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Numerical Analysis on Slope Stability Under Impact of Prolonged Antecedent Rainfall in Tropical Climates

Azman Kassim[a], Rini Asnida Abdullah[a*], Muhammad Irfan Shahrin[a], Nur Fatin Amirah Mohd Ali Hanafiah[a], Mohd Faisal Abdul Khanan[b], Muhammad Zulkarnain Abd Rahman[b], Mohd Asraff Asmadi[b] & AKM Badrul Alam[c]

[a]*Faculty of Civil Engineering, Universiti Teknologi Malaysia, Johor Bahru, Malaysia,*

[b]*Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, Johor Bahru,*

[c]*Department of Petroleum and Mining Engineering, MIST, Bangladesh,*

[*]*Corresponding author: asnida@utm.my*

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ABSTRACT

Within a few decades, there have been quite a number of rainfall-induced landslide events occurring in many parts of Malaysia, especially in the urbanised hilly areas. The changes in hilly morphology because of weathering activities in humid tropical climates have increased the potential for rainfall-induced landslides, especially during prolonged antecedent rainfall. In addition to the bedrock geology influencing geohazards, the weathering profiles, slope gradient and rainfall pattern also can be responsible for landslides. A series of site investigation works were undertaken in the designated landslide-prone study site to obtain data on the characteristics, composition and mechanical response of the soil as well as the groundwater table located below the ground surface. The numerical transient seepage analysis by applying recorded average annual rainfall of approximately 2440 mm and limit equilibrium slope stability analysis was carried out and simulated on the landslide area using commercial software GeoStudio of SEEP/W and SLOPE/W respectively. The simulation outcomes establish the occurrence of a landslide may not necessarily be dependent on a significant rainfall event, yet, the extended period of antecedent rainfall may exert a predominant influence in initiating failure of the landslide-prone area.

Keywords: Rainfall pattern; landslide; weathering profile; slope stability; tropical climates; simulation

INTRODUCTION

The occurrence of landslides is one of the geohazards that have caused damage to property and infrastructure, even leading to substantial loss of life. Some of the triggering factors could be caused by human engineering activities, agricultural activities and a combination of rainfall and earthquakes (Song et al. 2023). Furthermore, rainfall may contribute directly or indirectly whereas most landslide that occurs in Malaysia are often associated with the rainfall pattern of the country. This explains the correlation between how much precipitation is recorded throughout the year and the country's tropical climate. The rainfall trends from 1951 to 2013 in Malaysia showed an inconsistent rainfall pattern, likely due to its tropical climate, yet most situations experienced extreme rainfall variability (Alhoot et al. 2016). Temporal variations in runoff and evaporation will follow any significant changes in rainfall seasonality (Sa'adi et al. 2023).

Apart from the amount of precipitation, landslides also occur due to the distinct mechanical and hydraulic properties of the soil slope. Landslides are influenced by bedrock geology in a number of ways, including the mechanical strength of intact rock, the orientation and surface features of discontinuities, and the geologic history of the rock mass, terrain, and climate (Brideau & Roberts, 2022).

Landslide-prone regions in Malaysia typically correspond to areas characterised by extensive hillside development. These areas have been constantly affected by fatal landslides since a few decades back resulting in the collapse of residential areas and the loss of lives. Over the years, there have been numerous reports of catastrophic and small to medium-sized landslides documented. According to the data compilation by (Low et al. 2012) and (Majid et al. 2020), a total of 28 historical massive landslides were reported in the urban growth area, including the development of residential and commercial centres which were potentially triggered by rainfall. Recently in March 2022, a large urban landslide occurred in a hilly area of Taman Bukit Permai 2 in Ampang, Malaysia, killing four people and injuring a further individual as depicted in Figure 1.

FIGURE 1. Deadly urban landslide in Ampang (Bernama, 2022)

It is occurring majorly in hilly and terrain regions because they are highly vulnerable and sensitive to human alterations compared to the normal terrain. The predominant kinds of landslides observed in Malaysia are shallow slides characterized by a slide surface depth usually not exceeding 4 meters, commonly triggered by intense rainfall events (See-Sew & Tan, 2012). Landslides in Malaysia usually take place in hilly regions as a result of alterations in the ecosystem within the environment (Chuang & Shiu, 2018). Other than that, prolonged and intense rainfall, slope instability topography and soil characteristics also have considerable effects on landslide occurrence.

The nation experiences a substantial volume of annual precipitation throughout these monsoon periods (Syed Jamaludin 2007). Table 1 shows the compilation of landslide occurrences in mountainous regions of Malaysia categorized by monthly frequency. In conjunction with that process of intense chemical weathering promotes the formation of residual soil horizons. Weathered granitic materials, geological lineaments that promote sliding, and pre-existing landslide landforms that assist in groundwater accumulation may also contribute to the initiation of landslides in Malaysia (Chigira et al. 2011).

