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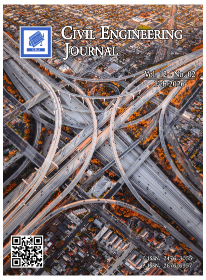

Evaluating Rainfall Effects on Soil Parameters and Slope Stability Using Hydrology Procedure (HP26)

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Abstract

Rainfall-induced slope failures are a major geohazard in tropical regions, often triggered by intense or prolonged rainfall that alters soil strength and pore water pressure conditions. This study evaluates the effects of rainfall duration on slope stability in Kota Belud and Ranau, Sabah, by applying Hydrology Procedure 26 (HP26) rainfall data with numerical modelling using SEEP/W and SLOPE/W under the Limit Equilibrium Method (LEM). Soil parameters were derived from site investigations, with strength values including cohesion (0.5-9.7 kPa) and friction angle (25.7°-30°). The results showed that short-duration rainfall (1 hour) had minimal impact on stability, while prolonged (24-hour) rainfall significantly increased pore water pressure, reducing the factor of safety (FOS) by 25-30%. A localized weak zone in Ranau was identified, with cohesion decreasing from 7 kPa to 5 kPa between 7.4 m and 13.5 m depth, corresponding to potential slip surfaces. Findings align with previous research on infiltration-driven failures, but this study demonstrates the practical use of HP26 rainfall design data for tropical slope analysis. The novelty lies in linking rainfall duration, soil-water interactions, and FOS reduction through a standardized rainfall procedure, providing a framework for improved slope risk assessment in rainfall-prone terrains.

Keywords: Slope Stability; Pore Water Pressure (PWP); Friction Angle; Cohesive Strength; GeoStudio; HP26.

1. Introduction

Slope stability is a critical concern in geotechnical engineering due to its direct implications for infrastructure safety, economic loss, and risk to human life. The stability of natural and engineered slopes is governed by key geotechnical parameters internal friction angle, cohesion, and pore water pressure that collectively determine the soil's shear strength and its ability to resist failure under changing hydrological conditions. Recent studies in Sabah have shown how hydraulic properties of unsaturated soils, including permeability and soil water characteristic curves, strongly influence slope response under long antecedent rainfall [1].

Similarly, Kumar et al. [2] integrated steady state and transient analyses under climate change scenarios, demonstrating that rainfall infiltration can reduce the factor of safety significantly. Xia et al. [3] provided a global sensitivity analysis linking effective rainfall to slope stability through unsaturated flow models, confirming that rainfall duration and amount are key drivers in reduced shear strength. In tropical embankments, Lalicata et al. [4] found that saturation profiles and the degree of saturation cause measurable changes in stability. Also, Espinosa Fuentes et al. [5] quantified how prolonged rainfall duration leads to heightened pore water pressure build-up and slope destabilization.

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Rainfall, one of the most dominant triggering mechanisms, elevates pore water pressure, reduces matric suction, and consequently decreases effective stress, leading to increased susceptibility to slope failure. In Malaysia, rainfall induced landslides are a recurrent hazard, particularly during the southwest and northeast monsoon seasons, with annual rainfall averaging 2,250 mm. Although various studies have examined landslide occurrences in tropical regions, there remains no standardized national procedure that explicitly links rainfall intensity with slope stability analysis.

To address this gap, the Department of Irrigation and Drainage Malaysia developed Hydrology Procedure 26 (HP26), which provides isopleth-based rainfall intensity estimates for design purposes. However, its application in slope stability analysis remains limited, and few studies have validated its suitability for predicting rainfall-triggered slope failures in Sabah. This research fills that gap by using HP26 data in combination with numerical modelling (GeoStudio SLOPE/W and SEEP/W) to evaluate slope stability under 1-hour and 24-hour rainfall durations.

The study sites representative of rainfall-prone hilly terrains in Sabah were selected based on historical landslide occurrences and data availability. This paper aims to quantify changes in pore water pressure, cohesive strength, and friction angle; compare responses across short and long duration rainfall events; and contribute to improved risk mitigation strategies for slope design in tropical environments.

2. Research Area

Kota Belud and Ranau, located in northern Sabah, Malaysia, were selected as study areas due to their high susceptibility to rainfall-induced landslides and the availability of reliable rainfall and soil data. Kota Belud is historically one of the most landslide-affected districts, with multiple failures recorded during the 2015 monsoon season that damaged roads and disrupted communities. A study conducted by Rosly et al. [6] utilized rainfall intensity data from Hydrology Procedure 26 (HP26) to assess slope stability in the area. The findings indicated that rainwater infiltration caused fluctuations in the groundwater level, which in turn affected the factor of safety of the slopes. Specifically, a reduction of approximately 27 to 33% in the factor of safety was observed after 24 hours of rainfall, highlighting the significant impact of rainfall on slope stability in Kota Belud.

Ranau, situated in a mountainous setting, experienced severe landslide activity following the 2015 earthquake and during subsequent monsoons. Both locations represent critical terrains where rainfall-triggered slope failures have resulted in infrastructure damage and socioeconomic losses, making them highly relevant for rainfall-based slope stability assessment. A study by Matlan et al. [7] analyzed ten landslide events in Ranau between 2007 and 2015, focusing on the effects of hourly rainfall intensity, cumulative antecedent rainfall, and soil water index (SWI) on slope stability. The research concluded that both short-duration intense rainfall and prolonged antecedent rainfall significantly contributed to landslide occurrences in the region. The study emphasized the need for proper scientific assessment of rainfall patterns to predict and mitigate future landslide events in Ranau.

