Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 9, Special Issue, 2023

"Innovative Strategies in Civil Engineering Grand Challenges"

Relationship of Rainfall Intensity with Slope Stability

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Received 12 September 2022; Revised 07 March 2023; Accepted 23 March 2023; Published 15 April 2023

Abstract

The impact of rainfall on landslides is not an uncommon issue worldwide, including in Malaysia. It is a major challenge for geotechnical engineers to ensure the constructed slope is safe and can sustain longer periods of time, including during heavy rainfall. Kota Belud, Sabah, has been selected as the study area to meet the study objectives. Heavy rainfall has been recorded every year within Kota Belud, which has caused a repetition of landslide occurrences within the hilly areas, especially during the monsoon season. Presently, there is no local procedure for determining the rainfall intensity value for slope stability analysis. This study utilized the rainfall intensity value from Hydrology Procedure 26. Seepage analysis conducted shows rainwater infiltration has caused the groundwater level to increase from rainfall starts until 0.5 m below ground level and decrease after rainfall stops, creating fluctuations in the groundwater level during the wet and dry conditions within the wetting front. The factor of safety of the slope shows a decreasing trend, with a reduction of around 27 to 33% after 24 hours of rainfall in conjunction with the changes in groundwater level. However, the factor of safety increased by around 3% from the initial condition after 48 hours. The objective of this study is to identify the factor of safety of a rainfall-induced slope within Kota Belud utilizing the rainfall intensity design limits from Hydrology Procedure 26.

Keywords: Slope Stability; Rainfall-induced Landslide; Hydrology Procedure 26; Groundwater.

1. Introduction

Rainfall-induced landslides are not uncommon disasters that happen in Malaysia due to the existing climatic conditions of the country, which is located within an equatorial region with tropical rainforest and has two monsoon seasons that are southwest starting from April to October and northeast starting from October until February. Malaysia received an average of 2,250 mm of rainfall annually throughout the country. A landslide is a process that results in the downward and outward movement of a slope that includes rocks, soil, artificial fill, or a combination of these materials. The common triggering factors of landslide occurrence in Malaysia are rainfall, then loading change on the slope, followed by groundwater level change, and finally slope geometry changes [1].

Previous researchers have stressed that most landslides occur because of hydro-climatic effects from prolonged or intense rainfall. The rainwater infiltration into the unsaturated soil increases the active force that causes the slope to fail due to the increase in weight and concurrently reduces the soil suction within the wetted front area in soil. Besides, Yoshida et al. (1991) [2] and Cai et al. (2019) [3] have conducted laboratory tests to prove that the shear strength of unsaturated soil decreases when the matric suction and negative pore pressure reduce, which contribute to a lower factor of safety.

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http://dx.doi.org/10.28991/CEJ-SP2023-09-06

As of now, there is no specific rainfall intensity procedure for the rainfall-induced slope stability analysis in Malaysia. Like other researchers from other countries approached, the researchers used actual rainfall data from nearby rain gauge stations to be incorporated into slope stability analysis without referring to any local procedures available [4, 5]. Hydrology Procedure 26 was developed by the Department of Irrigation and Drainage and contains rainfall intensity data constructed from rainfall data gathered via existing rain gauge stations to provide a guideline in rainfall intensity estimation for East Malaysia. The rainfall intensity data developed in the form of an isopleth map enabled rainfall intensity estimation to be interpolated for all districts, including those that did not have rain gauge stations [4, 6].

However, Hydrology Procedure 26 was developed for hydrologically related design. The utilization of this procedure for slope stability analysis is limited. Thus, this paper aims to determine the relationship between rainfall intensity and Hydrology Procedure 26 utilization for rainfall-induced slope stability in East Malaysia. Kota Belud, Sabah, was chosen for this study, and soil properties were obtained from subsurface investigation.

2. Study Area

Kota Belud is located in the northwest of Sabah and downstream from Mount Kinabalu. It is approximately 75 km away from Kota Kinabalu, the main capital of Sabah, and 82 km away from Ranau. The maximum elevation of Kota Belud is 53 km above sea level. Almost all of Kota Belud is low-lying, with flooding issues every monsoon season. However, Kota Belud is also having hilly terrain, especially in those areas near Mount Kinabalu. Figure 1 shows the location of Kota Belud. The study area had previously undergone slope stabilization due to landslide occurrences that impacted road traffic.