TABLE 1. Summary of landslide incidents in hilly areas in Malaysia (Low et al. 2012)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1993												X
1996						X						
2001										X		
2003											X	
2008				X								X
2009									X			
2011						X						
2020						X						

The trend of landslide disaster occurrence is gradually increasing from time to time whereby most slope failures are triggered not only by localized rainfall but associated with inherent weaknesses of the rock or soil combined with human activity. The instability of the existing slope will cause landslide occurrence, especially in hilly areas, thus important key points such as groundwater levels, soil water content, and precipitation are all essential indicators of soil slope stability. These indications can be identified using site characterization techniques, including drilling, refraction seismic surveys, geoelectrical monitoring, soil water content sensor networks, and groundwater stations (Moradi et al. 2021).

In this study, the finite element method of seepage analysis and limit equilibrium method of stability analysis was carried out on the slope by implementing commercial software GeoStudio. The seepage analysis was utilized to determine pore-water pressure distribution, which was then used to establish the factor of safety for determining the slope stability.

FACTORS INFLUENCING

POTENTIAL FACTORS

Rainfall intensity was identified as the primary influential triggering factor on landslides by utilizing data-driven analysis. In addition, subsurface hydrology plays a prominent role in the triggering of shallow landslides caused by rainfall, given that alterations in soil moisture content have a substantial impact on the shear strength of the soil. Other than changes in soil moisture, intense rainfall leads to a rapid increase in infiltration, resulting in elevated levels of groundwater and pore water pressure (Dahal et al. 2008). In the context of triggering factors for landslides in Malaysia, rainfall plays a significant role by contributing 58% (National Slope Master Plan 2009-2023, 2009) and serves as a primary triggering factor.

However, landslide occurrences are also frequently related to the subsoil conditions such as the soil wetness (Wicki & Hauck, 2022) and preferential flow pathways in weathered bedrock (Tsutsumi & Fujita, 2008) that have demonstrated a significant influence. The existence of saprolite or the interface with compacted bedrock is considered to be one of the most crucial soil characteristics. It was pointed out by (See-Sew & Siew-Wai, 2008) that the geological characteristics, including discontinuities in residual soils particularly sedimentary formations, give challenges in terms of identification.

By considering the geological structure, the influencing factors of landslides in soil slope is an important key to be analysed, in which this study considers the weathering process and antecedent rainfall at the study area as the main triggering factors. All these factors were analysed thoroughly to evaluate the possibility of slope failure.

WEATHERING PROFILES AND HETEROGENEITIES IN TROPICAL RESIDUAL SOIL

The advancement of chemical weathering in the geological profile demonstrates the alteration of rock into residual soil due to the impact of humid tropical climates in Malaysia. This tropical residual soil is a result of the weathering process exists in a wide range of properties called a soil profile and consists of different layers vertically as shown in Figure 2 (Raj, 2021).

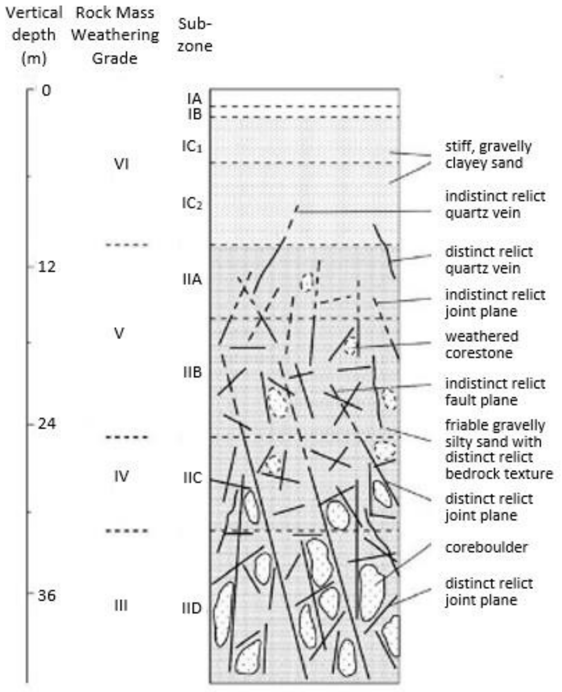

FIGURE 2. Schematic sketch of sub-zones within weathering profile (Raj, 2021)

The soil profile demonstrates a weathering classification that results in the formation of a vertical weathering profile. Commonly, the classification system distinguishes six distinct weathering profiles utilized in engineering applications such as residual soil (Grade VI), completely weathered (Grade V), highly weathered (Grade IV), moderately weathered (Grade III), slightly weathered (Grade II) and fresh rock (Grade I). The vertical weathering profile illustrates a sequential transition from the bottom of fully sound and fresh rock up to the top of the soil profile with completely weak residual soils. However, from previous study by (Ray et al. 2020) found that the existence of residual soils formed due to weathering processes on top of the underlying bedrock specifically in Zone 4 to Zone 6 represents a notable aspect contributing to slope failure.