Figure 1 illustrates the geographical context of the study sites within Malaysia, showing their location relative to Kota Kinabalu and surrounding districts. It is recommended to supplement this with photographs of typical slopes and rainfall-affected areas at both sites, providing visual evidence of slope conditions. Future versions should also label elevations, slope angles, and geomorphological features to better contextualize site characteristics.

Figure 1. Location of Kota Belud and Ranau, Sabah

2.1. Soil Behavior Parameters from Field Investigation

An underground investigation was performed to obtain the relevant soil parameters for the research area. The comparison between Kota Belud and Ranau reveals notable differences in soil properties. Kota Belud exhibits a wider range of soil textures, with clay content between 0-17%, silt 16-75%, sand 7-72%, and gravel 1-73%, indicating a highly heterogeneous composition. In contrast, Ranau shows more consistent values, with clay at 17-20%, silt 28-39%, sand 31-34%, and gravel 10-21%. Table 1 presents the soil characteristics derived from subsurface exploration.

Table 1. Soil Properties for Research Area

Parameter	Kota Belud	Ranau
Clay (%)	0-17	17-20
Silt (%)	16-75	28-39
Sand (%)	7-72	31-34
Gravel (%)	1-73	10-21
Liquid Limit (%)	28-54	32-35
Plastic Limit (%)	13-26	9-29
Plasticity Index (%)	9-28	18
Moisture Content (%)	8.52-25.28	8-15
Specific Gravity	2.59-2.74	2.69-2.70
Unit Weight (kN/m³)	20.96-21.68	21.1-22.8
Cohesion (kPa)	0.5-1.1	3.49-9.7
Friction Angle (°)	22.61-25.77	29.55-34.47

The findings reveal that both Kota Belud and Ranau exhibit relatively low natural moisture content. Specifically, moisture levels in Kota Belud range from 12.2% to 17.9%, whereas Ranau shows slightly lower values, between 8.3% and 11.6%. These variations suggest underlying differences in local site conditions, such as rainfall infiltration capacity or environmental factors affecting the soil's ability to retain moisture. Ranau displays more stable geotechnical properties with higher cohesion and friction angle, while Kota Belud shows greater heterogeneity in soil texture and lower strength parameters, making it potentially more susceptible to rainfall induced instability.

2.2. Design Rainfall Data as Provided by Hydrology Procedure 26

Kota Belud is equipped with a rain gauge station managed by the Department of Irrigation and Drainage Malaysia, identified as Station ID 6364001 in Hydrology Procedure 26. Similarly, Ranau is monitored through Station ID 5966003. Hydrology Procedure 26 has developed three limits as a guideline for rainfall intensity: Upper Confidence Limit, Estimated Design Rainstorm, and Lower Confidence Limit, with allocations for Average Recurrence Interval (ARI) for 2 years, 5 years, 10 years, 20 years, 25 years, 50 years, and 100 years [8].

Rainfall intensity thresholds for each return period were established based on storm durations of 24, 48, and 72 hours, as illustrated above in Table 2. These durations reflect the length of rainfall events. In Kota Belud, the maximum recorded rainfall intensity is 411.43 mm/hr, corresponding to the upper limit at a 72-hour storm duration with a 100-year Average Recurrence Interval (ARI). The minimum intensity is 88.37 mm/hr, derived from the lower limit at a 24-hour duration with a 2-year ARI. In comparison, Ranau's highest rainfall intensity is 338.80 mm/hr under the same storm duration and ARI, while its lowest is 99.20 mm/hr at the 24-hour duration with a 2-year ARI [8]. These values highlight the variability in extreme rainfall patterns between the two locations.

Table 2. Estimated Design Rainstorm for Long Durations

State	Station ID	Station Name	Analysis	Duration (hr)	Rainfall (mm)						
					2	5	10	20	25	50	100
Sabah	6364001	Kota Belud JPS	Upper Confidence Limit	24	112.24	152.94	180.5	207.09	215.54	241.61	267.51
				48	144.79	201.58	240.04	277.15	288.94	325.31	361.46
				72	164.27	229.05	272.93	315.26	328.71	370.2	411.43
			Estimated Design Rainstorm	24	106.4	142.7	166.7	189.7	197	219.5	241.9
				48	136.6	187.2	220.7	252.9	263.1	294.5	325.7
				72	154.9	212.7	250.9	287.6	299.2	335.1	370.6
			Lower Confidence Limit	24	100.52	132.38	152.85	172.34	178.5	197.47	216.26
				48	128.43	172.89	201.45	228.65	237.25	263.71	289.94
				72	145.61	196.32	228.91	259.93	269.75	299.93	329.84
Sabah	5966003	Ranau JPS	Upper Confidence Limit	24	105.23	147.03	175.34	202.65	211.33	238.09	264.7
				48	136.54	188.42	223.57	257.48	268.25	301.49	334.52
				72	156.71	213.86	252.58	289.93	301.8	338.41	374.79
			Estimated Design Rainstorm	24	99.2	136.5	161.1	184.8	192.3	215.4	238.4
				48	129.1	175.3	205.9	235.3	244.6	273.3	301.8
				72	148.5	199.4	233.2	265.5	275.8	307.4	338.8
			Lower Confidence Limit	24	93.19	125.91	146.94	166.95	173.28	192.76	212.06
				48	121.59	162.21	188.31	213.16	221.02	245.2	269.16
				72	140.24	184.99	213.74	241.11	249.77	276.41	302.8

2.3. The Correlation Between Rainfall Intensity and Slope Stability in Kota Belud and Ranau

The analysis of the estimated design rainstorm data for both 1 hour and 24 hour durations across different Average Recurrence Intervals (ARI) reveals notable trends in slope stability, as indicated by the Factor of Safety (FOS) values.

