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ASSESSMENT OF THE INFLUENCE OF THE TYPE OF SOIL AND RAINFALL ON THE STABILITY OF UNSATURATED CUT-SLOPES – A CASE STUDY

*The Viet Tran[1], Huy Dung Pham[2], Viet Hung Hoang[3], and Minh Thu Trinh[4]

[1,2,3,4]Department of Civil Engineering, Thuyloi University, 175 Tay Son, Dong Da, Hanoi, Vietnam

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ABSTRACT: This study aims to evaluate the stability of cut-slopes composing of either low hydraulic conductivity and high hydraulic conductivity soil under different rainfall conditions. To accomplish this aim, cut-slopes along Noi Bai - Lao Cai Highway in Yen Bai province, Vietnam were analyzed. A simplified cut-slope profile with a homogeneous residual soil layer was used. Specific amounts of rainfall were chosen by analyzing rainfall data in the study area recorded over a period of 10 years. These amounts were then distributed evenly to simulate different types of rainfall including small intensity with long duration and high intensity with short duration. The study used the coupled hydro-mechanical approach to simulate the change of the water pressure head within the slope during the rain and its consequence on the stability of the slope. The results indicate that the hydraulic conductivity of the soil and the rainfall conditions have a significant impact on the stability of unsaturated cut-slopes. For the low hydraulic conductivity soil slope, long-duration rainfall has a more significant impact on the stability of cut-slopes than high-intensity rainfall while a contrary trend was found when high-intensity rainfall indicates a greater impact in the case of high hydraulic conductivity soil slope.

Keywords: Cut-slope, Slope failure, Hydraulic conductivity, Unsaturated soil, Soil type

1. INTRODUCTION

Landslides and slope failures are severe and dangerous natural disasters in Vietnam, a tropical country with about 75% of the land is in the mountainous and hilly area, having a complicated geological structure, and high annual rainfall [1]. According to statistics from the Central Steering Committee for Flood in the period from 2000 to 2014, landslides have resulted in the death of 646 people and the damage of about 150 million USD. Over the past decade, many cut-slope failures along highways have been observed causing considerable damages and loss [1, 2, 3]. Slope failures have usually occurred after rainstorms with heavy intensity and long duration [2, 4, 5, 6]. However, up to now, the actual mechanism of such rainfall-induced hydro-geological disaster has not been extensively explained [2, 5, 7, 8].

The occurrence of rainfall-induced slope failures in residual soil slopes is frequent in tropical regions where the groundwater table is often located deeply beneath the unsaturated zone [2, 9]. According to Ng and Shi (1998) [10], the major difference between water flow in saturated and unsaturated soils is the assumption on the hydraulic conductivity, which is conventionally accepted to be constant in saturated soils and is a function of the degree of saturation or matric suction in unsaturated soils. Therefore, rainfall-induced slope instability involves infiltration through the unsaturated zone above the groundwater table, and it is necessary to study unsaturated soil mechanics in order to understand the mechanism of rainfall-induced slope failures [11, 12, 13].

In literature, due to the complicated interdependent relationship between water and soil regarding slope stability [14], numerous studies have been conducted in rainfall-induced slope failures [2, 5, 6, 8, 15, 16, 17, 18, 19]. However, this is still a debatable topic. Different experiences from various regions often give different conclusions due to the complicated impact of rainfall on the occurrence of slope instability. Because rainfall-induced landslides in residual soil slopes are a recurrent threat along many highways in Vietnam [20], more studies are needed to find out the actual mechanism of the incident.

In general, in residual soil slopes, when the rain starts, water will infiltrate into the pore spaces and narrow the unsaturated zone down. This process leads to an increase in the water pressure head (WPH) and the reduction of the matrix suction, subsequently decreasing the shear strength of the soil. When the shear strength mobilized along the potential slip surface is not adequate to support the shear stress, slope failure will occur [5]. During this process, the study conducted by Dahal and Hasegawa (2008) [16] and Tran et al. (2016) [5] showed that the hydraulic properties of the slope material play an important role in rainfall-induced landslides. High hydraulic conductivity soils (HK soils) tend to be more sensitive to extreme rainfall events with short duration (HI rainfall), while low hydraulic conductivity soils (LK soils) are more sensitive to long-duration with low-intensity rainfall (LD rainfall). Therefore, additional studies are needed to further verify this conclusion, especially in our case study with specific types of soil, rainfall, as well as local materials [21].