Heterogeneity in tropical residual soil is a result of the weathering process possessed by saprolitic soil. The origins of heterogeneity are mainly attributed to relict discontinuities which influenced the saturated hydraulic conductivity (k_{sat}) of the soil, thus resulting in changes in soil characteristics (Kassim et al. 2012). This complex behaviour can give control on failure and deformation of soil slope but the large variability type and scale of changes might not easily be detected on ground investigations. Thus, numerical modelling has been utilized in this study to explore the pore water pressure changes in the subsoil.

In most cases, relict discontinuities are indicated as a plane of vulnerability within soil formations specifically in the saprolitic zone which are influenced by heterogeneities either directly or indirectly. The existence of these discontinuities like fractures or fissures, within the rock formation may result in failure surfaces (Xu et al. 2013). The geometric characteristic of residual joint features plays a crucial role in determining the permeability of remaining soil. Research by (Talib et al. 2016) discovered that the permeability of the residual soil exhibits a significant variation influenced by the quantity and arrangement of existing ancient fractures.

Moreover, the existence of corestones and the weathered environment in which they are situated to have the potential to greatly diminish the structural integrity of the rock mass, thereby increasing its susceptibility to failure. In a study by (Regmi et al. 2013), the occurrence of severe weathering along a failure zone led to a tendency to expand upon the absorption of moisture. This process contributes to increasing the instability of the slope, consequently aiding the occurrence of widespread landslides and debris flows specifically during the monsoon season.

The porewater pressure distribution within tropical residual soil slope mass becomes more intricate because of the diverse permeability in the soil matrix caused by the heterogeneous nature of saprolites which resulted from the weathering process. The infiltration of water through the residual soil is a critical factor in slope stability which is influenced by the permeability of the soil can vary with depth and either prevent or allow water to seep into deeper layers (Talib et al. 2016). The research undertaken by (Regmi et al. 2013), assessed that the vertical hydraulic conductivity of weathering covers on metamorphic and igneous formations indicates that weathering covers of granite rocks demonstrate the highest permeability. (Gupta et al. 2023) highlights the importance of minor variations in hydraulic conductivity among stratified slope materials, which can influence the dispersion of porewater pressure, as indicated in his numerical evaluation. Therefore, it emphasizes the need to consider these fluctuations in specifying slope stability.

ANTECEDENT RAINFALL

The other main factor emphasized in this study is the rainfall pattern whereby can be the triggering factor in most landslide cases across the world. Mechanism of rainfall infiltrating into the soil causes the increasing moisture content of soil above the phreatic surface then reducing the suctions. As the water flows downward, it will result in capillary water at shallow depth and also potentially rising phreatic line finally causing instability of slope. Various form of rainfall patterns on site conditions provides complex relationships between surface runoff and distribution of rainfall depending on the soil's initial condition and movement of the soil particles impacted by raindrops. According to (Cheng et al. 2025), considering the delayed effects of precipitation through antecedent effective precipitation in landslide prediction models is essential for generating more comprehensive landslide susceptibility maps.

The rainfall threshold is likely to trigger landslides when the rainfall amount reaches a minimum or maximum level for the process to take place. However, it could be a combination between a number of rainfall events and a prolonged antecedent rainfall. Pre-storm soil wetness also could be a factor of rainfall-induced landslides where it can cause shallow landslides that triggered by intense rainfall events associated with previous rainfall conditions. Additionally, soil instability can occur before full saturation is reached, thereby challenging conventional assumptions (Thuong et al. 2024). Period of time for the antecedent rainfall should be determined depending on the current local rainfall condition at one time. Previous studies suggested that it should be in 14 days (Chien-Yuan et al. 2005), 15 to 18 days (Chen et al. 2018) and 5 days (Nor Khalid et al. 2022) with different rainfall data collection.

DATA ACQUISITION OF THE STUDY SITE

AREA OF STUDY

A study site located in the hilly area of Selangor was utilized in this study. A series of site investigations that consisted of six exploratory boreholes with different ranges of depths described the soil profile of the desired areas. The rotary boring method was carried out to explore the subsoil condition and groundwater level underneath the ground surface. Furthermore, other site investigation works had been performed on-site such as Standard Penetration Test, collecting undisturbed and disturbed samples, installing and monitoring ground settlement markers and pneumatic piezometers as well as installing Temporary Bench Mark (TBM). In addition, geophysical surveys employing the resistivity method, specifically 2D electrical resistivity and induced polarization (IP) were conducted at identified critical slope locations.