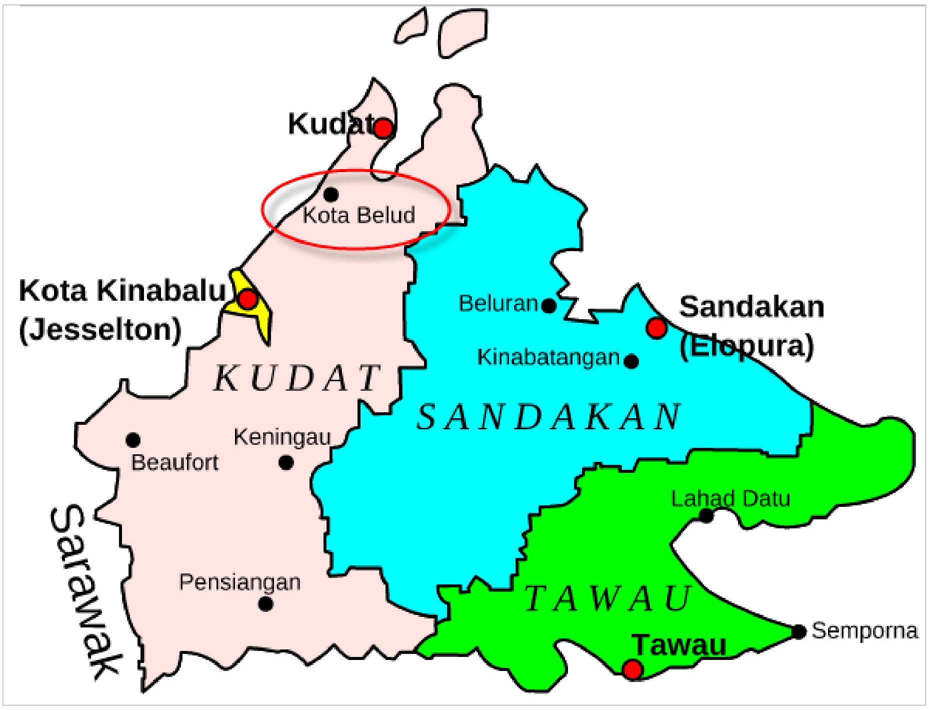


Figure 1. Location of Kota Belud, Sabah, Malaysia

2.1. Rainfall Data from Hydrology Procedure 26

Kota Belud has its own rain gauge station operated by the Department of Irrigation and Drainage Malaysia with station ID 6364001 as per listed in Hydrology Procedure 26. Hydrology Procedure 26 has developed three limits as a guideline for rainfall intensity: the upper limit, the design limit, and the lower limit, with allocations for Average Recurrence Interval (ARI) for 2 years, 5 years, 10 years, 20 years, 25 years, 50 years, and 100 years.

The rainfall intensity limits in each limit were developed for 24 hours, 48 hours, and 72 hours of storm duration, as shown in Figure 2. This storm duration represents the duration of rain. For Kota Belud, the highest rainfall intensity limit is 411.43 mm/hr from the upper limit with 72 hours of storm duration at 100 ARI, and the lowest rainfall intensity limit is 88.37 mm/hr from the lower limit with 24 hours of storm duration at 2 ARI [4].

2.2. Soil Properties from Subsurface Investigation

A subsurface investigation was conducted to identify the soil parameters for the study area. Three boreholes were drilled, with a total depth of 44.14 m for soil boring and 6.00 m for rock coring. Table 1 shows the soil properties obtained from subsurface investigation.

Based on Table 1, the study area shows a high number of sand and gravel, around 72 to 73%. This has indicated that this area is formed from coarse-grained soil. Correspondent to that, the low value of cohesion, ranging from 0.5 to 1.1 kN/m^3, shows a lower amount of cohesive soil presence in this area and a higher value of friction angle.

