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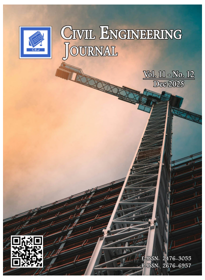

Quantifying Slope Stability and Landslide Susceptibility Through Rainfall-Induced Geotechnical Assessment

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Abstract

Landslides are a major hazard to people and infrastructure, especially in areas with weak geology and high rainfall. This study examined soil properties and slope stability in Ranau (RNU) and Kota Belud (KB), Sabah. Soil tests showed that RNU had 2–21% clay with cohesion of 3.49–9.7 kPa, while KB soils contained 2–17% clay, more sand and gravel, and much lower cohesion of 0.5–1.1 kPa, indicating weaker strength and higher permeability. Rainfall data from 2013–2023, provided by the Malaysian Meteorological Department, were used to develop Intensity-Duration-Frequency (IDF) curves. Results showed that 1-hour intensities increased from 0.92 mm/hr at ARI-2 to 2.18 mm/hr at ARI-100, reflecting the variation of extreme rainfall. Slope stability was analyzed using GeoStudio's SEEP/W and SLOPE/W to simulate infiltration and compute the Factor of Safety (FOS). In RNU, FOS rose from 2.481 to 2.565 after 24 hours, showing stable slopes. In KB, FOS declined from 2.495 to 2.379 under ARI-100 rainfall, along with higher pore-water pressures. Both slopes remained above the safe limit of 1.50, but KB proved more vulnerable to long rainfall. Compared with earlier studies, this research introduces a decade-long dataset combined with numerical modelling to demonstrate the dynamic response of tropical slopes. The findings provide practical contributions to slope design, drainage management, and disaster risk reduction in regions experiencing similar climatic and geological conditions.

Keywords: Sabah; MetMalaysia; Slope Stability; Rainfall; Factor of Safety.

1. Introduction

Landslides are recognized as one of the most critical natural hazards worldwide, posing severe threats to both human safety and infrastructure. Globally, they affect an estimated 3.7 million square kilometers of land and endanger nearly 300 million people, representing about 5% of the total population [1]. Beyond the immediate loss of life and property, landslides often disrupt transportation networks, damage utilities, and cause long-term economic and environmental impacts. In tropical regions, where intense rainfall and steep terrain are common, the risk of slope failure is particularly acute. Malaysia, with its complex geological formations and humid equatorial climate, is especially vulnerable to landslides. Events have been recorded in diverse settings ranging from highland mountains and steep valleys to riverbanks and even low-lying coastal areas [2]. This broad distribution illustrates the pervasive nature of the hazard across the country. Majid (2020) [3] reported approximately 21,000 landslide-prone sites throughout Malaysia, with 16,000 in Peninsular Malaysia, 3,000 in Sabah, and 2,000 in Sarawak. These figures not only highlight the widespread occurrence of slope failures but also emphasize their potential to disrupt socioeconomic development, threaten critical infrastructure, and degrade natural ecosystems. Consequently, Malaysia remains one of the Southeast Asian countries most exposed to rainfall-induced landslide disasters.

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Several interrelated factors contribute to the occurrence of landslides, including geological setting, climatic conditions, slope gradient, vegetation or land cover, and human activities such as deforestation, road construction, and uncontrolled hillside development. Among these, rainfall and geological characteristics are widely recognized as the most critical external and internal triggers, respectively [4]. Prolonged or high-intensity rainfall increases pore water pressure within the soil, reduces effective stress, and weakens shear strength, ultimately leading to slope instability. Rahardjo et al. (2007) [5] confirmed this in their study on homogeneous soil slopes, demonstrating that rainfall infiltration increases pore pressure and reduces matric suction, which directly decreases shear strength and overall slope stability. These findings highlight the strong link between rainfall, infiltration, and slope failure, explaining why tropical regions frequently experience rainfall-induced landslides. In contrast, geological factors such as weak lithology, highly weathered formations, and the presence of discontinuities or faults define the inherent susceptibility of a slope to failure. In Malaysia, landslides occur most often during the monsoon season, when rainfall can exceed 700 mm per month [6]. Figure 1 shows major landslide locations across different states [7], reflecting the country's rugged topography and heavy seasonal rainfall, which make it especially prone to both gradual and sudden slope failures that threaten lives, infrastructure, and the environment.