METHOD OF DATA EXPLORATION

From the borehole method exploration, the general soil profile of the study area consists of soil layers from top firm soil sandy silt, firm to stiff sandy silt, very stiff to hard sandy silt, loose to medium dense silty sand or boulder, medium to dense silty sand and very dense sand or rock at the bottom. To highlight that loose to medium dense silty sand or boulder is the relict tropical residual soil type which aforementioned as one of the factors influencing landslide that plays an important role in controlling the movement of particles in subsoil thus leading to failure of slope.

The subsoil conditions were characterised by three major parts which are topsoil, residual soil, bedrock and groundwater table. On the top surface of the ground is found to be a sandy silt and silty sand type of soil with a range of thickness up to 1.5 m. Followed by residual soil level, it consists of completely decomposed granitic rock that went through the weathering process over time. Lastly, the hardest part of the bedrock can only be cored and present in various ranges of depth until 19.1 m downward. Meanwhile, the ground water table was observed from exploratory boreholes and it varies from 2 m to 7.5 m below surface level. For the purpose of analysing the soil slope, a few parameters were taken into consideration. A summary of soil properties data in different soil layers such as saturated permeability (k), effective cohesion (c’), effective friction angle (ϕ') and soil unit weight (γ) are shown in Table 2.

TABLE 2. Soil properties information

Soil layer	Soil type	k	c’	φ'	γ
Layer 1	Firm Sandy SILT	3.44×10^{-4}	3	26	17
Layer 2	Firm to Stiff Sandy SILT	5.0×10^{-7}	8	32	18
Layer 3	Very Stiff to Hard Sandy SILT	6.79×10^{-8}	10	34	18.5
Layer 4	Loose to Medium Dense Silty SAND/ Boulder	1.6×10^{-5}	0	25	16
Layer 5	Medium to Dense Silty SAND	3.68×10^{-6}	10	38	20
Layer 6	Very Dense SAND/ROCK	-	(c_u = 350)	-	26

In addition, the implementation of a vibrating wire pneumatic piezometer and ground settlement marker contributes to slope monitoring works. To establish benchmarks for the survey, two reference points or control points (TBMs) were placed on the concrete foundation. The result of monitoring works indicates that groundwater seeps through the flow in a downslope direction. Different piezometric levels, along with irregular distributions and varying seepage rates were observed in horizontal drains within cut slopes and landslide scars to provide evidence of the complex nature of groundwater storage and percolation patterns in saprolitic profiles. Under certain circumstances, a notable variation in porewater pressure indicates the presence of a rapid rate in water flow from the crest to the toe of the slope.

Based on the compilation of results from exploratory borehole and geophysical surveys, it can be concluded that the prone landslide areas in this study mostly happened on the weathered granitic rocks. This formation produced Grade V and Grade VI sandy silt residual soils within a thickness of approximately 15 m. Due to the complexities of soil layers, the residual soil layer is commonly characterised by substantial variability of engineering properties as a result of various degree of weathering process.

RAINFALL PATTERN

Based on the data collected previously, the area of interest in this study received about 2440 mm of precipitation annually. Malaysia is a tropical humid country and the rainfall distribution area is recognized by two monsoon seasons. The history of landslide occurrence, shows an agreement between the landslide occurrences and the rainfall characteristics during two monsoon seasons. Over 60% of landslides occurred within the months of April, May, October and November representing both southwest monsoon and northwest monsoon. This signifies a relationship between landslide events the rainfall infiltrations in certain periods of time. Figure 3 below illustrates the distribution of the monthly landslide occurrence of 21 cases in between 1990 and 2011 exclusively in the hilly areas.

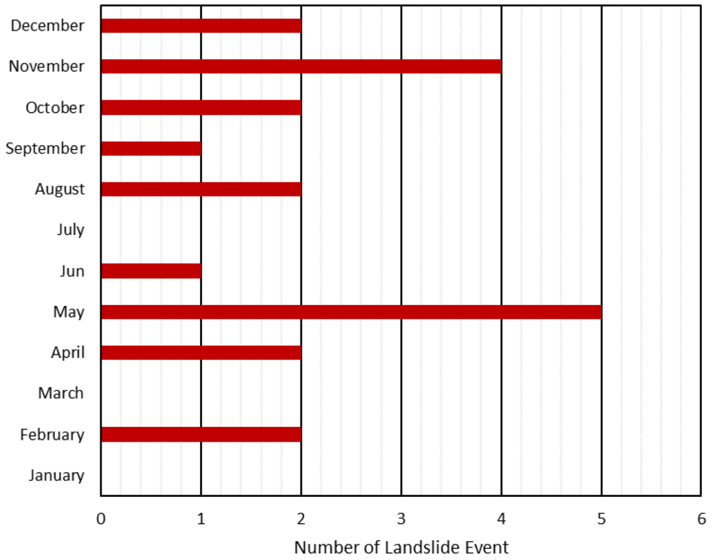

FIGURE 3. Statistic on the month of landslide events (Lee et al. 2014)

