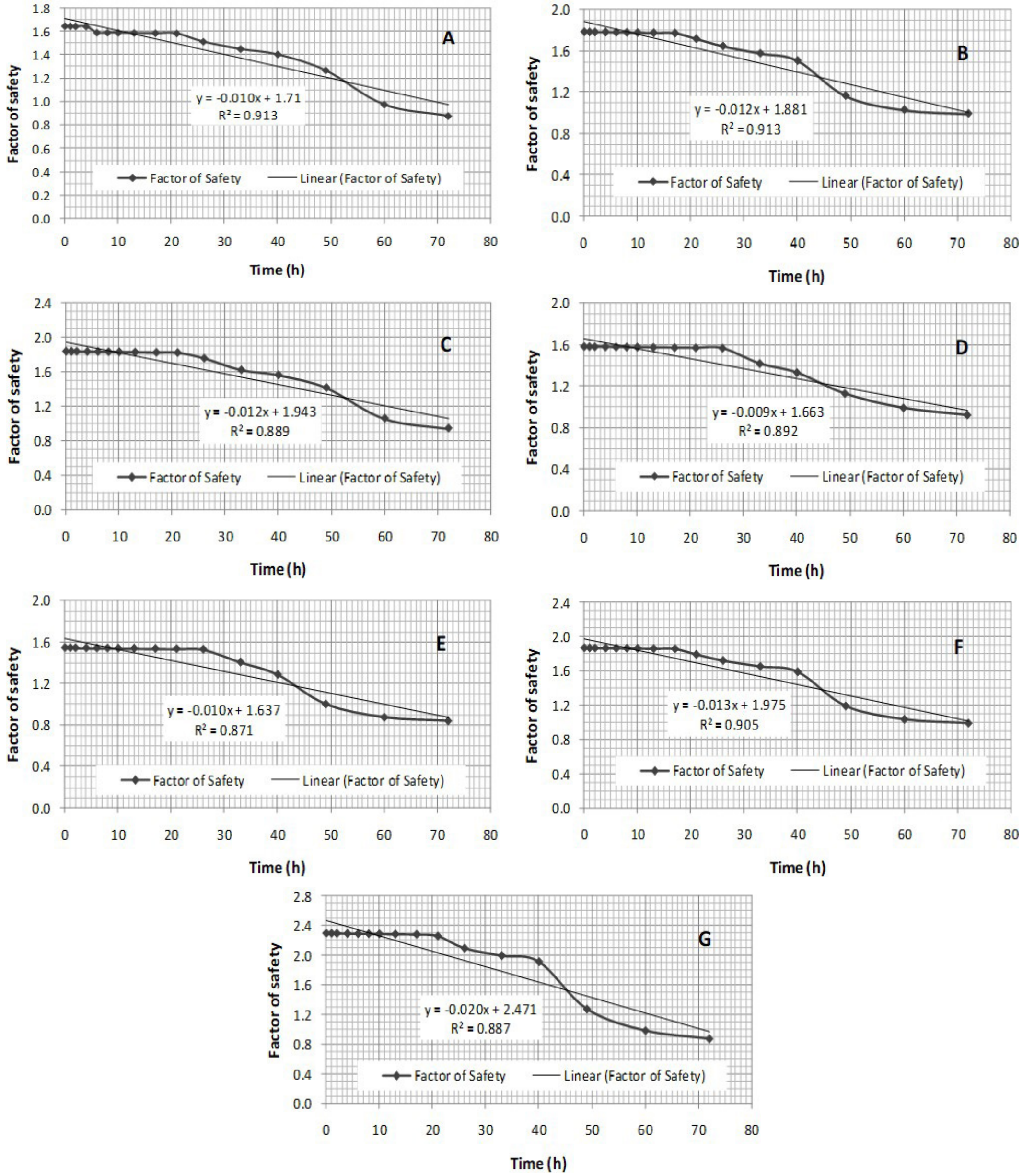

Figure 10. A factor of safety distribution over time in slope failure A, B, C, D, E, F and G

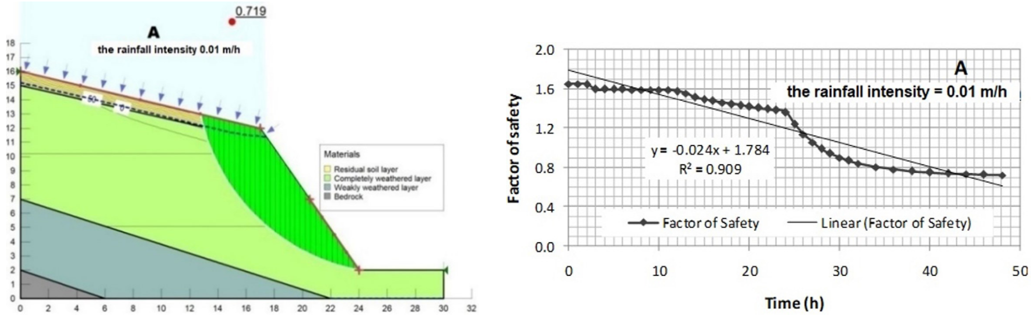

Figure 11. The sliding mass simulated in GeoSlope 12 software and its FS value (left) and the graph of FS value distribution over time (right) in slope failure A with the rainfall intensity = 10 mm/h