Table 3. Estimated Design Rainstorm for Kota Belud

		1 hour	24 hours
ARI 2	FOS	2.304	2.329
	Friction Angle	25.77	25.77
	Cohesion	1.1	1.1
ARI 5	FOS	2.279	2.291
	Friction Angle	25.77	25.77
	Cohesion	1.1	1.1
ARI 10	FOS	2.253	2.268
	Friction Angle	25.77	25.77
	Cohesion	1.1	1.1
ARI 20	FOS	2.243	2.246
	Friction Angle	25.77	25.77
	Cohesion	1.1	1.1
ARI 25	FOS	2.206	2.241
	Friction Angle	25.77	25.77
	Cohesion	1.1	1.1
ARI 50	FOS	2.154	2.225
	Friction Angle	25.77	25.77
	Cohesion	1.1	1.1
ARI 100	FOS	2.154	2.214
	Friction Angle	25.77	25.77
	Cohesion	1.1	1.1

Table 3 reports the Factor of Safety (FOS) for slopes subjected to design rainstorms with Average Recurrence Intervals (ARI) from 2 to 100 years, evaluated for 1-hour and 24-hour durations. Across all cases, the friction angle and cohesion are fixed at 25.77° and 1.1 kPa, respectively. FOS declines as ARI increases; for the 1-hour event, it decreases from 2.304 (ARI 2) to 2.154 (ARI 100), and for the 24-hour event, from 2.329 to 2.214 over the same range, indicating that rarer, more severe storms pose greater stability risks. Duration effects show FOS values for 24-hour storms are consistently higher than for 1-hour storms at every ARI, implying that short, intense rainfall is more detrimental to stability than longer storms of the same ARI.

Mechanistically, brief high-intensity bursts can rapidly elevate pore water pressures and promote failure, whereas longer events tend to infiltrate more deeply but at a slower rate, permitting gradual dissipation of pore pressures and preserving higher shear strength. This behavior is consistent with the higher FOS observed for 24-hour storms in the table and accords with prior findings; Rosly et al. [6] noted a 27-33% FOS reduction after 24 hours of rainfall, underscoring the role of infiltration in weakening slopes, and with work in Frontiers in Earth Science showing deterioration of stability with increased peak rainfall duration. Collectively, these studies reinforce the need to incorporate detailed rainfall intensity duration characteristics in slope stability assessments, particularly in regions exposed to extreme events.

Table 4. Estimated Design Rainstorm for Ranau

		1 hour	24 hours
ARI 2	FOS	2.377	2.562
	Friction Angle	29	29
	Cohesion	5	5
ARI 5	FOS	2.349	2.558
	Friction Angle	29	29
	Cohesion	5	5
ARI 10	FOS	2.341	2.556
	Friction Angle	29	29
	Cohesion	5	5
ARI 20	FOS	2.338	2.554
	Friction Angle	29	29
	Cohesion	5	5

ARI 25	FOS	2.331	2.553
	Friction Angle	29	29
	Cohesion	5	5
ARI 50	FOS	2.325	2.551
	Friction Angle	29	29
	Cohesion	5	5
ARI 100	FOS	2.325	2.550
	Friction Angle	29	29
	Cohesion	5	5

Evaluation of the design storm scenarios shows a progressive decline in the Factor of Safety (FOS) with increasing Average Recurrence Interval (ARI), evidencing the adverse influence of higher rainfall intensities on slope stability. The drop is noticeably steeper for the 1-hour cases, indicating that short-duration, high-intensity events are more destabilizing than longer storms at the same ARI. For the 24-hour inputs, FOS also decreases but more gradually, consistent with slower, deeper infiltration that allows partial pore pressure dissipation, though a pronounced reduction emerges at ARI 100, suggesting cumulative saturation, elevated pore water pressures, and attendant strength loss over extended wet periods.

With friction angle and cohesion fixed, these patterns implicate rainfall forcing, rather than changes in intrinsic shear strength parameters, as the primary driver. The trends align with Rahardjo et al. [9], who reported progressive weakening under prolonged infiltration, and Iverson [10], who showed that brief, intense rainfall can rapidly raise pore water pressures and trigger failure. Overall, the results confirm an inverse FOS-rainfall intensity relationship and underscore the need for robust slope management in rainfall-prone regions.

2.4. Previous Study and Research Gap

Previous research was screened and analyzed to identify the gap related to rainfall induced landslides to identify the research gap. Table 5 shows the summary of the research gap for this study.