In this study, precipitation data of the desired area was obtained from the Department of Irrigation and Drainage, Malaysia (DID). To represent rainfall in the real situation in the study area, calculation of Intensity Duration-Frequency (IDF) Curves, Average Recurrence Interval (ARI) and rainfall depth have been developed as a temporal approach in this study. The IDF curve of 2 ARI, 5 ARI, 10 ARI, 20 ARI, 50 ARI and 100 ARI are depicted in Figure 4 and used for the slope stability analysis.

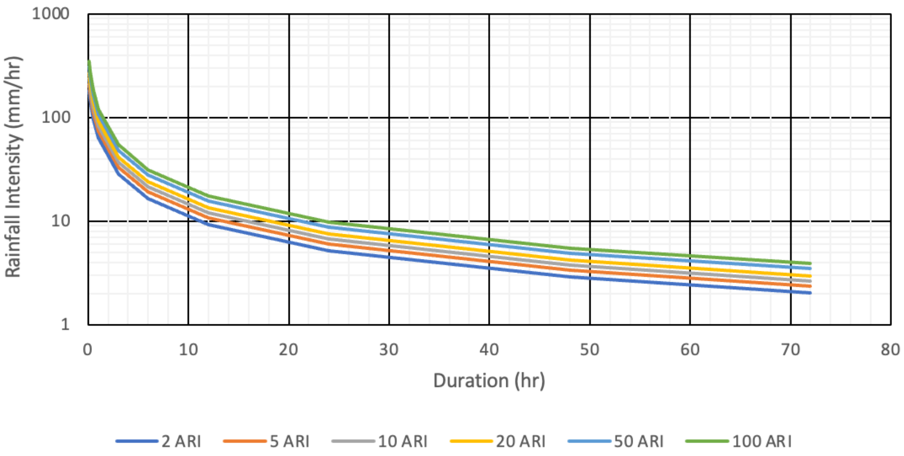

FIGURE 4. The Intensity Duration-Frequency (IDF) curve of the study site

Daily rainfall patterns of the study site were analysed for a duration of 3 months and it was observed that most of the history landslides did not occur on days with the highest recorded daily rainfall. These observations indicate that the quantity of daily precipitation might not be the single variable influencing the stability of slopes. To provide a comprehensive analysis of the influence of prior rainfall on the initiation of landslides, the operational rainfall durations of 1-hour, 1.5-hour, 2-hour, 72-hour, 96-hour, 120-hour, and 144-hour were calculated to establish the pivotal timeframe of antecedent rainfall for the occurrences of landslides.

RESULTS OF SLOPE MODELLING

By using the GeoStudio commercial software, the failure mechanism can be modelled in various situations. In this study, transient numerical seepage analysis was performed in the SEEP/W module and then it was incorporated into the SLOPE/W module to determine the soil slope stability. The height of the slope model was set approximately at 170 m and 230 m in length thus forming an inclination in about 20 degrees. The seepage model consisted of 8285 nodes and 8069 mesh elements, with quadrilateral elements (1m × 1m) utilized throughout all soil layers. The input parameters included in the model were obtained from data acquisition in soil investigation works and the outcomes of IDF curves.

The specification of restricting the presence of negative porewater pressure at the initial water table is defined as no-flow boundaries (Q = 0) located above the groundwater table. To simulate the effect of rainfall, a unit flux (q) equivalent to the intensity of the applied rainfall was utilized to demonstrate infiltration on the sloping surface. The simulation was conducted over a span of 30 days preceding the previous incident of landslides. The initial condition such as the estimated SWCC and hydraulic conductivity function was imposed on each layer of residual soils depicted in Figure 5 considering on-site conditions, however, the minimum suction, y_{min} was assumed to be 60 kPa.