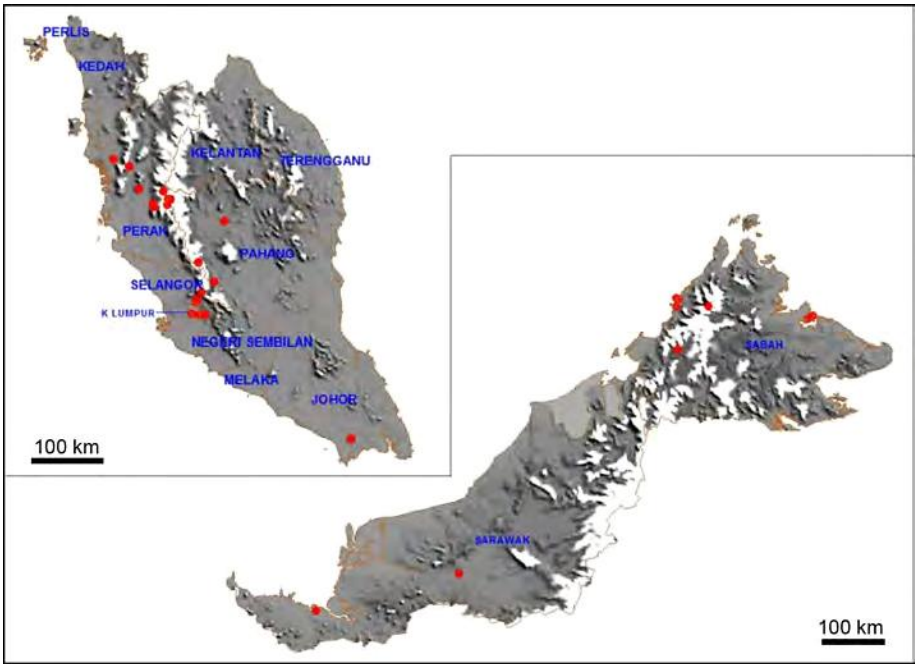

Figure 1. Locations of major landslides in each state of Malaysia

Recent studies in Sabah and other tropical regions have reinforced the importance of rainfall thresholds and soil variability in influencing slope stability. Ligong et al. (2022) [8] identified both short-duration and cumulative rainfall as significant triggers of landslides in Ranau, while Roslee & Tongkul (2018) [9] highlighted the role of highly weathered geological formations in increasing susceptibility to slope failures in mountainous areas. Similarly, Ayu Sufiah Khairul & Musta (2022) [10] reported that soils derived from the Trusmadi Formation exhibit high plasticity and compressibility, making them especially vulnerable to rainfall-induced instability. Despite these valuable contributions, there remains a lack of studies that combine long-term rainfall records with detailed soil property investigations to quantify their combined influence on slope stability in Sabah. This research gap limits the ability to accurately evaluate the dynamic relationship between rainfall, soil behaviour, and the factor of safety (FOS) in landslide-prone areas.

In light of this gap, the present study focuses on Ranau and Kota Belud, two districts identified as high-risk landslide-prone areas. The paper is structured as follows: Section 2 describes the study area and data sources, including soil investigations and rainfall records from 2013 to 2023. Section 3 presents the research methodology, with emphasis on the development of Intensity-Duration-Frequency (IDF) curves and numerical slope stability modelling using SEEP/W and SLOPE/W. Section 4 discusses the results of soil properties analysis and slope stability simulations under varying rainfall scenarios and provides a comparative discussion with previous studies while Section 5, concludes with recommendations for slope management and hazard mitigation strategies in Sabah.

2. Study Area

Sabah, located on the island of Borneo in Malaysia, is particularly susceptible to landslides due to its complex topography of mountains, valleys, and coastal plains. Its steep and irregular terrain, combined with unstable geological formations and a documented history of slope failures, creates a high-risk environment for landslide occurrence [11].

Geological mapping is essential for identifying slope instability in mountainous areas of Sabah, where highly weathered formations and steep topography increase the risk of landslides [9]. Within Sabah, Ranau and Kota Belud have been identified as critical landslide-prone districts, consistent with the findings of Rosly et al. (2022) [12]. Ranau, situated in the interior region of Sabah, is known for its mountainous landscapes and is home to Mount Kinabalu, the highest peak in Malaysia. Previous research by Sharir et al. (2019) [13] documented the recurrence of slope failures in Kundasang, where 494 landslides were recorded, including 92 incidents in 1984, 284 in 2009, and 118 in 2012. These figures demonstrate the persistent nature of landslide hazards in the district.

The rugged terrain and steep slopes, coupled with intense rainfall, have frequently disrupted local communities, transportation networks, and tourism activities. Heavy rainfall was recorded in Ranau and Kota Belud, which typically receive between 60 and 100 inches of precipitation annually [14], as shown in Figure 2. This map represents the long-term mean annual rainfall distribution in Sabah, illustrating historical averages over multiple years rather than short-term variations. The patterns observed here provide valuable context for understanding rainfall-induced slope hazards. In fact, rainfall thresholds in Ranau have been identified as major triggers, with both short-duration intense rainfall and long-duration cumulative rainfall capable of initiating slope failures [8]. Similarly, studies confirm that increases in rainfall and soil water index significantly reduce the factor of safety of slopes in Ranau, indicating high rainfall sensitivity [15]. Kota Belud, located along the northern coast of Sabah and bordering the South China Sea, features a mix of steep terrains, rolling hills, and lowlands. Although not a designated highland region, several areas within the district are prone to slope failures. The presence of human settlements, agricultural land use, and expanding road networks on unstable slopes further elevate the risk of landslides. Clayey soils from the Trusmadi Formation in Bundu Tuhan, which extends into parts of Kota Belud, also exhibit high plasticity and compressibility, making them highly susceptible to rainfall-induced instability [10, 16].