5. Discussion

The factors that influence the stability of a slope are various, and most are closely related. It is undeniable that shallow landslides are triggered by short, intense storms. The effect of rainfall on landslides varies significantly depending on the size of the landslide, the kinematics material involved, etc [3], [26], [27]. Seepage is a function of infiltration, soil properties, rainfall and local settings. The main important features of soil properties are hydraulic characteristics and suction, whereas soil saturation is governed by rainfall intensity and duration. Soil moisture content and antecedent rainfall are considered as other factors controlling the duration and quantity of the critical precipitation [3]. Therefore, to establish different warning thresholds of safety factors, it is necessary to understand the relationship between soil failure initiation and rainfall intensity and duration.

In seepage simulations of the study area, transient positive and negative pore-water pressure were changed at all the sites along the potential slip surfaces during rainfall. As can be seen in Figure 10, the pore water pressure had changed significantly FS values after 72 hours of continuous rainfall at the locations where the 7 soil samples were taken. The results of the slope stability analysis showed that FS was <1 at all sites after 72 hours. In these positions, 4 sites (A, D, E, G) had FS value < 1 after 60 hours and the remaining 3 had FS value < 1 after 72 hours of continuous rainfall. Based on Figure 10, it is clear that most FS values changed very little in the first 20 hours and they changed drastically after 20 hours of continuous rain, and these values will be less than 1 in most locations after 60 hours of rain. This proves that the rainfall intensity and duration significantly affected the stability of the slopes in the study area.

6. Conclusions

In this paper, the main objectives evaluated the stability of the cut slopes and to investigate the potentiality of failure during rainfall, coupled SEEP/W-SLOPE/W models were employed in the GEOSTUDIO 2012 software to complete the works. 7 sites (A, B, C, D, E, F, G) soil samples were taken to analyze the soil properties and hydraulic characteristics to evaluate the slope stability under the influence of rainfall conditions.

The results showed that the slope failures are closely related to the rainfall intensity and duration and the geotechnical properties of the soils in the study area. The FS values of all 7 locations were calculated and validated in the coupled SEEP/W-SLOPE/W model using geotechnical properties of the soils combined with the hourly rainfall data of four days (1, 2, 5 and 18 July 2013) that landslide hazards had occurred. Two hourly rain intensity values, 5.3 mm/h and 10 mm/h, were assigned to the calculation model, respectively. The results showed that, with the rainfall of 5.3 mm/h, most locations have FS value of less than 1 after 60 hours of rain, and with the rainfall intensity of 10 mm/h, after 24 - 28 hours of rain the FS value will be less than 1.

Although all the analytical results provided reasonable, however, the selection of correct models for slope stability analyses is not an easy task. Any soil could become unstable when high rainfall intensity has remained for long periods, thus extreme rainfall conditions must be accurately examined.

The analysis results of this research will assist local authorities in land-use planning and applying structural measures for vulnerable slopes in the study area to prevent and minimize the damages caused by landslide hazards.

Author Contributions: *Do Minh Hien wrote the manuscript, prepared and analyzed the data, designed and performed the experiments, and subsequent edit; Quach Duc Tin commented the scientific integrity and improved the manuscript. All authors read and approved the final manuscript.*

Acknowledgements: *We want to thank the editor and the anonymous reviewers for their constructive comments, which helped us improve the quality of the manuscript.*

Disclosure statement: *No potential conflict of interest was reported by the authors.*