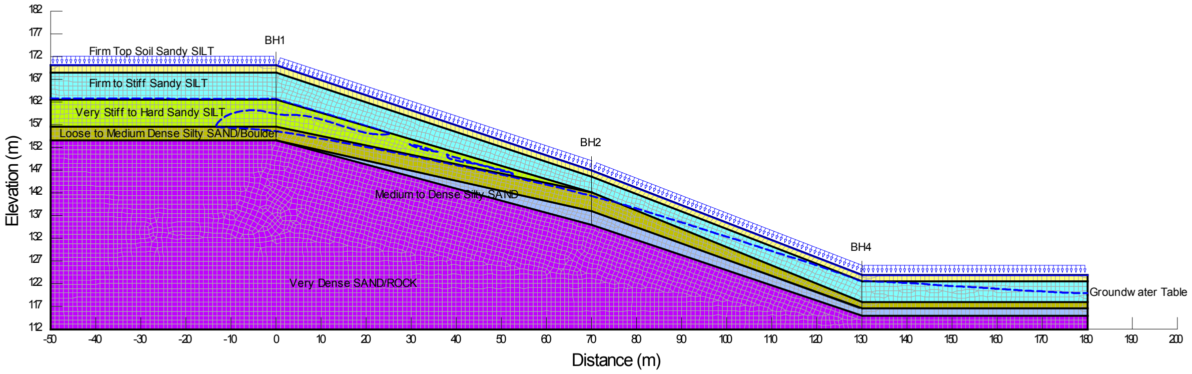

FIGURE 5. The slope model simulated in SEEP/W

Then, the slope stability analysis was performed in SLOPE/W by implementing the Mohr Coulomb model in the simulation as in Figure 6. The frictional resistance angle due to matric suction is represented as $\varphi^{b'}$ and was proposed to be equal to two-thirds of φ'. Other than that, the soil strength properties were specified as effective parameter values for the analysis of effective stress c'≈ 0 kN/m2 and total stress parameter values with $f_u = 0$.

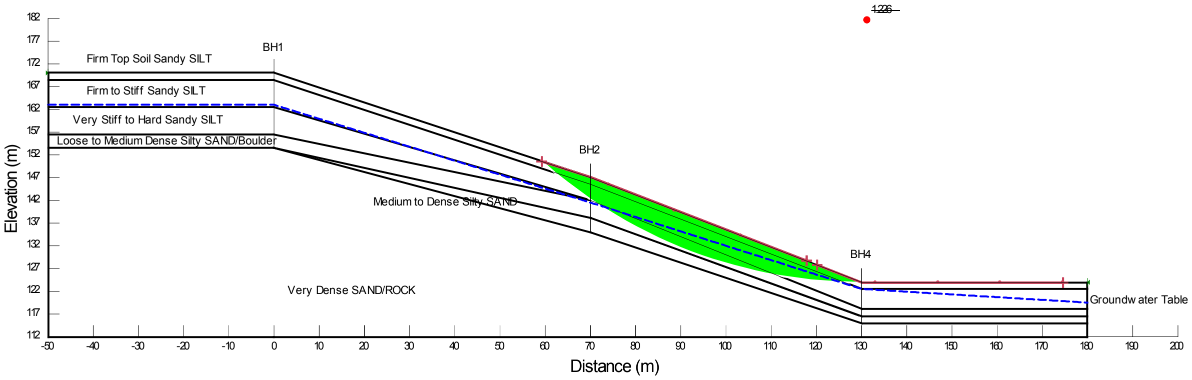

FIGURE 6. The slope model simulated in SLOPE/W

The numerical simulation in SEEP/W analysis shows that the porewater pressures increased gradually over time at the crest (a), middle (b), and toe (c) of the slope as depicted in Figure 7. The changes were observed above the red colour dashed line illustrated on the graph which represents the subsoil condition in the upper 4 m layer at the crest and middle part of the slope as well as the 2 m layer at the toe of the slope. It is important to emphasize that there was no substantial increase in positive porewater pressure above the initial water table during the simulation period, except at the toe whereas a significant rise in groundwater level detected. The initiation of the landslide may have predominantly occurred at the toe due to the reduction of matric suction or the presence of negative porewater pressure within the soil.