This study focused on assessing the influence of soil types and rainfall conditions on the hydrological response of the WPH within the cut-slopes of the Noi Bai - Lao Cai Highway Project in Yen Bai province and their influence on the occurrence of slope failures. To be more specific, the stability of unsaturated cut-slopes composed of LK or HK soil slopes under different rainfall conditions was assessed.

2. METHODOLOGY

Rainfall-induced slope failures have often been reported to occur during, right after, or sometimes after an intense rainstorm, or a long-duration rainfall with low-intensity [2, 5, 15, 22]. In reality, modeling rainfall-induced slope failures presents complex hydro-mechanical processes that significantly alter the distribution of matric suction within the slope during the rain [23]. In this study, we analyzed the response of LK and HK soil slopes under different types of rainfall conditions. To reach this aim, a typical slope cross-section was constructed in the first step, and then two typical saturated hydraulic conductivities represented the slope material with HK and LK soils were selected. The observed rainfall data in 10 years from 2000 to 2009 were analyzed to find a critical event with extreme intensity and short duration, and another event with long duration and low intensity. The variation of the WPH and the corresponding factor of safety of the slope was analyzed in the next step.

The rainfall-induced slope failure process was modeled coupling module SEEP/W [24] and module SLOPE/W [25]. SEEP/W was used to simulate the transient pore-water pressure within the slope caused by rainfall infiltration. The subsequent limit equilibrium analysis of slope failure at a specific time step can be performed using the transient hydraulic conditions simulated by SEEP/W as one of the input data.

SEEP/W uses the finite element method to solve the governing differential equation defining the flow through a two-dimensional unsaturated soil as follows:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)+Q=\left(\frac{\partial \theta_w}{\partial t}\right) \quad (1)$$

where h- total hydraulic head; k_x and k_y the hydraulic conductivity in the x- and y- direction, respectively, Q- the applied boundary flux on the surface of the slope, θ_w - the volumetric water content, t- the time.

The slope stability was simulated using SLOPE/W. In this module, the Bishop's simplified method was utilized. SLOPE/W uses unsaturated shear strength conditions with the modified Mohr-Coulomb failure criterion. In literature, several available equations are used to describe the shear strength of unsaturated soils. Fredlund et al., (1978) [11] introduced a linear relationship that is expressed in the following form:

$$\tau = c' + (\sigma_n - u_a)tan\phi' + (u_a - u_w)tan\phi^b \quad (2)$$

where τ - the shear strength; c' - the effective cohesion; $(\sigma_n - u_a)$ - the net normal stress on the failure plane; σ_n – the total normal stress; u_a - the pore-air pressure; u_w - the pore-water pressure; $(u_a - u_w)$ - the matric suction; ϕ' - the friction angle, and ϕ^b - the angle linking the rate of increase in shear strength with increasing matric suction. ϕ^b varies with the degree of saturation and it decreases when the soil becomes desaturated.

In literature, the link between the unsaturated shear strength and the volumetric water content of the soil has been proved [2, 26, 27, 28]. Vanapalli et al. (1996) [29] proposed a non-linear shear strength equation that considers a normalization of the volumetric water content function given by:

$$\tau = c' + (\sigma_n - u_a)tan\phi' + (u_a - u_w)S_e tan\phi' \quad (3)$$

where S_e- effective degree of saturation given by:

$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r) \quad (4)$$

where θ - the volumetric water content; subscript r and s imply θ at residual and saturated state.