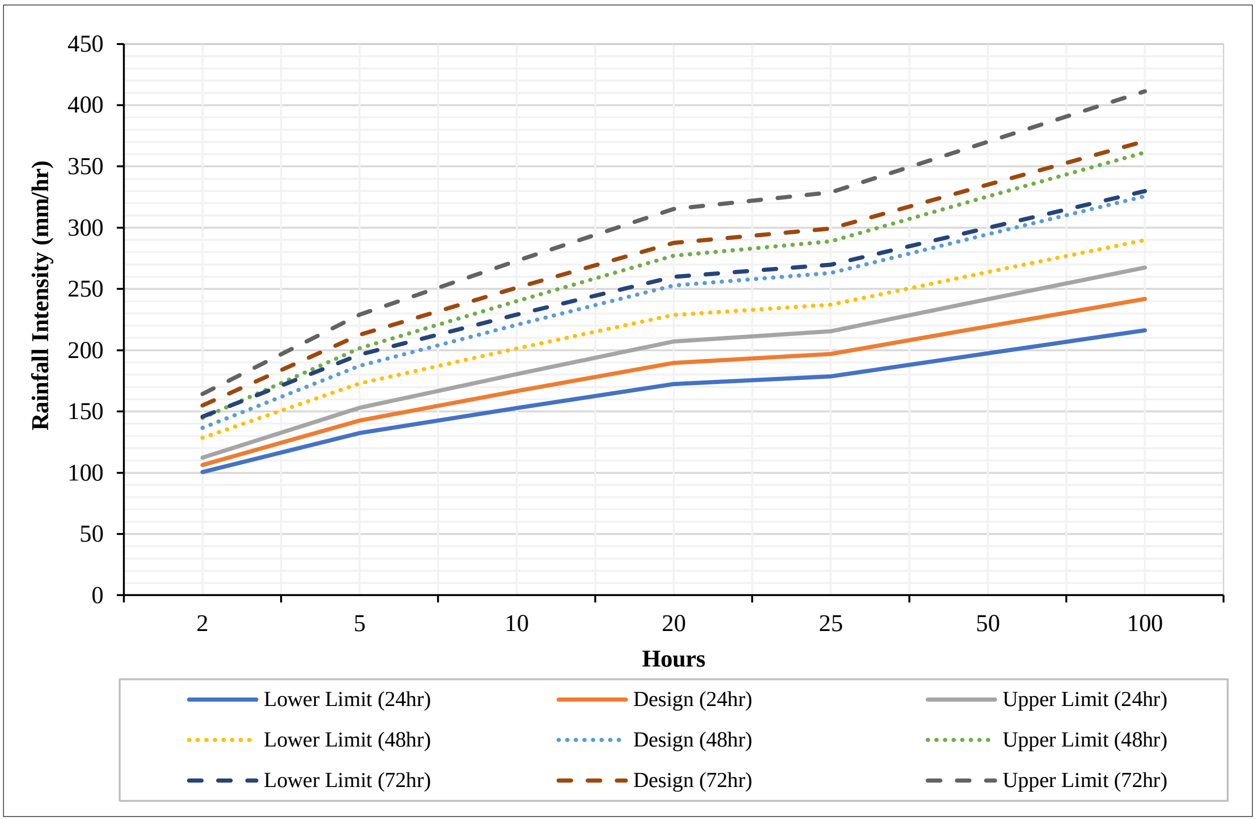


Figure 2. Rainfall Intensity for Kota Belud from Hydrology Procedure 26

Table 1. Soil properties for study area

Soil Properties	Unit	Value
Clay	%	0-17
Silt	%	16-75
Sand	%	7-72
Gravel	%	1-73
Liquid Limit	%	28-54
Plasticity Index	%	9-28
Moisture Content	%	8.52-25.28
Specific Gravity	-	2.59-2.74
Unit Weight	kN/m^3	20.96-21.68
Cohesion	kPa	0.1-1.1
Friction Angle	^{o}	22.61-25.77

The soil profile for the study area consists of three layers. The top layer, with a depth of 15 m, is sandy silt, and the middle layer is silty clay, with a depth of 5 m. While the bottom layer is shale mixed with mudstone. The original groundwater level is approximately two meters below the existing ground level, as measured using a piezometer during the subsurface investigation.

3. Methodology

This study focuses on the numerical modeling and analysis of slope stability to investigate the relationship between rainfall intensity design limits from Hydrology Procedure 26 with slope stability at Kota Belud.

3.1. Soil Parameter

Soil parameters used for the numerical modeling and analysis are shown in Table 1. However, the soil suction parameter for the Soil Water Characteristic Curve (SWCC) is estimated using an equation from Fredlund & Xing [5] utilizing particle size distribution input from subsurface investigation, coefficient of volume compressibility (m_v) from Carter & Bentley [6], and estimated hydraulic conductivity (k_s) from Day (2006) [7] as shown in Table 2.