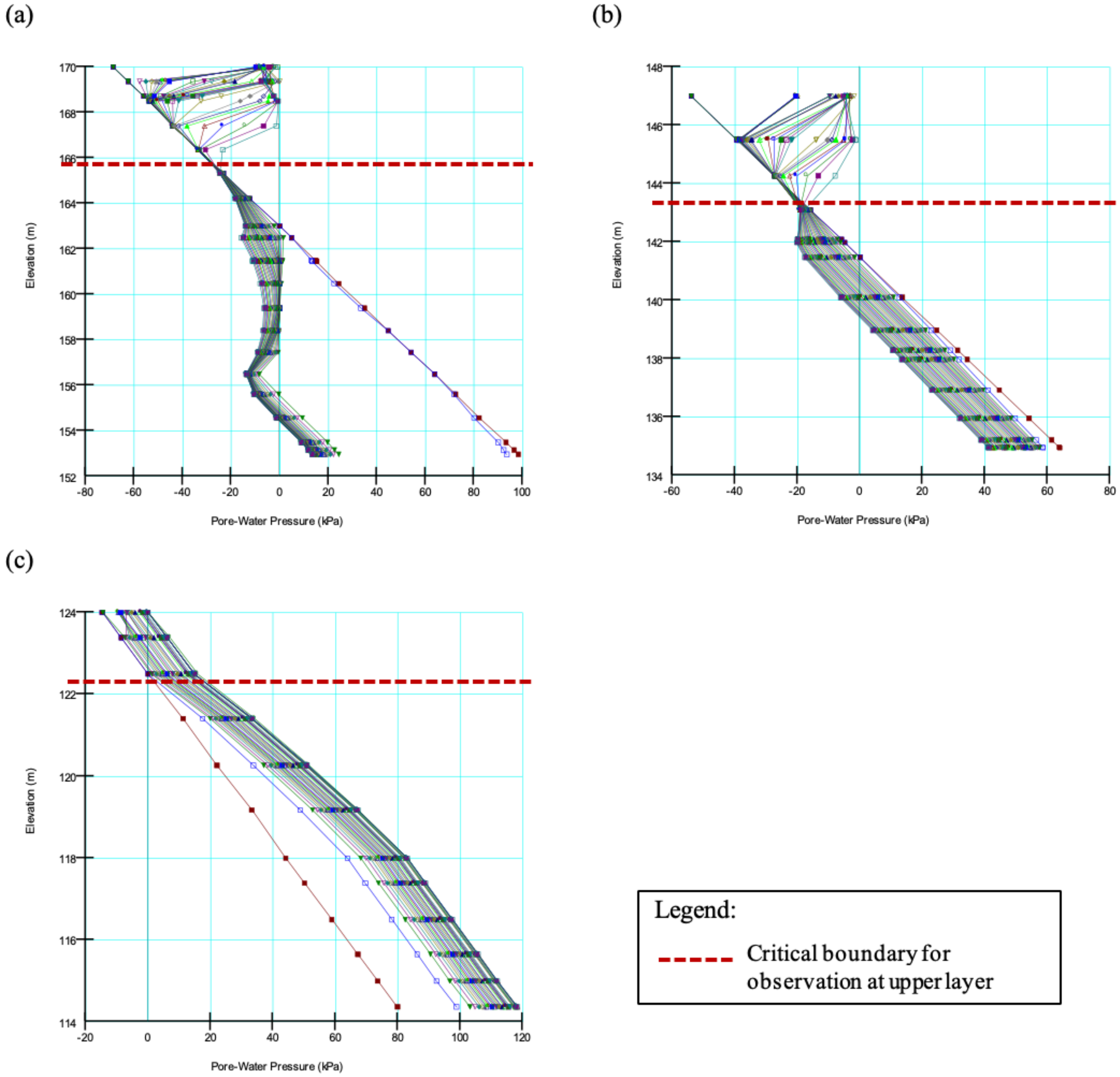

FIGURE 7. The changes of porewater pressure at (a) crest, (b) middle and (c) toe of the slope during a period of 30 days prior to the landslide

The factor of safety (FOS) results during simulation represents the slope stability analysis in three possible features of the failure mechanism which are at the crest, middle and toe. Numerical analysis was computed for the secure slope to have an initial FOS of 1.586, 2.432 and 1.352 at the middle slope, local at the crest and local at the toe, respectively as shown in Figure 8. This demonstrates the most possible failure part of the slope, will be at the toe compared to a deep-seated failure from the crest. The variation in FOS observed over a 30-day period also reveals a comparable pattern to the porewater pressure, in which the FOS shows a gradual reduction.