Table 5. Previous Study and Research Gap

No.	Researcher	Title	Description	Gap Identified
1	Rosly et al. (2022) [11]	An Overview: Relationship of Geological Condition and Rainfall with Landslide Events at East Malaysia.	In conclusion, both regions are vulnerable to landslides because of the significant average rainfall and the geological characteristics, specifically shale interbedded with sandstone, which are prone to landslide events.	The goal of this research is to examine the association between landslides and geological conditions and rainfall in Ranau, Sabah, and Canada Hill Miri, Sarawak.
2	Rosly et al. (2023) [6]	Relationship of Rainfall Intensity with Slope Stability.	The goal of this research is to use numerical modeling and analysis to determine the correlation between the rainfall intensity design constraints from Hydrology Procedure 26 and slope stability at Kota Belud.	This research aims to assess the factor of safety for a rainfall-induced slope in Kota Belud by utilizing the rainfall intensity design thresholds specified in Hydrology Procedure 26.
3	Awang Ismail et al. (2023) [12]	Numerical modelling of slope stability and transient seepage analysis: Jalan Puncak Borneo Road case study.	This study aimed to provide a method of slope stability analysis using Limit Equilibrium Method utilizing GeoStudio feature Slope/W and Seep/W with presence of rainfall and earthquake.	The main methodology for the factor of safety analysis is performed through numerical modelling using GeoStudio with soil properties input from the soil investigation activities.
4	Rahardjo et al. (2016) [13]	Effects of Rainfall Characteristics on the Stability of Tropical Residual Soil Slope.	The research was conducted to analyse the relationship of historical rainfall data with soil slope and to understand the rainfall characteristics in Singapore.	This study is based on rainfall data obtained from existing rain stations around Singapore Island, which will be used in slope analysis.
5	Matlan et al. (2018) [7]	Effect of working rainfall and soil water index on slope stability in Ranau, Sabah.	The study aimed to investigate the methods for assessing the effectiveness of rainfall and soil water index in predicting landslide events in Ranau, Sabah.	This study focuses on the laboratory test on the Soil Water Index to determine the influence of rain from antecedent and significant rainfall, as well as Open 19 protracted rainfall. Rainfall data was obtained from existing rain gauge records provided by municipal authorities. Numerical analysis was not employed to verify the outcomes of the laboratory experiments.
6	Tohari et al. (2007) [14]	Laboratory rainfall-induced slope failure with moisture content measurement.	The research was conducted to investigate the flow type of slope failures with different moisture content.	This research focused on laboratory tests to define a mode of failure of slope based on the moisture content that is interrelated with its pore pressure. Numerical analysis is not performed to validate the findings and the factor of safety is not clearly mentioned to relate with the failure.
7	Suhaimi & Selaman (2013) [15]	A Study on Correlation Between Pore Pressure, Rainfall and Landslide Occurrence	The study was conducted to investigate the relationship between rainfall and pore water pressure that contributes to landslides in Bau, Sarawak.	This research focuses on the correlation between the variables that leads to landslide which are rainfall and pore water pressure. Numerical analysis is not performed to verify the finding made based on direct comparison between the variables and landslide occurrence.
8	Abd Rahim & Raffee Usli (2017) [16]	Slope Stability Study around Kampung Kuala Abai, Kota Belud, Sabah, Malaysia.	The research conducted to determine mode of failures, factor of safety and suggested slope mitigations at Kota Belud, Sabah. Geological approach is used to determine the slope stability such as the kinematic analysis.	This research focuses on the geological impact of slope towards the factor of safety. The analysis used is different compared to Limit Equilibrium method. The factor of safety calculation refers to the geological characteristic and no contributing factor is discussed that cause landslide occurrence.
9	Rahimi et al. (2011) [17]	Effect of Antecedent Rainfall Patterns on Rainfall Induced Slope Failure.	The research conducted was related to rainfall-induced landslides attributed from antecedent rainfall at Singapore. The objective of this research is to determine the effect of antecedent rainfall patterns on the stability of slopes. The analysis was performed using the GeoStudio Seep/W feature with selected rainfall data from an online monitoring source.	The research conducted focused on two types of soil which are High Conductivity and Low Conductivity residual soils. The origin of the soils tested is not discussed properly and might be random sample have been taken for the analysis.

3. Research Methodology

This research emphasizes numerical modeling and slope stability analysis to examine the correlation between rainfall intensity design thresholds outlined in Hydrology Procedure 26 and slope stability conditions in Kota Belud and Ranau.

3.1. Rainfall Intensity and Soil Parameter

The rainfall intensity data provided by Hydrology Procedure 26 are classified into three categories: Lower Limit, Design Limit, and Upper Limit, across multiple Average Recurrence Intervals (ARI) of 2, 5, 10, 20, 25, 50, and 100 years, as illustrated in Table 2. For this study, only the Estimated Design Rainstorm values were utilized, specifically under a 24 hours storm duration, as summarized in Table 6. Slope stability was assessed by calculating the factor of safety following both 1 hour and 24 hours rainfall periods. Additionally, variations in the groundwater table were monitored for both durations to evaluate the hydrological response of the slope system.

Table 6. Rainfall Intensity Estimated Design Rainstorm for Research Area

ARI (Year)	Rainfall Intensity (mm/hr) Kota Belud	Rainfall Intensity (mm/hr) Ranau
2	106.4	99.2
5	142.7	136.5
10	166.7	161.1
20	189.7	184.8
25	197.0	192.3
50	219.5	215.4
100	241.9	238.4

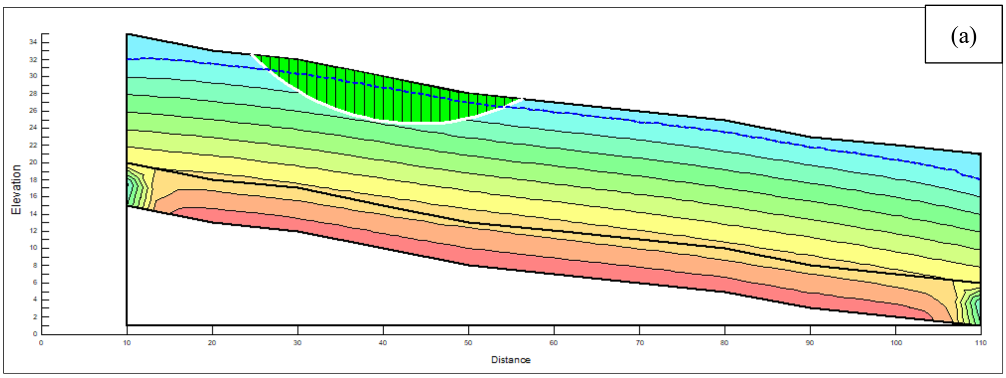
3.2. Numerical Modelling and Analysis

This study employs the Limit Equilibrium Method (LEM) using GeoStudio software to evaluate slope stability. The SLOPE/W and SEEP/W modules were applied to compute the factor of safety through the method of slices and to assess the influence of rainfall infiltration on groundwater levels, which subsequently reduces matric suction and the shear strength of the soil. Although numerical modelling was conducted using SLOPE/W and SEEP/W, model calibration was constrained by limited availability of in situ monitoring data. To enhance reliability, soil parameters were cross validated with laboratory test ranges reported in recent studies in Sabah (Nassor et al. [1]; Rosly et al. [6]). However, a full back analysis of documented failures was not feasible within this study. Sensitivity analyses on cohesion and permeability values were also not included, but are strongly recommended in future work to test model robustness and convergence. These steps would provide additional confidence in the predictive capability of rainfall induced slope failure simulations.