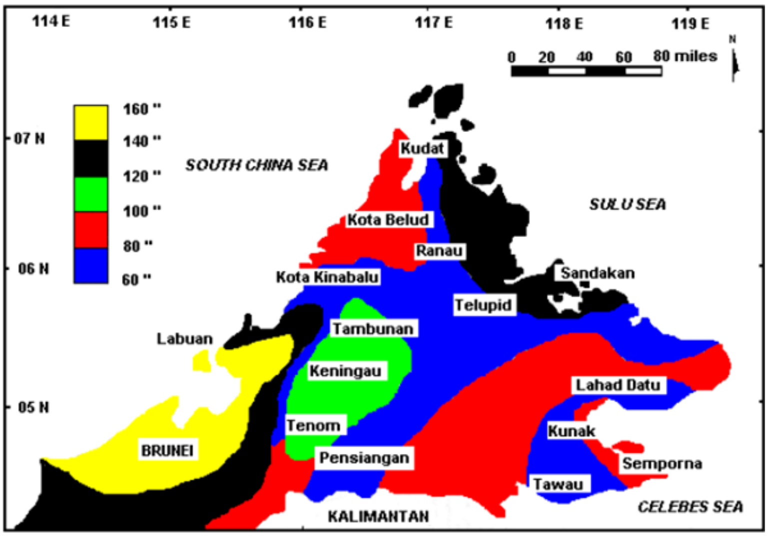

Figure 2. Distribution of Sabah mean annual rainfall

Exacerbating this risk is Sabah's tropical climate, characterized by high annual rainfall. The monsoon season, from November to February, brings particularly intense rainfall, while the dry season lasts from March to October. This climatic pattern further heightens landslide vulnerability. Increased rainfall intensity can significantly reshape the landscape and trigger larger volume landslides [17]. Walsh et al. (2013) [18] warned that rising frequencies of extreme daily rainfall events—exceeding 100 mm and even 200 mm—could escalate landslide occurrences if such trends continue. Correspondingly, Akter et al. (2019) [19] and Matlan et al. (2018) [20] emphasized that the correlation between rainfall intensity and landslides is well-established, with high seasonal rainfall commonly acting as the main trigger for slope failures. As rainwater infiltrates the soil, it increases saturation, reduces shear strength, and compromises soil stability.

Over the years, both Ranau and Kota Belud witnessed a rise in landslide incidents, significantly affecting transportation networks, housing areas, and agricultural lands. Table 1 shows recent landslide events in Ranau and Kota Belud that demonstrate the ongoing risks faced by these districts. On 30 January 2023, a landslide at KM167.9 in Hutan Simpan Taviu blocked the Ranau–Sandakan Road, leaving it impassable until clearing work was carried out. On 23 September 2023, several hours of heavy rain caused landslides, mudflows, and flash floods in Ranau, damaging roads including the route to Mesilau resort. In June 2024, continuous rainfall triggered landslides on Mount Kinabalu, where debris entered the Mesilau River and threatened the Liwagu River water supply. Residential areas were also affected: on 12 January 2025, a landslide struck a house in Kampung Pituru Darat, Kota Belud, forcing nine people to evacuate, while on 16 January 2025, a homestay in Kundasang was damaged by slope failure.

Table 1. Landslide event in Ranau and Kota Belud, Sabah

No	Date	Location	Description	Reference
1	30th January 2023	KM167.9, Hutan Simpan Taviu, Ranau	 Ranau–Sandakan Road was rendered impassable due to landslides and fallen trees. No alternative road was available, and cleanup works were initiated.	Bernama (2023) [21]
2	23th September 2023	Ranau	 Several hours of heavy rain caused landslides, mudflows, road collapses, and flash floods. Two roads were damaged, including one leading to Mesilau resort.	Clarence Dol (2023) [22]
3	23rd June 2024	Kundasang, Ranau	 Heavy rain over the last 48 hours triggered landslides on Mount Kinabalu in Kundasang, Ranau. Debris entered Mesilau River, threatening Liwagu River water intake and treatment plant.	Fong (2024) [23]
4	12th January 2025	Kampung Pituru Darat, Kota Belud	 Intermittent rain triggered a landslide that struck a house, forcing evacuation of nine residents (family of five women, three children, and a man).	Sandra Sokial (2025) [24]
5.	16th January 2025	Kampung Cinta Mata Kundasang, Ranau	 Landslide in hilly Kundasang damaged a homestay structure.	Kristy Inus (2025) [25]