References

1. Hien MD, Yin KL. (2018), *"Rainfall threshold analysis and Bayesian probability method for landslide initiation based on landslides and rainfall events in the past[J]", Open Journal of Geology* 8: 674-696. https://doi.org/10.4236/ojg.2018.87040
2. Caine, N., (1980), *"The rainfall intensity–duration control of shallow landslides and debris flows", Geografiska Annaler* 62A, 23–27.
3. Crosta, G., (1998), *"Rationalization of rainfall threshold: an aid to landslide hazard evaluation", Environmental Geology* 35, 131–145
4. Rahardjo H et al. (2007),*"Factors controlling instability of homogenous soil slopes under rainfall", Journal of Geotechnical and Geoenvironmental Engineer,* Vol. 133(12): 1532-1543
5. Hien MD et al. (2020), *"A comparative study on the integrative ability of the analytical hierarchy process, weights of evidence and logistic regression methods with the Flow-R model for landslide susceptibility assessment", Geomatics, Natural Hazards and Risk*, 11:1, 2449-2485. DOI: 10.1080/19475705.2020.1846086
6. Pourghasemi HR et al. (2012), *"Application of fuzzy logic and analytical hierarchy process (AHP) to landslide susceptibility mapping at Haraz watershed, Iran", Nat Hazards* 63: 965-996. DOI 10.1007/s11069-012-0217-2
7. Khien NX et al. (2012), *Assessment of status geohazards in four mountainous provinces in North of Viet Nam: Ha Giang, Bac Kan, Cao Bang, Tuyen Quang. Identification of sources, prediction and propose preventive measures and consequences mitigation,* Viet Nam Institute of Geosciences and Mineral Resources (In Vietnamese).
8. Dieu TB et al. (2012), *"Spatial prediction of landslide hazards in Hoa Binh province (Viet Nam): A comparative assessment of the efficacy of evidential belief functions and fuzzy logic models", Catena* 96: 28-40. doi:10.1016/j.catena.2012.04.001.
9. Anderson SA et al. (1995), *"Analysis of rainfall induced debris flows", Journal of Geotechnical Engineering*. Vol. 121(7): 522-544.
10. Chen H et al. (2004), *"Causative mechanisms of rainfall-induced fill slope", Journal of geotechnical and geoenvironmental engineering*. Vol. 130(6): 593-602
11. Fredlund DG. (1995), *"The stability of slopes with negative pore-water pressures", Ian Boyd Donald Symposium on Modern Developments in Geomechanics, Melbourne*. Monash University. pp: 99-116.
12. Craig RF. (2004), *Craig's soil mechanics.* Seventh edition 2004. Spon Press: Taylor & Francis group. London and Newyork. *Section 9: Stability of slopes.*
13. Collins BD, Znidarcic D, ASCE SM and ASCE M. (2004), *"Stability analyses of rainfall induced landslides", Journal of geotechnical and geoenvironmental engineering.* Vol. 130 (4): 362-373.
14. Cho SE and Lee SR. (2001), *"Instability of unsaturated soil slopes due to infiltration", Computer and Geotechnics.* Vol. 28(3): 185-208
15. GEO-SLOPE International Ltd. (2015 Edition), *Seepage Modeling with SEEP/W*. pp 205
16. GEO-SLOPE International Ltd. (2015 Edition), *Stability Modeling with SLOPE/W*. pp 252
17. Lee LM et al.(2009), *"A simple model for preliminary evaluation of rainfall induced slope instability", Eng Geol*. Vol. 108: 272-285
18. Dahal RK, et al (2009), *"Comparative analysis of contributing parameters for rainfall-triggered landslides in the Lesser Himalaya of Nepal", Environ Geol*. Vol. 58: 567-586
19. Muntohar AS, Liao HJ. (2010), *"Rainfall infiltration: infinite slope model for landslides triggering by rainstorm", Nat Hazards.* Vol. 54: 967-984.
20. Rahimi A et al. (2010), *"Effect of hydraulic properties of soil on rainfall induced slope failure", Eng Geol*. Vol. 114: 135-143.
21. Schnellmann R et al. (2010), *"Effect of rising water table in an unsaturated slope", Eng Geol.*

Vol.114: 71-83

22. Acharya KP. et al. (2016), *"Seepage and slope stability modelling of rainfall induced slope failures in topographic hollows", Geomatics, natural hazards and risk*. Vol. 7(2): 721-746. http://dx.doi.org/10.1080/19475705.2014.954150
23. Mein RG and Larson CL. (1973), *"Modelling infiltration during a steady rain", Water Resources Research*. Vol. 9(2): 384-396
24. Pack, R. T. et al. (1998), *"The Sinmap Approach to Terrain Stability Mapping. Proc. 8th Congress of the International Association of Engineering Geology", Vancouver, British Columbia*. pp 21-25
25. Róbert J, Peter W. (2007), *"Landslide hazard zonation by deterministic analysis (Vel'ká Causa landslide area, Slovakia)", Landslides* 4: 339-350. doi:10.1007/s10346-007-0089-9
26. Aleotti, P., (2004), *"A warning system for rainfall-induced shallow failures", Engineering Geology* 73, 247–265
27. Guzzetti F, et al. (2008), *"The rainfall intensity–duration control of shallow landslides and debris flows: an update", Landslides* 5, 3–17.