According to Geoslope International Ltd (2020b) [25], the non-linear strength equation provides a better representation of unsaturated soil behavior. Therefore, in this study, the strength equation provided by Vanapalli et al. (1996) [29] was employed in the stability analysis

3. STUDY AREA

3.1 Typical Cross-section of Cut-slope in the Study Area

The Noi Bai – Lao Cai highway completed in September 2014, is the longest freeway in Viet Nam with a total length of 245 km passing through Ha Noi, Vinh Phuc, Phu Tho, Yen Bai, and Lao Cai. It is considered to be the most innovative highway in the country at the time of completion. After six years of operation, the road has been suffered from considerable deterioration. Annually, in rainy seasons, numerous sliding locations have been observed along the Noi Bai-Lao Cai Highway talus resulting in significant damage to people's life and the economy. Figs. 1a and 1b present two typical sliding sites along the Noi Bai – Lao Cai highway during the rainy season in 2018.

The longest segment is located in Yen Bai province, running from the interchange (IC) IC12 to IC16 with a length of about 84 km. Due to the complexity of the topography, the cut-slope profile varies significantly along this segment. Based on the technical design document, we found that most of the cut-slopes have a height from 15.0 m to 25.0 m, except that some slopes are very high at sections along Km-148, Km-162, and Km-190. Therefore, in this study, by analyzing the talus along the study area, we ignored the influence of the steepness of the slope and proposed a typical cross-section of the cut-slope of the highway in Yen Bai province as presented in Fig. 2.

Fig.1 Typical sliding site along the Noi Bai – Lao Cai highway during the rainy season in 2018.

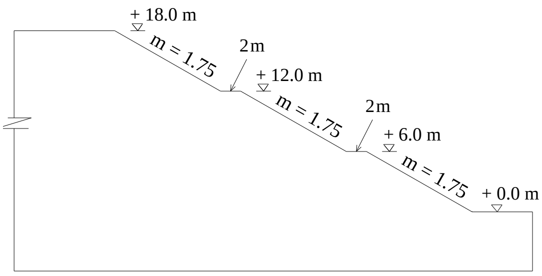

Fig.2 Typical cross-section of cut-slopes along Noi Bai – Lao Cai highway

3.2 Soil Parameters for Stability Assessment of Unsaturated Slopes

From the Geological and Mineral Resources Map of Viet Nam on a 1:200,000 scale [30], it is found that the segment belongs to Co Phuc Formation (N13) which is distributed along the Red River [31]. This formation consists of two main types of rocks namely sandstone and shale. As a result, the weathering productions of these materials demonstrate different features in terms of conductivity. It means that, the weathering productions of sandstone show much higher permeability than those of shale. Therefore, as indicated in the Methodology section, in this study, two types of soil were considered. The one with high conductivity (HK) represents the final weathering production of sandstone, and the other with low conductivity (LK) represents the final production of shale.

To make sure that rainfall-induced pore water pressure change is the main contributing factor for the stability of cut-slopes, in this study, geotechnical parameters related to the hydraulic properties of soil were carefully considered. The shear strength parameters of soil which include the cohesion and internal friction angle were kept constant for both the HK and LK soils. For all the data used in the coupling models, soil samples are taken at two locations Km-134 (LK) and Km-172 (HK). According to ASTM D2487 (2006) [32], the LK and HK soils in the study area can be classified as CL and ML respectively (Table 1). Additionally, laboratory tests were conducted to determine the density, saturated shear strength parameters, and hydraulic conductivity.

Table 1 Identification of soil samples

Soil type	Group name	Group symbol	Plasticity
LK soil	Lean clay with sand	CL	15.3
HK soil	Sandy silt with gravel	ML	10.2

For each parameter, three tests were conducted under identical conditions. Their average values which were used for the simulation are summarized in Table 2.