Recent landslide events recorded in Ranau and Kota Belud between 2023 and 2025 as summarized in Table 1 correspond well with the model outcomes. For example, the ARI-100 rainfall simulation produced a sharp short-term decline in FOS, consistent with the road-blocking failures in Ranau as reported by Bernama (2023) [21] and Clarence Dol [22] and residential slope failures in Kota Belud reported by Sandra Sokial (2025) [24] and Kristy Inus (2025) [25]. These events disrupted roads, threatened essential services, and caused property damage and evacuations. This alignment supports the reliability of the model in reflecting real-world slope responses. Although terrain variability exists across Ranau and Kota Belud, the selected soil sampling sites are representative of the dominant Crocker and Trusmadi geological formations. While local heterogeneity may influence slope behaviour at smaller scales, the results are broadly applicable to the prevailing geotechnical conditions of the districts [9, 10].

2.1. Soil Properties

Based on Table 2, the soil characteristics of RNU and KB show notable differences that influence slope stability. Clay content in RNU ranges from 2–25%, slightly broader than KB (2–17%), while silt is higher in KB (16–75%) compared to RNU (19–56%). Sand content is more dominant in RNU (19–60%), whereas KB soils show a wider spread (7–72%). Gravel is present in both, with higher maximum values in KB (up to 73%) than RNU (35%). The Atterberg limits show similar ranges: liquid limits of 29–53% (RNU) and 28–54% (KB), and plastic limits of 29–53% (RNU) and 28–54% (KB). Plasticity index ranges are also comparable, with RNU at 14–25% and KB at 13–26%. Moisture content in RNU (13–28%) is slightly higher than KB (9–28%). Specific gravity values overlap (8–15 in RNU; 8.52–25.28 in KB), though KB shows a wider range. Unit weights are comparable: RNU (2.69–2.70 kN/m³) and KB (2.59–2.74 kN/m³). Mechanically, cohesion is higher in RNU (21.1–22.8 kPa) than KB (20.96–21.68 kPa). Friction angles are significantly greater in RNU (3.49–9.7°) compared to KB (0.5–1.1°), indicating weaker shear strength in KB soils. Overall, RNU soils exhibit higher shear strength and stability, while KB soils are more permeable and vulnerable to rainfall-induced instability. Among the soil parameters, cohesion and friction angle exerted the greatest influence on FOS variation, with small changes producing notable differences in stability outcomes. Permeability primarily affected pore-water pressure development, controlling infiltration rates and recovery time. These observations are consistent with previous studies that highlighted shear strength parameters as critical drivers of slope behavior under rainfall infiltration [5, 26].

Table 2. Soil Properties of the Study Area

No.	Parameter	RNU	KB
1	Clay (%)	2 -25	2 – 17
2	Silt (%)	19 - 56	16 – 75
3	Sand (%)	19 -60	7 – 72
4	Gravel (%)	2 - 35	1 – 73
5	Liquid Limit (%)	29 - 53	28 - 54
6	Plastic Limit (%)	29 - 53	28 - 54
7	Plasticity Index (%)	14 - 25	13 - 26
8	Moisture Content (%)	13 - 28	9-28
9	Specific Gravity	8-15	8.52 - 25.28
10	Unit Weight (kN/m³)	2.69 - 2.70	2.59 - 2.74
11	Cohesion (kPa)	21.1 - 22.8	20.96 - 21.68
12	Friction Angle (°)	3.49 - 9.7	0.5 - 1.1

2.2. Rainfall Intensity

Based on Figure 3, rainfall intensity increases with higher ARI values, indicating a direct correlation between recurrence intervals and extreme rainfall events. This trend underscores the necessity for designing drainage and flood mitigation systems to withstand intense, less frequent storms. Specifically, for a duration of 3600 minutes (1 hour), rainfall intensity values exhibit a progressive increase across different ARI levels. The 2-Year ARI shows an intensity of 0.9225 mm/hr, which increases to 1.2580 mm/hr for a 5-Year ARI, 1.4801 mm/hr for a 10-Year ARI, and continues rising for longer recurrence intervals, reaching 2.1756 mm/hr for the 100-Year ARI. This pattern demonstrates that higher ARI values result in significantly greater rainfall intensities, with the 100-Year ARI intensity being more than two times greater than the 2-Year ARI value.