4. Results and Discussion

4.1. Pore Water Pressure

The graph illustrates the variation of pore water pressure (kPa) with distance (m) for ARI2 and ARI100 across two rainfall durations 1 hour and 24 hour for the Kota Belud. In the 1 hour duration (Figure 2-a), the blue dotted line representing pore water pressure (PWP) appears lower, indicating limited rainfall infiltration and reduced soil saturation during this shorter duration event.



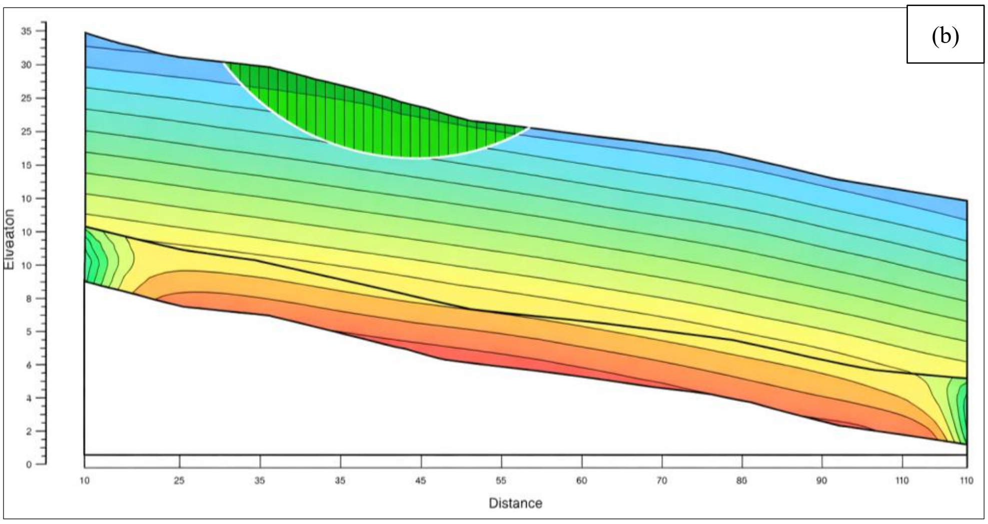


Figure 2. Pore Water Pressure Condition at (a) 1 Hour; and (b) 24 Hours Duration for Kota Belud

Under short duration rainfall conditions, lower pore water pressure contributes to maintaining higher shear strength, thereby enhancing slope stability. In contrast, during the 24 hours rainfall scenario (Figure 2(b)), the blue dotted line rises markedly, indicating substantial water infiltration and elevated soil saturation. This increased saturation reduces effective stress, elevates pore water pressure, and consequently diminishes the shear strength of the soil, leading to a higher likelihood of slope failure. The comparison clearly demonstrates that extended rainfall duration (24 hour) induces significantly higher pore water pressure levels than shorter events (1 hour), resulting in a more pronounced reduction in slope stability. These findings are consistent with prior research by Ng & Shi [18], Griffiths & Lane [19], and Collins & Znidarcic [20].

In Figure 3-a, the blue dotted line illustrates the pore water pressure (PWP) profile following a 1 hour rainfall event. Its lower position within the soil profile indicates limited infiltration and low saturation, which is expected given the short duration, allowing minimal water absorption by the soil. As a result, the unsaturated zone remains dominant, and capillary rise has not substantially affected the deeper soil layers. This condition favors higher slope stability due to reduced pore pressure within the soil matrix.