Table 2. Soil parameter input for SWCC for study area

Parameter	Unit	Value
m_V	m^2/MN	0.0003
k_S	m/s	$5\times10^{-6} - 5\times10^{-4}$

3.2. Rainfall Intensity

Rainfall intensity value obtained from Hydrology Procedure 26 is categorized as Lower Limit, Design Limit, and Upper Limit for Average Recurrence Interval (ARI) of 2 years, 5 years, 10 years, 20 years, 25 years, 50 years, and 100 years, as shown in Figure 2. However, this study only focuses on the design limit as tabulated in Table 3, and this study focuses only on a 24-hour storm duration. The factor of safety of the slope was calculated right after the 24 hours of rainfall and 48 hours. Besides, the fluctuation of groundwater is also recorded for both 24 and 48 hours.

Table 3. Rainfall intensity design limits at Kota Belud

ARI (Year)	Rainfall Intensity (mm/hr)
2	106.4
5	142.7
10	166.7
20	189.7
25	197.0
50	219.5
100	241.9

3.3. Numerical Modelling and Analysis

The limit equilibrium method is used for this study, utilizing GeoStudio software to calculate the slope stability. SLOPE/W and SEEP/W features were used to determine the factor of safety of the slope and the method of slices used, and to analyze the impact of rainfall on groundwater levels that eventually reduce the suction and shear strength of the soil. Figure 3 shows the overall workflow for this study, from data collection to results and discussion.

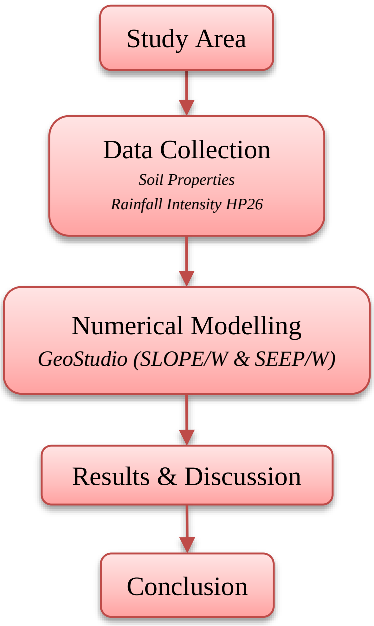
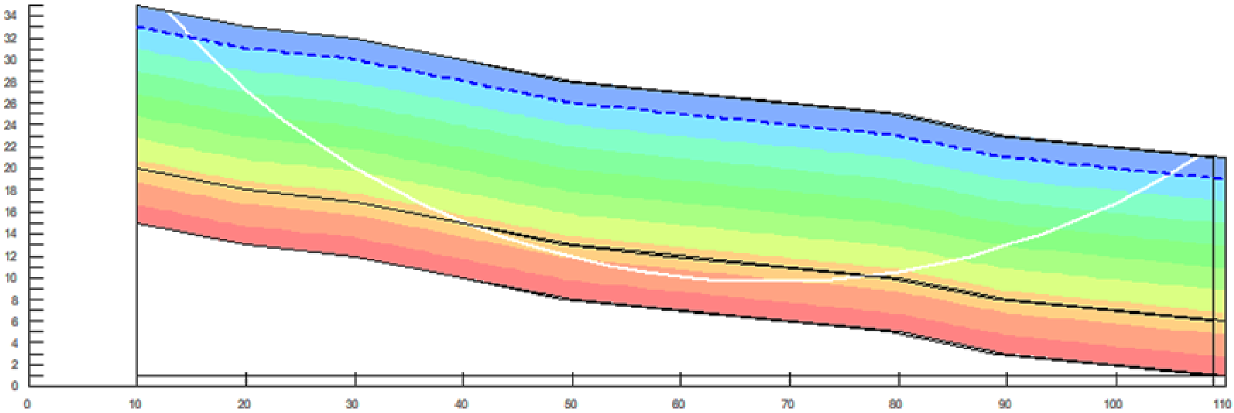