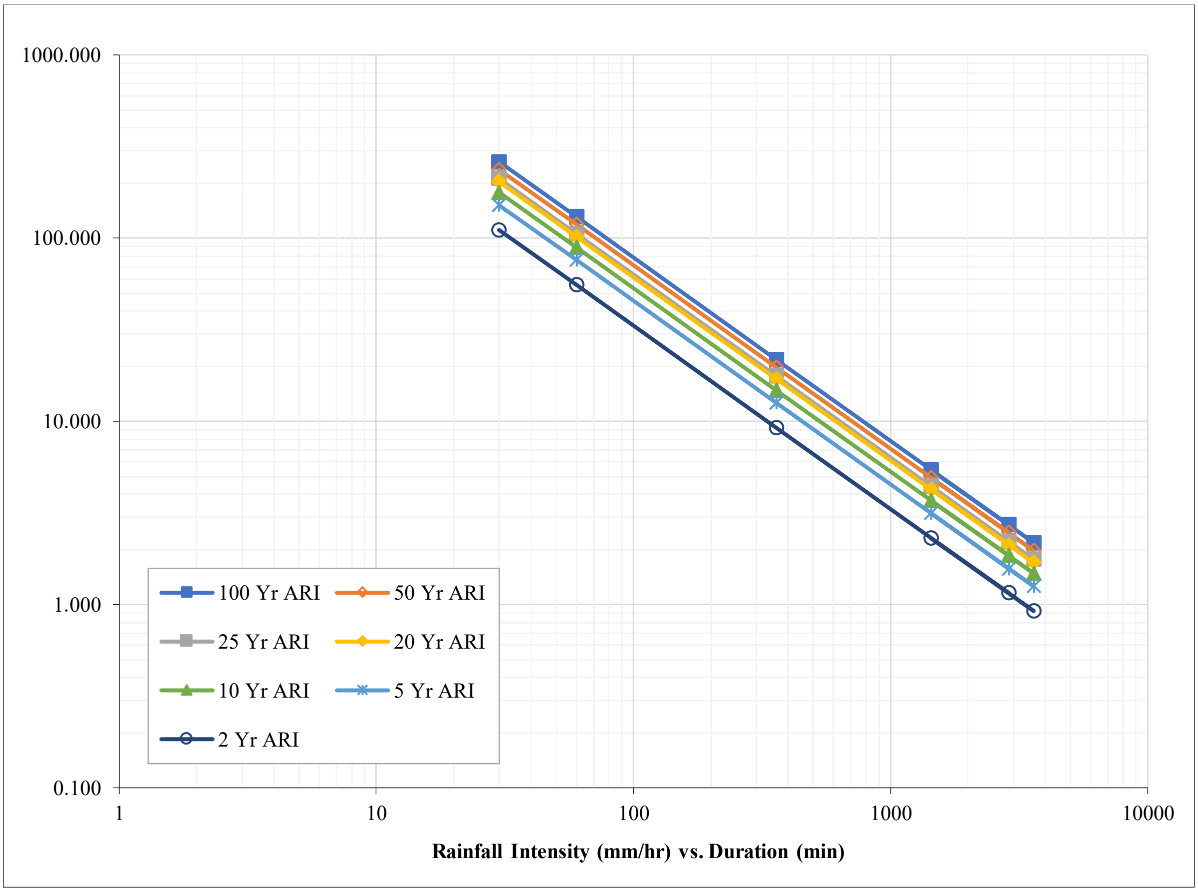

Figure 3. Intensity Duration Frequency

3. Research Methodology

Figure 4 depicted the flowchart illustrating the methodology employed in this study. The research began with the selection of Ranau and Kota Belud as study areas due to their susceptibility to rainfall-induced landslides. Data collection involved two key components: soil characteristics and engineering properties obtained from site investigations, and rainfall data provided by the Malaysian Meteorological Department (MetMalaysia). Rainfall records spanning 2013 to 2023 were retrieved from existing rain gauge stations and processed to develop Intensity-Duration-Frequency (IDF) curves. These curves were then used to calculate rainfall intensity values across different Average Recurrence Intervals (ARIs). The data were subsequently applied in numerical modelling using GeoStudio software, specifically the SEEP/W and SLOPE/W modules. SEEP/W simulated rainfall infiltration, while SLOPE/W assessed the Factor of Safety (FOS) of slopes under varying rainfall scenarios. The results were analyzed and discussed in relation to soil properties and rainfall characteristics, before being consolidated into conclusions that highlight the critical influence of rainfall on slope stability.