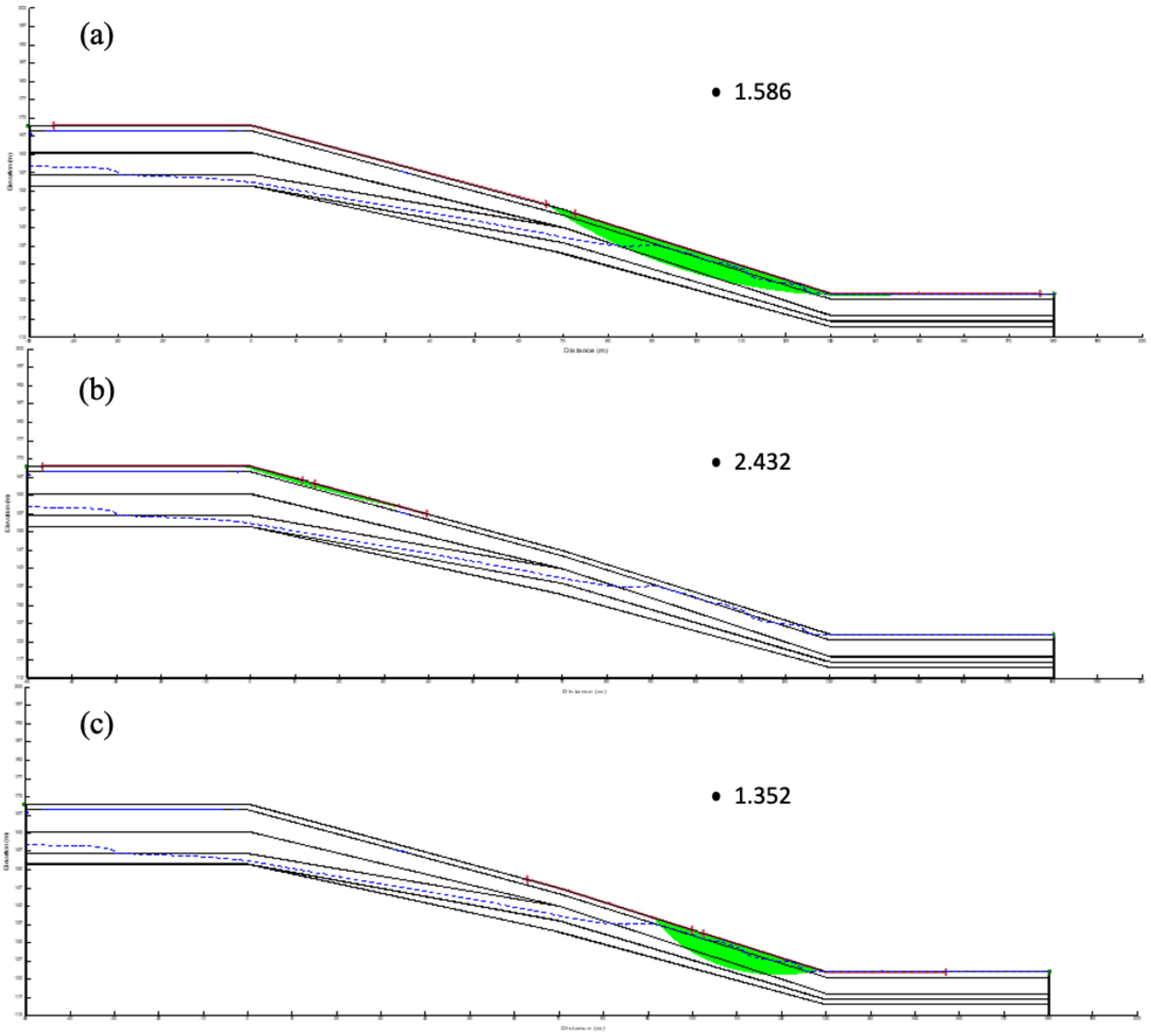

FIGURE 8. The potential failure at global (a), local at crest (b) and local at toe (c)

By considering a period of time prior to the landslide events, 3-month daily rainfall distribution data were observed in this study and it shows that intermittent rainfalls with very high intensity can trigger landslides. Based on the simulation, it can be emphasized that the gradual reduction in the factor of safety was mostly caused by these prolonged antecedent rainfalls and the redistribution of infiltrated rainwater, in which the continuous infiltration increased pore water pressures, reduced matric suction in the unsaturated zone, and raised the overall weight of the soil mass. These processes collectively lowered the effective stress and shear strength of the slope materials, thereby reducing slope stability over time. Furthermore, a landslide is not necessarily triggered by only major rainfall events, instead, the prolonged antecedent rainfall plays a dominant role as a triggering factor.

CONCLUSION

This study focused on the effect of antecedent prolonged rainfall on slope stability that is governed mostly by the weathering process in substrata and rainfall pattern. The general composition at the study site is dominated by in-situ granite produced by the weathering process over time. Soil characterisation and study site data were acquired through borehole method exploration and resistivity method, then all the parameters were set as input in the numerical modelling. As a result, landslides could have mostly been initiated at the toe by the lack of matric suction or negative porewater pressure in the soil.

The findings strongly suggested that amount of the daily rainfall is not the major factor affecting the stability of a slope. Otherwise, cumulative antecedent rainfall is the determining factor in the formation of the landslide mechanism. The other main factor, bedrock geological that underwent the weathering process over time created the heterogeneities in soil layers, thus reducing the strength of the underground formation. The simulation results also confirm that the factor of safety and the matric suction both gradually dropped over time. Moreover, most of the previous landslide incidents that have been observed did not occur during peak daily rainfall.

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DECLARATION OF COMPETING INTEREST

None.

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