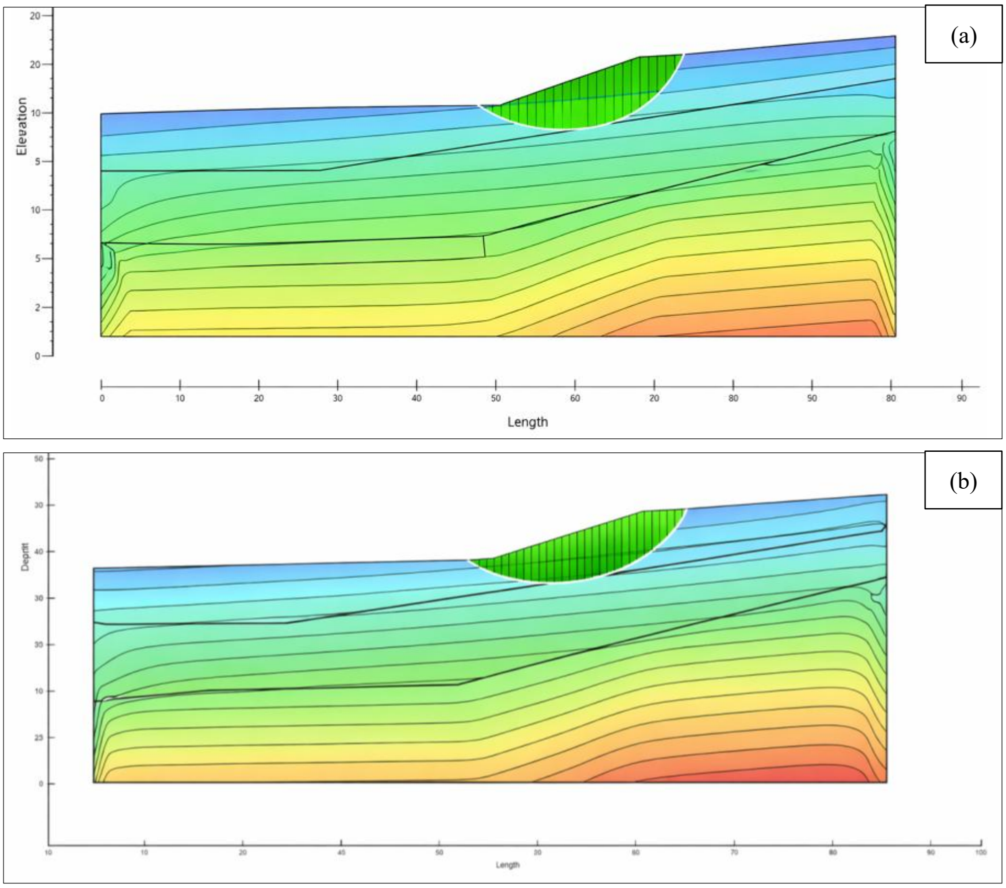


Figure 3. Pore Water Pressure Condition at (a) 1 Hour; and (b) 24 Hours Duration for Ranau

Conversely, Figure 3-b shows a significantly elevated blue dotted line, representing the PWP after 24 hours of continuous rainfall. The extended infiltration period enables deeper water penetration, resulting in increased saturation across a greater soil depth. This rise in PWP is particularly pronounced within the critical slip surface, where it reduces effective stress and compromises slope stability. The elevated pore pressure lowers the shear strength of the soil, increasing susceptibility to slope failure.

The comparison between the two figures clearly demonstrates the influence of rainfall duration on pore water pressure behavior. While the 1 hour rainfall event results in minimal PWP development due to limited infiltration, the 24 hours event leads to substantial increases in pore pressure, particularly within zones prone to failure. These observations are consistent with previous studies by Ng et al. [21], Wang et al. [22], and Peng et al. [23], which collectively emphasize the significant role of prolonged rainfall in enhancing PWP and reducing slope stability.

4.2. Friction Angle

Figure 4 presents a comparison of the friction angle (25.77°) at various distances for Kota Belud under two rainfall conditions: 1 hour and 24 hour durations. Notably, the friction angle remains uniform at 25.77° across all measured points in both scenarios, indicating no observable changes in shear strength related to either spatial variation or rainfall duration. This consistency suggests a homogenous soil profile along the investigated section, with frictional resistance unaffected by short term or prolonged rainfall exposure in this dataset.

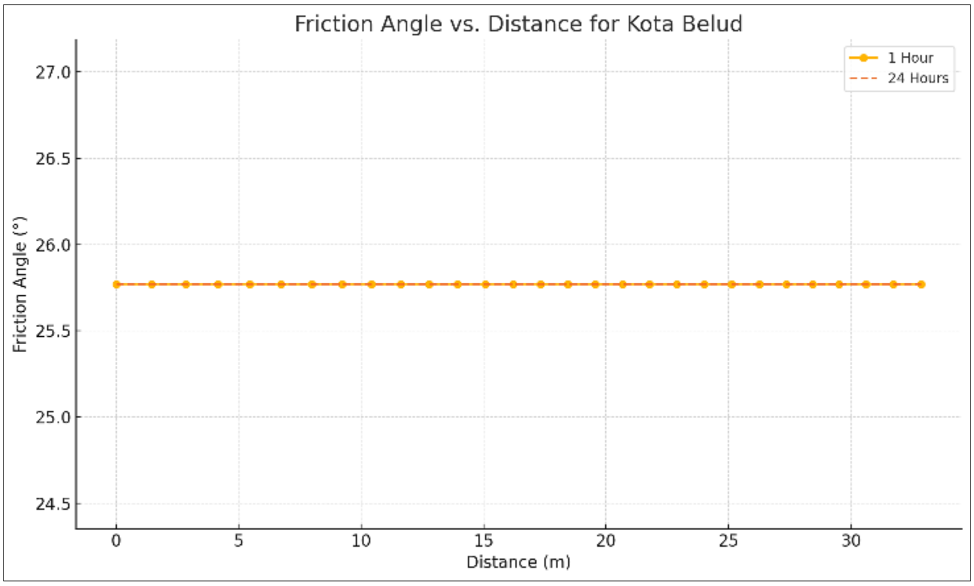


Figure 4. Comparison of Friction Angle for Kota Belud (1 Hour vs. 24 Hours Duration)

The observed consistency in friction angle suggests that, in this case, external influences such as rainfall duration do not affect the soil's internal frictional resistance. As the friction angle is a critical parameter in determining slope stability, its uniformity implies that any variations in slope response are likely attributed to other factors such as changes in pore water pressure, soil cohesion, or overall hydrological conditions rather than alterations in friction angle alone.

However, as noted by Rahardjo et al. [24], even when the friction angle remains unchanged, slope stability can still be significantly affected by increases in pore water pressure and reductions in soil cohesion during rainfall events. Similarly, Li et al. [25] highlighted that slope failures may occur despite a constant friction angle, driven by elevated pore pressure and decreased effective stress. These findings reinforce the importance of evaluating multiple interacting soil parameters when analyzing slope behavior under rainfall influence.

Meanwhile for the Ranau, the friction angle distribution is presented in the graph above comparing values over distance for both 1 hour and 24 hours rainfall durations. The data reveal a consistent trend across both durations, with the friction angle maintaining a value of 30° at initial distances. A reduction to 29° occurs beyond approximately 7 meters and persists until around the 14 meter mark, after which the friction angle resumes a constant value of 30°. This pattern is identical in both the 1 hour and 24 hours scenarios, indicating that the duration of rainfall has no significant effect on the friction angle in this particular dataset (Figure 5).