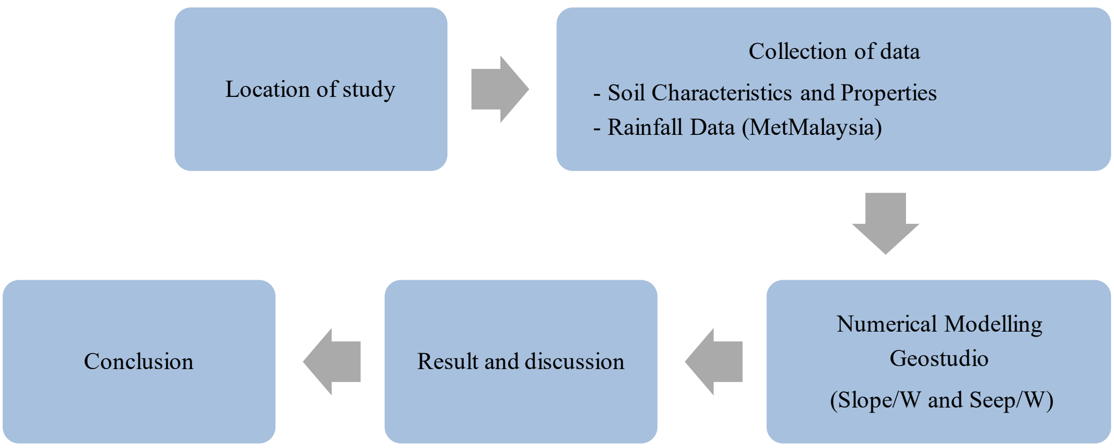

Figure 4. Workflow for this study

4. Results and Discussion

4.1. Slope Stability Analysis for Rainfall-Induced Landslide: 1-Hour Rainfall Duration

Figures 5 and 6 depict the variation in the factor of safety (FOS) with respect to time (in hours) under different Average Recurrence Intervals (ARIs) ranging from 0 to 100 years for slope conditions at Ranau (RNU) and KB, respectively, during a 1-hour rainfall event. These graphs show that the FOS increases progressively over time, with a steeper rise in the initial hours, eventually stabilizing as infiltration reaches equilibrium.