Table 2 Geotechnical parameters of the soil slope used in this study

Parameters	Symbol	Range	Average
Unit weight *(kN/m³)*	γ	16.5÷18.0	17.0
Friction angle (°)	ϕ'	23.5÷28.3	26.0
Cohesion *(kN/m²)*	c'	9.5÷14.1	13.0
Saturated volumetric water content	θ_{HK}	0.45÷0.50	0.48
	θ_{LK}	0.42÷0.47	0.45
Hydraulic conductivity *(m/s)*	K_{HK}	$(3.5÷5.4)\times10^{-6}$	4.2E-6
	K_{LK}	$(2.5÷6.0)\times10^{-8}$	4.5E-8

For the consideration of the proper unsaturated characteristics of the soil, laboratory tests were conducted to determine the soil-water characteristic curve (SWCC) by a pressure chamber with a ceramic plate. SWCC was defined as a continuous sigmoidal function that represents the water storage capacity of soil when it is subjected to increase soil suction or the amount of equilibrium water that the soil can take at a given suction [27]. Specifically, the curve represents the relationship between volumetric water content versus the soil suction stress. The results of the SWCC test for the HK and LK soils are presented in Fig. 3. The unsaturated hydraulic conductivity is also a non-linear function of the matric suction, this parameter is highly dependent on the soil water content, it was derived empirically by integrating along the corresponding SWCC [27]. In addition, the increase in the soil unit weight caused by rainfall infiltration was also considered in the stability assessment by calculating from the SWCC.

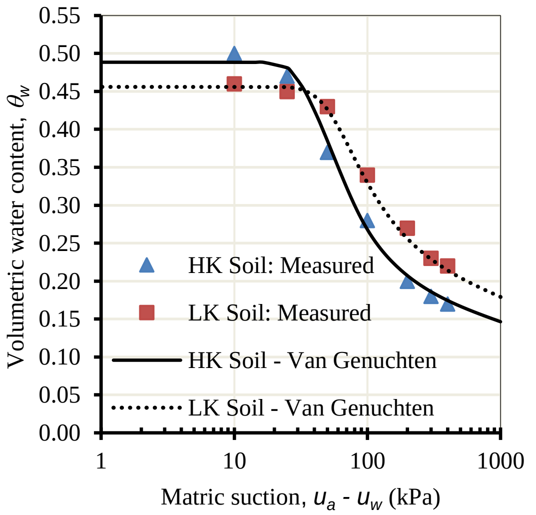

Fig. 3 SWCC of HK and LK soils

3.3 Modeling Profile and Rainfall Data

From the typical cross-section of the cut-slopes in the study area as presented in Fig. 2, the SEEP/W model with the infinite mesh is illustrated in Fig. 4. In this figure, the mesh properties, the initial water table, and the hydraulic boundary conditions are also presented. Specifically, the initial groundwater as illustrated in Fig. 4 was assumed to be deep below the ground surface and it was defined by analyzing the general trend of groundwater table in the rainy season in the study area. The rainfall was assigned as the water flux versus time boundary condition in SEEP/W. A total head of 0.0 m was assigned to the right of the model domain representing the field conditions (water is collected by drainage systems along the highway).

According to Tran and Trinh. (2019) [28] and Rahardjo et al. (2007) [33], the actual failure conditions are controlled by the properties of the soils within the slope and the characteristics of the rain. To serve the objectives of this study, we analyzed the recorded hourly rainfall data over the duration of 10 years from 2000 to 2009. This data indicates that high-intensity rainfall often occurred in a period of 1.0 ÷ 4.0 hours; the long duration rainfall may last for up to 4.0 days. The maximum hourly rainfall intensity was recorded to be 70.2 mm/hr (recorded on August 16, 2000), and the longest rainfall duration was 4.0 days (recorded on August 07 ÷ 10, 2008) with a cumulative intensity of 210.3 mm. Therefore, to analyze the response of the slope under different rainfall conditions, two kinds of rainfall were classified: the HI rainfall and the LD rainfall. The HI rainfall is the one with the observed maximum intensity (70.2 mm/hr) and lasts for 4.0 hours. The LD rainfall has a duration of 4.0 days. This rainfall is evenly distributed with the intensity as the ratio between the cumulative rainfall (210.6 mm) and the selected duration.