Figure 3. Overall workflow

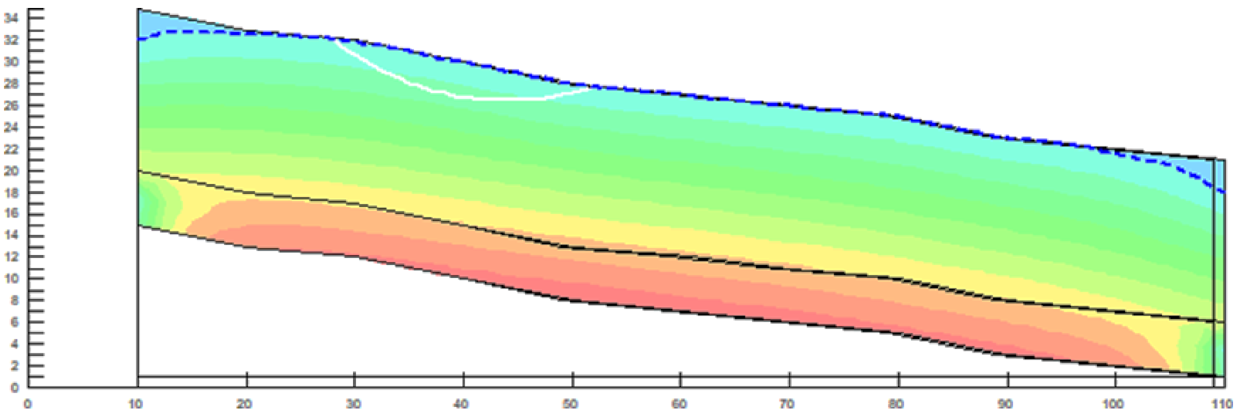
4. Results and Discussion

4.1. Fluctuation of Groundwater

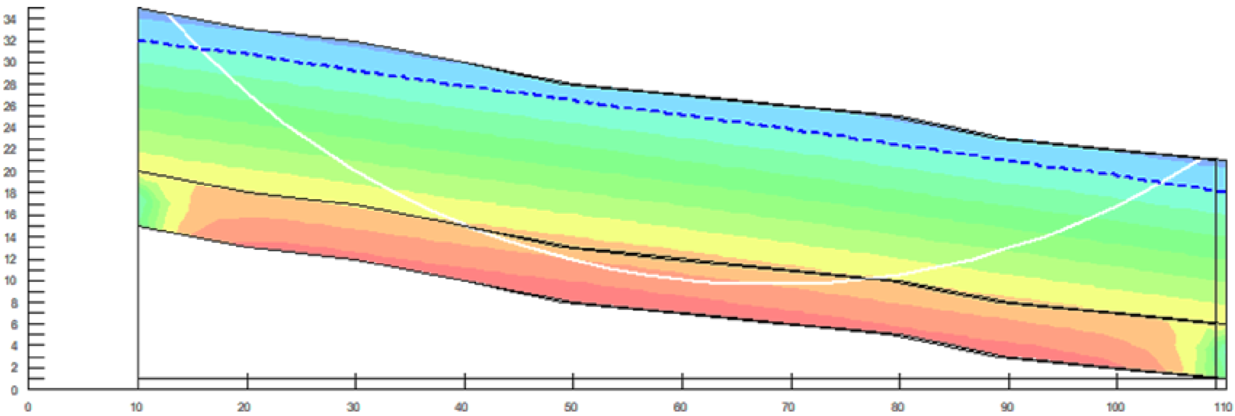
Figure 4 shows the changes in groundwater level in the SEEP/W analysis for 2 years of ARI rainfall. The initial groundwater level for the study area was two meters below ground level, as indicated in Figure 4-a. However, the groundwater level has increased from its initial position and reached almost full saturation based on seepage analysis using SEEP/W due to an increase in pore pressure from rainwater infiltration into the ground starting from the rainfall until the rainfall stopped at 24 hours as per Figure 4-b.



(a)



(b)



(c)

Figure 4. a) Initial groundwater level and slip plane, b) Groundwater level and slip plane after 24 hours rain, c) Groundwater level and slip plane after 48 hours

However, the groundwater level has decreased almost back to its initial range of 1.5 m to 2.5 m after 48 hours, as shown in Figure 4-c. This has indicated that the study area has high permeability that allows the water to be raised and drained within 24 hours during and after a rainfall event, matched with the subsurface investigation that stipulates the presence of high-quality coarse-grained soil in this area.

The groundwater level is also represented through the color contour that shows the level of water presence in soils. The red color shows a high volume of water, while the darker blue color represents otherwise. As the water infiltrates into the ground, the darker color disappears, showing the water content in the soil increasing as shown in Figure 4-b and the color contour returning to its initial condition in Figure 4-c. The white color line shows the slip failure plane with the lowest factor of safety from the Bishop method analysis. The slip failure plane during initial and 48-hour duration shows deeper depth compared to right after 24 hours of rainfall, which shows a shallow slip plane.