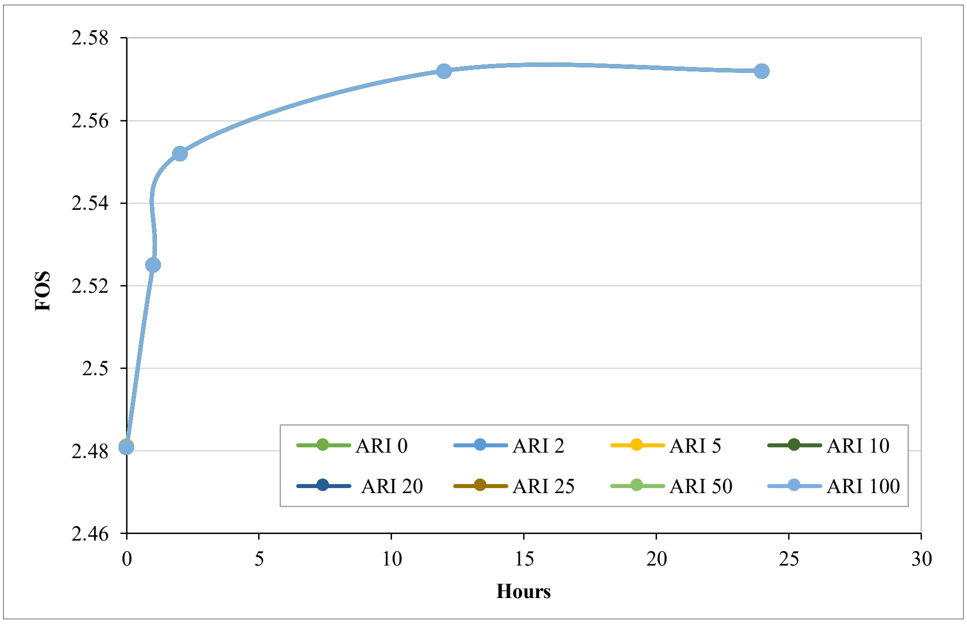

Figure 5. Factor of safety for slope at RNU for 1-Hour Rainfall

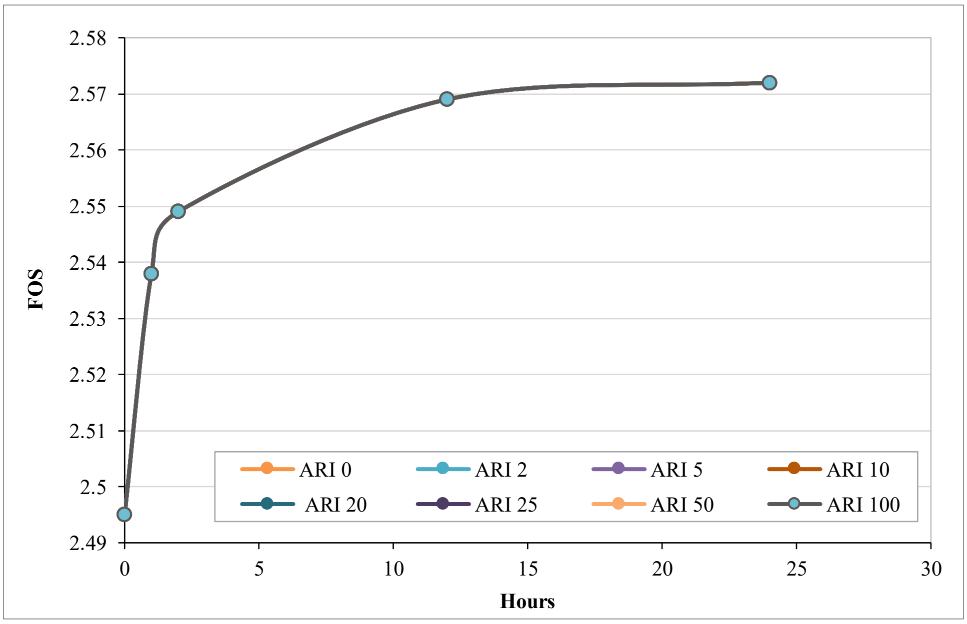

Figure 6. Factor of safety for slope at KB for 1-Hour Rainfall

As shown in Figure 5, the factor of safety initially increases sharply with a steep rise in the first few hours, particularly from ARI 0 up to ARI 5. During this period, the factor of safety changes significantly. The FOS starts at 2.481 for the 0-hour mark across all ARIs, indicating the initial safety margin. As the duration increases to 1 and then to 2 hours, there is a slight increase in the FOS to 2.525 and 2.552, respectively. By the 12-hour mark, the FOS reaches 2.572 and remains consistent through the 24-hour mark. FOS values are uniform across all ARIs, from ARI 0 to ARI 100, meaning that the recurrence interval or frequency of an event does not impact the safety factor. Kristo et al. (2017) [27] indicates that there exists a maximum amount of rainfall capable of infiltrating the soil to destabilize the slope; beyond this maximum amount, excess water will contribute to surface runoff, yielding only negligible impacts on slope stability.

Next, as shown in Figure 6, for slope at KB, for all ARI values, the FOS starts at 2.495 at 0 hours and increases incrementally with each time interval. By 1 hour, the FOS reaches 2.538, followed by 2.549 at 2 hours, 2.569 at 12 hours, and finally stabilizes at 2.572 by 24 hours. This gradual increase in FOS over time indicates that, initially, the safety factor strengthens with increased duration, reflecting a slight stabilization effect on the slope. This trend suggests that short-duration rainfall events have a limited impact on slope stability, and as the duration progresses, the safety factor reaches a stable level, maintaining the slope's resilience. Such a pattern implies that slope stability is more sensitive to the duration of rainfall rather than its recurrence interval, reinforcing the notion that antecedent rainfall or extreme events may not necessarily impact stability in short durations [28].

4.2. Slope Stability Analysis for Rainfall-Induced Landslide: 24-Hour Rainfall Duration

Conversely, Figures 7 and 8 illustrate the outcomes of slope stability analysis for RNU and KB respectively, with a rainfall duration of 24 hours. Initially as shown in Figure 7, at 0 hours, the FOS values are uniform across all ARIs, starting at 2.481, indicating a consistent baseline stability. Nonetheless, within a span of up to 2 hours, there is a significant reduction in FOS, with the decline being more pronounced for elevated ARIs. For instance, ARI 2 decreases marginally from 2.481 to 2.444 at 2 hours, whereas ARI 100 experiences a more pronounced decline from 2.481 to 2.369, highlighting that elevated ARIs correlate with increased short-term instability. Zhang et al. (2016) [29] has discovered that higher rainfall intensities result in increased infiltration rates, which in turn raise pore-water pressures within the slope, resulting in a decrease in the soil's shear strength and overall stability.