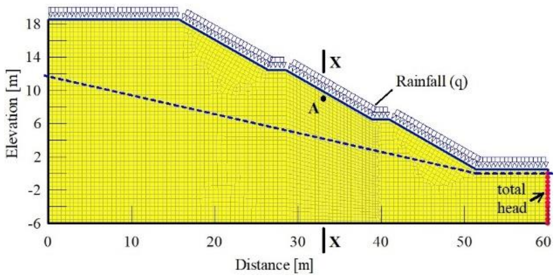

Fig. 4 Modeling profile with SEEP/W boundary conditions

4. RESULTS AND DISCUSSION

4.1 Influence of HI and LD Rainfalls on the Distribution of Transient Water Pressure Head with the Slope

This section assessed the influence of HI (4 hours of continuous rainfall and 20 hours of drying period) and LD (4 days of continuous rainfall and 2 days of drying period) rainfall types on the variation of the WPH of slopes composed of HK and LK soils. To fulfill the aim of this study, we also analyzed the variation of WPH at section X-X (Fig. 4) in the middle of the slope to see the change with depth and at point A in section X-X (about 1.5 m below the slope surface to analyze the change with time).

Fig. 5 indicates the variation of the WPH at point A in HK and LK soil slopes when the HI rainfall was applied. The figure shows that the WPH in HK soil slope varies significantly compared to those in LK soil slope. As soon as the rain started, the WPH increased considerably and reached a peak until the end of the rain. It plunged right after the rain stopped and then decreased slightly after that. The trend is very different in the case of LK soil slope. The WPH showed a slight change over the whole duration of the rain (4 hours) as well as during the drying period (20 hours). Furthermore, unlike in the case of the LK soil slope, the difference among WPH values before and after the rain in the case of HK soil slope is considerable.

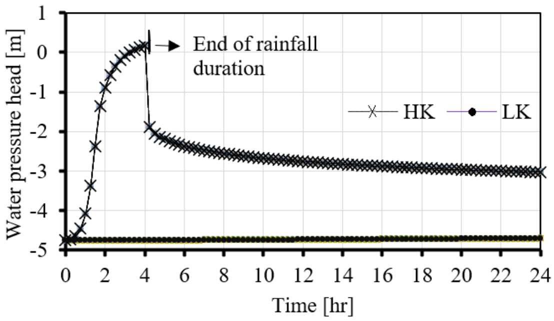

Fig. 5 Variation of WPH with time at point A in the HK and LK soil slopes under HI rainfall.

Fig. 6 presents the variation of the WPH at point A in HK and LK soil slope when the LD rainfall was applied. In this case, we analyzed the rainfall duration of 6.0 days (4.0 days of continuous rainfall and 2.0 days of drying period). One can observe from the graph that an adverse trend is seen in comparison to the case of HI rainfall. It means that the WPH is more sensitive to the rain in LK soil than that of HK soil during and after the rain.

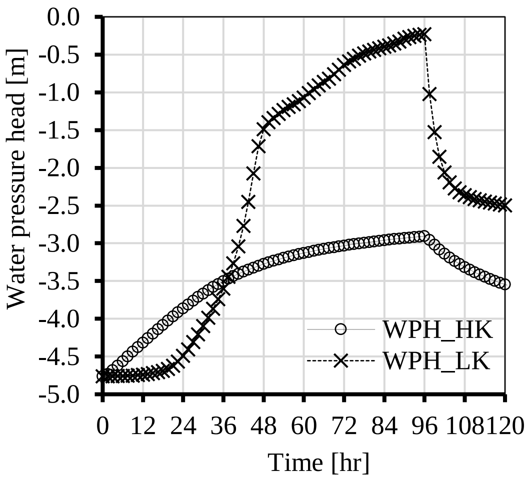

Fig. 6 Variation of WPH with time at point A in the HK and LK soil slopes under LD rainfall, the rain stopped at t = 96 hrs.