Similar results for groundwater level and slip failure plane were obtained for other ARIs. Fluctuation of groundwater levels has impacted the factor of safety of a slope, as agreed by Hemid et al. [8]. The pore pressure of water reduces the soil's effective stresses, which consequently reduce the soil's shear strength. Numerical calculations made by Latief & Zainal [9] show that the factor of safety of a slope reduces as the groundwater level gets shallower. This is due to the loss of suction within the wetting front, which eventually reduces the shear strength.

4.2. Factor of Safety of Slope

The calculation of the factor of safety for a slope was conducted using the SLOPE/W feature in GeoStudio. The calculation of the factor of safety is conducted specifically for slope stability in the original condition with no rainfall, after 24 hours of rainfall, and after 48 hours. The results of the factor of safety against rainfall intensity are shown in Figure 5.

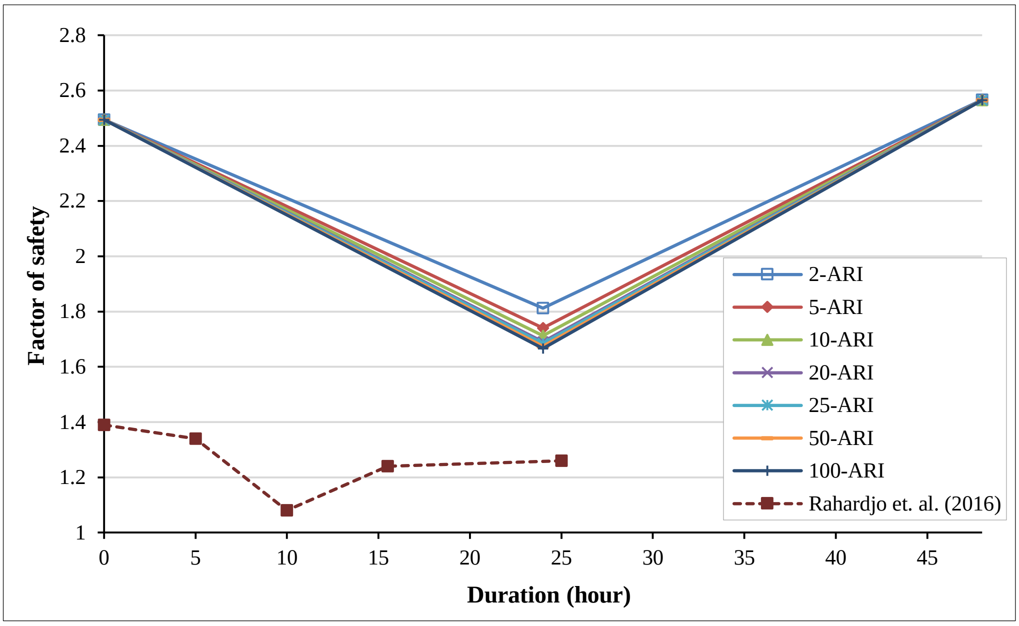


Figure 5. Factor of safety of slope against duration

The comparison with other researchers made by Rahardjo et al. [10] uses 36 mm/hr rainfall obtained from rain gauge stations for 10 hours of rainfall. The slope geometry for Rahardjo et al. [10] is considered steeper, with a slope angle of 27 degrees. Meanwhile, this study has a gentler slope with an average of 20 degrees.

The factor of safety of the slope shows a maximum reduction of around 27% to 33% from the initial condition. Meanwhile, Rahardjo et al. [10] show a maximum reduction of the factor of safety of around 22% from the initial condition. In general, both researchers have indicated a similar trend: that the factor of safety reaches its lowest peak as soon as the rainfall stops and gains stability as the slope gets dry. However, the difference in the overall factor of safety is due to the difference in slope angle. Rahardjo et al. [10] had a steeper slope angle, leading to lower factor safety compared to this study. The factor of safety for this study shows that the study location is having shallow slope failure since the lowest factor of safety was recorded during the slope failure plane, which is shallow at 24 hours, and the factor of safety returns to its original position right after the rainfall stops.