The localized decrease to 29° suggests the presence of a weaker soil zone or a variation in subsurface conditions, potentially influenced by differences in moisture content, material composition, or other geotechnical properties. The absence of variation between the two durations implies that short term and moderate duration rainfall does not significantly alter the internal friction angle at Ranau within the timeframe considered.

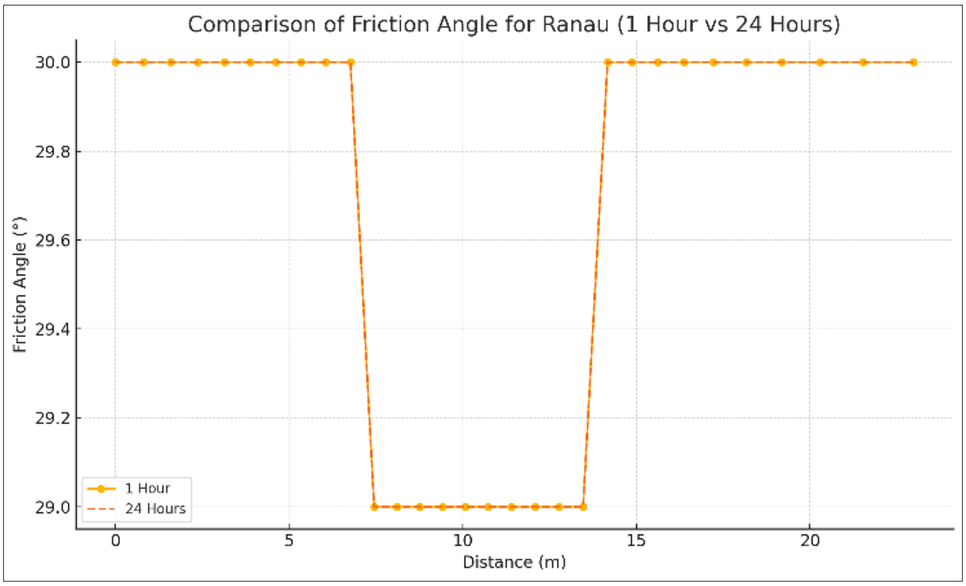


Figure 5. Comparison of Friction Angle for Ranau (1 Hour vs. 24 Hours Duration)

These findings align with observations by Fredlund et al. [26], who noted that the friction angle in unsaturated soils generally remains stable over short periods unless subjected to extensive environmental changes, such as sustained saturation or repeated loading. This supports the interpretation that, in this context, the friction angle is relatively time-independent under the tested conditions.

4.3. Cohesive Strength

Figure 6 illustrates the comparison of cohesive strength at Kota Belud for both 1 hour and 24 hours rainfall durations across varying distances. The cohesive strength consistently remains at 1.1 kPa for both scenarios, indicating that the duration of rainfall has no observable effect on soil cohesion within this dataset. This uniformity suggests that the soil possesses inherently low cohesion, which may increase its vulnerability to shear failure, especially under saturated conditions.

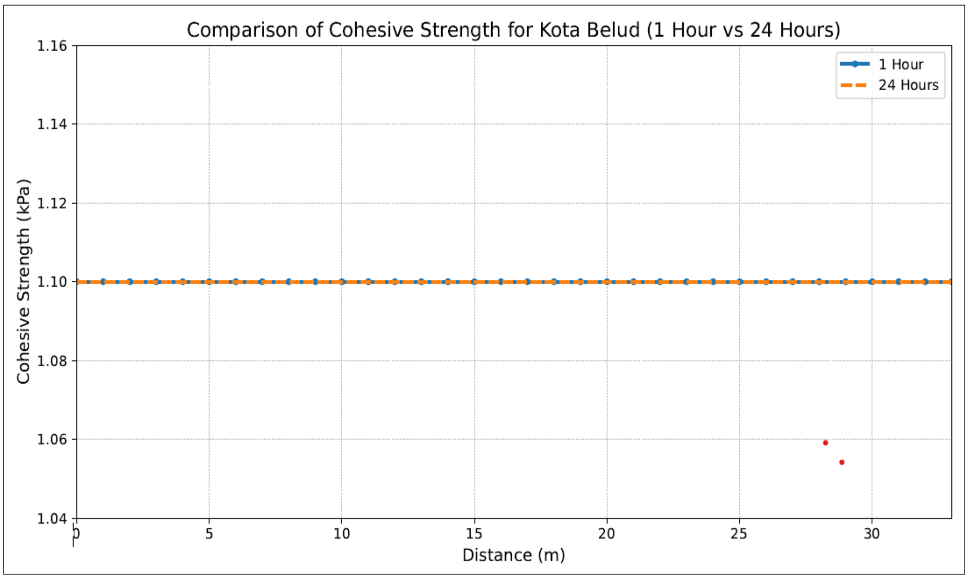


Figure 6. Comparison of Cohesive Strength for Kota Belud (1 Hour vs. 24 Hours Duration)

The consistent cohesion value of 1.1 kPa indicates that the soil at Kota Belud does not experience significant cohesion reduction with prolonged rainfall exposure. This behavior is characteristic of soils dominated by silt or loose sand, which typically exhibit naturally low cohesion. As cohesion is a key component of shear strength and plays an essential role in slope stability, its persistently low value across both rainfall durations suggests that potential slope failures in this area are more likely driven by variations in pore-water pressure and effective stress, rather than by direct loss of cohesive strength.