The achieved results presented above can be explained by the balance between the amount of rainwater that is able to infiltrate into or drain out of the slope through the surface boundaries. In the case of HK slope, it is more sensitive to the HI rainfall because within a short amount of time, the quantity of infiltrated water is much larger as compared to the amount that is drained away. It is also due to the high capability of water to seep out of the model, the WPH also varies considerably right after the rain (during the drying period). However, as for the LD rainfall, there is a balance between the infiltrated and drained water; therefore, the WPH of the slope is not much affected by the rain. In the case of LK, the difference between the water seeping in and out of the model is not significant, however, because the rainfall duration is long, rainwater will keep infiltrating into the slope to increase the water pressure head.

To assess the variation of WPH with different types of rainfall, we also analyzed its value along section X-X. Fig. 7 and Fig. 8 show the distribution of WPH with the depth at the end of HI and LD rainfalls.

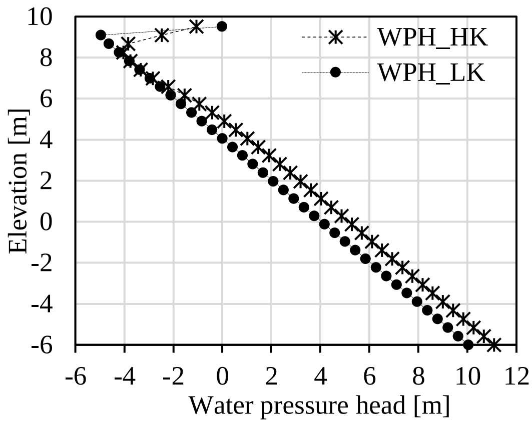

Fig. 7 WPH profile at Section X-X at the end of HI rainfall (after t = 4 hrs).

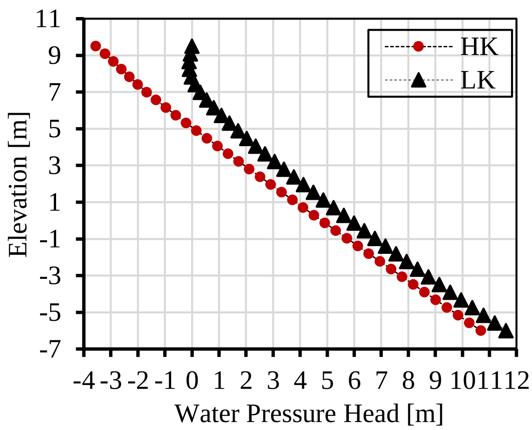

Fig. 8 WPH profile at Section X-X at the end of LD rainfall (after t = 96 hrs)

As can be seen in Fig. 7 and Fig. 8, the two soil types responded differently to the two kinds of rainfall. In the case of HI rainfall, the HK soil slope presented a higher value of WPH at all depth along the profile than that of LK soil and the difference tends to increase with depth. The simulated water level in the case of the HK slope is also higher than that in the case of the LK slope. It is contrary in the case of LD rainfall when the WPH shows a much larger value along the selected section in comparison with the HK slope. The deeper the depth, the smaller the difference between the two soil types. The groundwater level also shows a more significant difference between HK and LK slope. Therefore, in the case of LD rainfall, the influence of rainfall-induced groundwater level rise in slope failure is much more significant.

4.2 Rainfall and Slope Stability

In the case of HI rainfall, Fig. 9 illustrates the variation of FS value during and after the rain. As can be seen in this figure, it is consistent with the variation of WPH. In the case of HK soil, right after the rain starts or ends, the Factor of safety (FS) of the slope varies significantly corresponding to the wetting and drying periods. It even reduces to below the FS threshold as suggested by the Ministry of Transport (2005) [34], leading to the high risk of slope stability. However, LK soil slope experiences the opposite trend when the FS values reduce gradually with time and the FS value is above the FS threshold during the whole process.