This is interrelated with the fluctuation of groundwater levels. Unsaturated soil remains intact due to its matric suction, which contributes to higher shear strength. Unsaturated soil is affected by rainfall when rainwater infiltrates through a gravity-driven process, affecting the uniform water content and pore water pressure behind the wetting front. The decrease in matric suction is opposed by the increase in pore pressure. Yoshida et al. [2] and Cai et al. [3] have confirmed that the shear strength of unsaturated soil decreases as the matric suction is reduced. Matric suction is the inter-particle force generated by the negative pore pressure. Thus, the inter-particle force is reduced with the increase in pore pressure in soil.

Based on the numerical modeling and analysis, it shows that the slope stability is highly influenced by the rainfall-time history relationship, as agreed by Chen et al. [11]. It means that a landslide triggered solely by rainfall would not happen in a short period of time. Instead, it took some time to initiate the slope before it started to fail into a landslide.

Figure 5 stipulated that the factor of safety of the slope at the study area increased after 48 hours compared to the initial condition by approximately 3% higher. Similar findings were found by Latief & Zainal [9] via the numerical method that the dry condition shows the second highest factor of safety value after groundwater level 0.5 m below ground level. This can be treated as the optimum increase in soil suction because some researchers [12–16] conclude that the increase in pore pressure does not always reduce the shear strength of soil. Besides, soil cohesion and internal friction angle increase as the soil suction increases. However, the increment was found not to be linear. This also shows that during the dry condition, the shallow ground depth has a higher shear strength and factor of safety compared to the deeper ground [17–18]. This is highly dependent on the soil profile layers of slopes, which have different shear strength values for different types of soil.

In summary, the factor of safety of a slope is reduced as the pore pressure increases and reaches its lowest right after the rain stops. Slopes regain their stability as the groundwater level is drained out. However, the factor of safety regained may not be similar to the initial condition.

5. Conclusions

This study demonstrates the relationship of rainfall intensity from Hydrology Procedure 26 with slope stability at Kota Belud. Referring to the results obtained, the following can be concluded:

- Numerical modeling and analysis via SEEP/W show the presence of groundwater fluctuation during wet and dry conditions within the wetting front from the time the rainfall starts until the rainfall stops. The groundwater level tends to increase during the rainwater infiltration as the pore pressure increases until 0.5m below ground level, and it almost reaches a fully saturated condition after 24 hours of rainfall. During this situation, the slip failure plane is shallow due to a loss of matric suction and a reduction of shear strength within the wetting front. However, the groundwater level is decreasing as the rainfall stops approximately 1.5 to 2.5 meters below ground level due to water content loss. The slip failure plane for both the initial condition and after 48 hours of duration shows similar traits, which is a deep circle.
- Based on SLOPE/W analysis, the safety factor of a slope decreases approximately by 27 to 33% after 24 hours of rainfall from the initial condition as the groundwater level increases. The factor of safety increased by approximately 3% from the initial condition, and the groundwater level decreased after 48 hours. This is due to the shear strength being influenced by matric suction in unsaturated soil. The matric suction relationship is reciprocal to the pore pressure. Rainwater infiltrated into the wetting front of soil has increased the pore pressure and will eventually reduce the shear strength of soil when the matric suction decreases. This explained the lower shear strength when rainwater infiltrated the ground and resulted in a lower factor of safety.
- Hydrology Procedure 26 is a useful tool and shall be utilized for slope stability analysis that is related to rainfall-induced landslides as a guideline for the rainfall intensity value with different limits and wider coverage using the isopleth maps concept. This procedure is suitable to be used for rainfall-induced landslide analysis in remote locations with an absence of rainfall data, as this study proves that the data from Hydrology Procedure 26 match with the previous findings that show rainfall is impacting the slope stability of the study area.

6. Declarations

6.1. Author Contributions

Conceptualization, M.H.R. and H.M.M.; methodology, M.H.R.; software, M.H.R.; validation, H.M.M.; formal analysis, M.H.R.; investigation, M.H.R.; resources, M.H.R.; data curation, M.H.R.; writing—original draft preparation, H.M.M.; writing—review and editing, N.B.; visualization, N.S.H.H.; supervision, H.M.M. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Acknowledgements

The author wishes to express gratitude to University Malaysia Sabah (UMS) for the UMSGreat Scheme (GUG0492-1/2020), Department of Irrigation and Drainage Malaysia and Department of Works Sabah for the data provided to support this study.

6.5. Conflicts of Interest

The authors declare no conflict of interest.

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