Here is the graph showing the comparison of cohesive strength for Ranau under 1 hour and 24 hours rainfall durations. The cohesive strength remains constant at 7 kPa across most of the profile, except between approximately 7.4 m and 13.5 m, where it decreases to 5 kPa for both durations. This localized reduction suggests a zone of weaker soil cohesion, likely due to changes in moisture content or soil structure. The consistency between the two durations indicates no time dependent variation in cohesive strength within the observed timeframe (Figure 7).

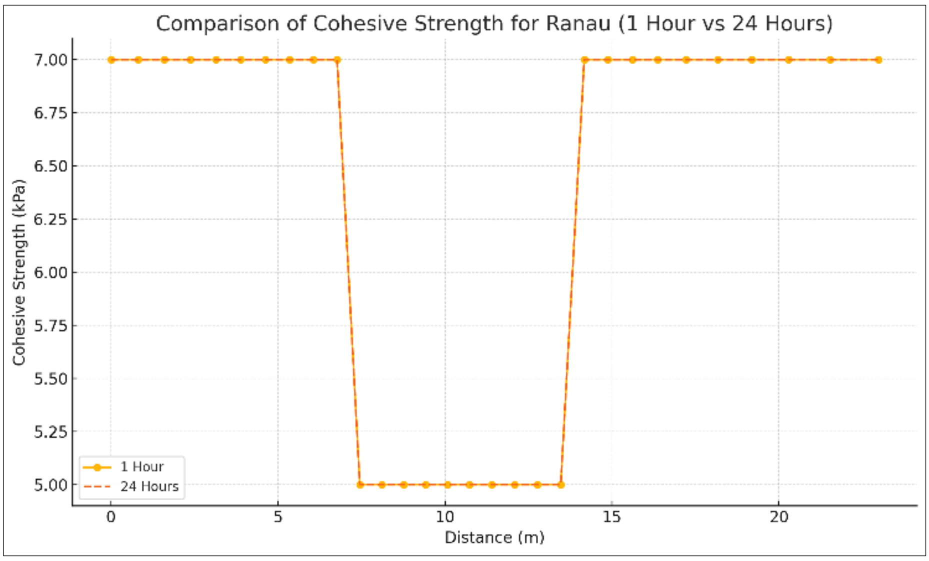


Figure 7. Comparison of Cohesive Strength for Ranau (1 Hour vs. 24 Hours Duration)

The localized cohesion reduction in Ranau (from 7 kPa to 5 kPa between 7.4-13.5 m) coincides with weathered volcanic deposits and colluvium typically found in the area. Such geomaterials exhibit lower shear strength under saturation, aligning with geomorphological evidence of shallow translational slides documented in the district. These findings align with Rahardjo et al. [9] and Iverson [10], who demonstrated that prolonged infiltration elevates pore water pressures, while short, intense rainfall events trigger immediate shallow failures. Quantitatively, the ~25-30% reduction in FOS observed here is consistent with Rosly et al. [6], who reported a 27-33% reduction after 24 hours of rainfall in Kota Belud.

5. Conclusion

This research examined the influence of rainfall duration on slope stability at Kota Belud and Ranau, Sabah, using Hydrology Procedure 26 (HP26) rainfall data integrated with SEEP/W and SLOPE/W under the Limit Equilibrium Method (LEM). The results demonstrated that rainfall duration strongly affects pore water pressure responses and stability conditions. In Kota Belud, prolonged 24 hour rainfall caused a significant rise in pore water pressure, leading to a 25 30% reduction in FOS compared to short duration rainfall. In Ranau, the friction angle remained relatively constant (29 30°), but a critical weak zone was identified where cohesion dropped from 7 kPa to 5 kPa between 7.4m and 13.5m depth, indicating a potential slip surface. These findings confirm that pore pressure buildup, rather than changes in friction angle, is the dominant factor influencing slope instability under rainfall infiltration.

The results are consistent with previous studies (Iverson [10]; Awang Ismail et al. [12]; Rahardjo et al. [13]), reinforcing the mechanism of infiltration induced destabilization. The novelty of this study lies in validating HP26 as a practical design tool for rainfall based slope analysis in tropical conditions. However, limitations remain, including the absence of detailed calibration data, limited sensitivity testing, and no explicit consideration of antecedent soil moisture. Future studies should incorporate field monitoring, parameter sensitivity analyses, and seasonal rainfall effects to improve model reliability. Overall, the study provides new insights into rainfall slope interactions in Sabah and supports safer slope design and landslide risk mitigation in tropical regions.

5.1. Limitations and Future Work

This research was subject to several limitations that should be acknowledged. First, rainfall infiltration and pore water pressure responses were modeled using input data from HP26 and soil investigations, but the absence of long term field monitoring limited calibration and validation of the model outputs. Second, the study assumed homogeneous soil layers at each site, whereas natural slopes often exhibit spatial heterogeneity and structural discontinuities that may further influence stability. Third, sensitivity analyses on soil strength parameters (cohesion, friction angle, and permeability) were not performed, which may restrict the robustness of the results. Additionally, the modelling did not explicitly account for seasonal antecedent moisture conditions, which are known to significantly affect slope response to rainfall. Future studies should therefore integrate continuous in situ monitoring, sensitivity analyses of critical soil parameters, and scenario testing under projected climate change rainfall patterns. These steps would strengthen the predictive capability and reliability of rainfall induced slope stability assessments.

6. Declarations

6.1. Author Contributions

Conceptualization, H.A.O. and H.M.M.; methodology, H.A.O.; software, H.A.O.; validation, H.M.M., N.M., and N.S.A.A.; formal analysis, H.A.O.; investigation, H.A.O.; resources, H.A.O.; data curation, H.A.O.; writing—original draft preparation, H.M.M.; writing—review and editing, N.F.N. and M.H.R.; visualization, N.M. and N.S.A.A.; 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

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6.4. Acknowledgments

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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