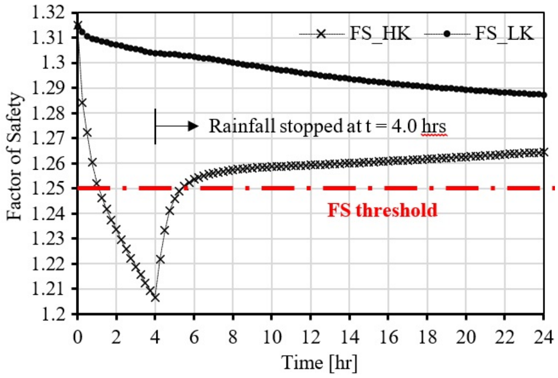

Fig. 9 Variation of FS value during the HI rainstorm and the drying period

Fig. 10 shows the relationship between FS and time during the LD rainfall. One can be seen that FS in the case of HK soil presents an insignificant decrease over time. During this process, the FS is much larger than the FS threshold. In LK soil slope, however, the FS decreases noticeably throughout the rainfall duration. It is also lower than the FS threshold at the end of the rain. In both cases, the FS shows a considerable recovery after the rain. Therefore, for both soil types, together with the infiltration process, there is a reduction in the negative WPH and an increase in the volumetric water content. As a result, the self-weight of the soil increases, the soil shear strength, and the effective stress reduction, and as a result, failure might occur. This result explains the fact that HI rainfall often causes a high risk for HK soil slopes, while LD rainfall is usually more critical for LK soil slopes.

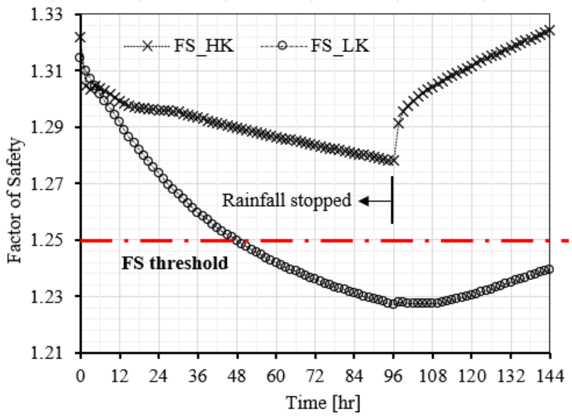

Fig. 10 Variation of FS value during the LD rainfall and the drying period

5. CONCLUSION

This study focused on assessing the influence of two types of rainfall and soil type on the hydrological response of the WPH within the slope and their link to slope failures. From the results obtained as presented in the Results and discussion section, several conclusions can be drawn:

+ The coupling between SEEP/W and SLOPE/W for simulation of the variation in FS values during the time with rain and during the drying stage proves to be a promising tool for rainfall-induced slope failures simulation. The approach can simulate the variation of FS due to the increase or dissipation of WPH with time.

+ The results of this study provided an overall picture of the relationship between rainfall and the occurrence of landslides and therefore providing an extensive view of the mechanisms associated with the recurrence of slope failures along the Noi Bai – Lao Cai highway. The hydraulic conductivity function of the slope material, the rainfall characteristics are important factors that control the infiltration amount of rainfall into the slope. Particularly, the results reveal that the HK soil is more sensitive to HI rainfall rather than the LK soil while a contrary trend was found when the slope is subjected to LD rain. The results of this study can be served as the key to explaining the mechanism of rainfall-induced slope failures.

6. RECOMMENDATIONS

As the identification of soil types in the study area is an important factor to deal with in the rainy season, more studies are needed to develop the early warning system of slope failures based on the types of soil and rainfall. A critical rainfall threshold for the different types of slope materials or rainfall conditions can also be simulated. Furthermore, additional studies can be conducted on the influence of the physical and chemical composition of the soil, the clay mineralogy, the grain size distribution, the shape of the SWCC of soil for rainfall-triggered slope failure process.

The study used a typical slope cross-section for the simulation of rainfall-induced slope failure; therefore, the influence of the slope steepness is ignored. Furthermore, the results of this study were based on the two-dimensional assumptions which may fail to model the actual mechanism of the slope failure in numerous situations. Such kinds of effects are open to future studies.

7. ACKNOWLEDGMENTS

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