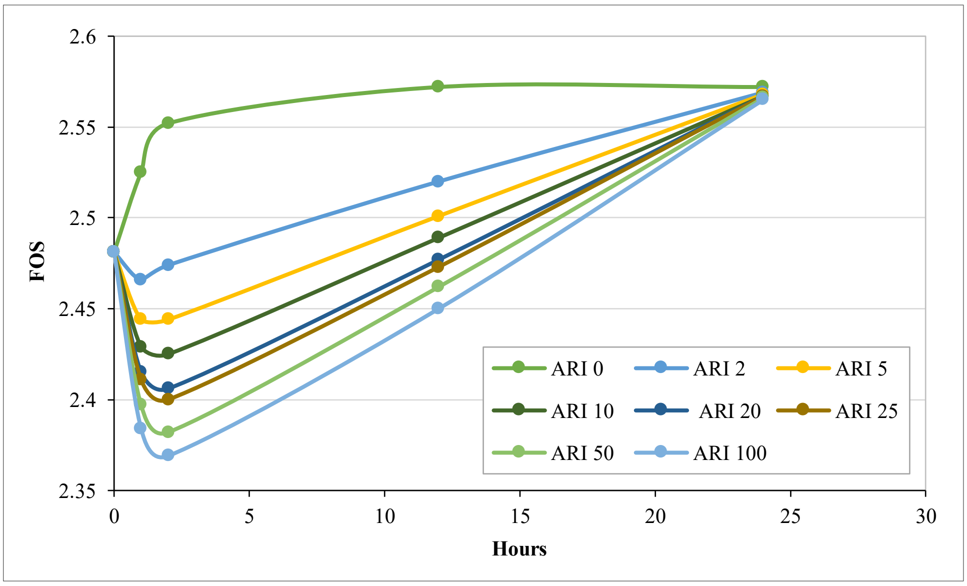

Figure 7. Factor of Safety for Slope at RNU for 24-Hour Rainfall

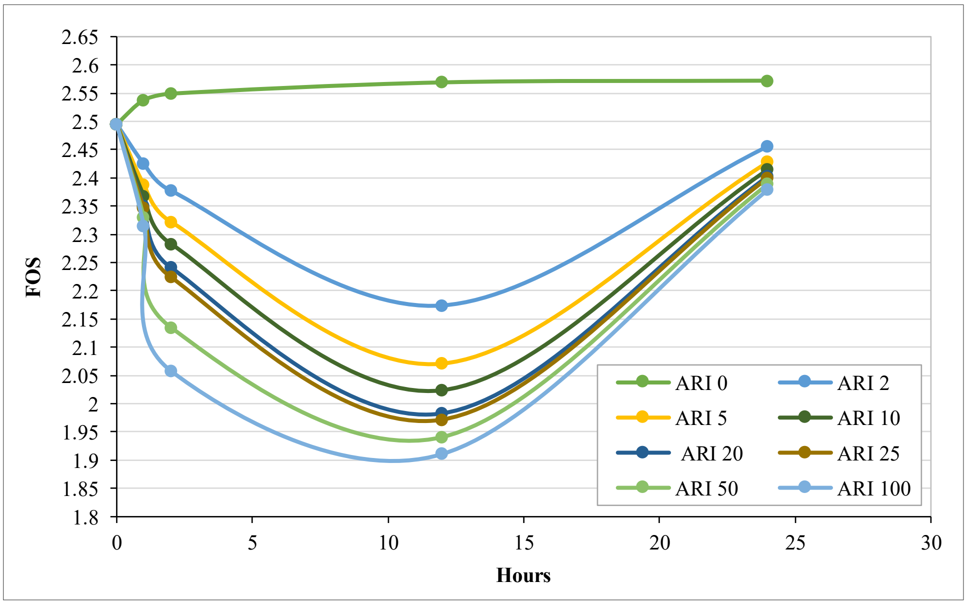

Figure 8. Factor of safety for slope at KB for 24-Hour Rainfall

After an initial decline, the FOS values show a steady recovery and eventually stabilize within 12 to 24 hours, with the recovery rates varying slightly across different ARI levels. For example, as illustrated in Figure 6, the ARI 2 level increases from 2.474 at 2 hours to 2.569 at 24 hours, while the ARI 100 level rises from 2.369 to 2.565 during the same timeframe. This trend highlights a consistent stabilization process, suggesting that the adverse effects of prolonged exposure to intense environmental conditions diminish over time as the system regains equilibrium. This observation aligns closely with the findings of Rosly et al. (2023) [30], who reported a similar pattern of FOS recovery after an initial drop during rainfall. Their study attributed this recovery to the gradual reduction of pore water pressure and the restoration of shear strength as groundwater levels recede. The stabilization process observed across varying ARI levels emphasizes the resilience of the system to environmental stress, as it adjusts to and mitigates the impacts of these conditions over time.

Between 0 and 2 hours, the FOS experienced a sharp decline for all ARI levels, suggesting an immediate stress response phase. This decline was more pronounced for higher ARI values, such as ARI 50 and ARI 100, while lower ARI values like ARI 0 and ARI 2 exhibited a less steep drop. After the 2-hour mark, the FOS began to recover gradually, indicating a stabilization process. The recovery phase was slower for higher ARI values compared to lower ones, but all ARI levels followed a similar upward trend. By hour 24, the FOS across all ARI levels converged to a stable value, ranging approximately between 2.565 and 2.572. This demonstrated that despite the initial variations in stress impact, the slope eventually stabilized regardless of the ARI level. The observed trends highlighted how higher ARI values intensified the initial stress response but did not significantly influence the long-term stability of the system.

FOS of slope at KB for 24-Hours Rainfall was summarized into Figure 8. At 0 hour, the FOS for all ARI values began uniformly at 2.495, reflecting identical starting conditions for the system. Between hour 0 and hour 2, the FOS underwent a notable decline for all ARI levels, signifying an immediate stress response phase. For instance, by hour 2, the FOS for ARI 0 slightly decreased to 2.549, maintaining relative stability compared to higher ARI levels. In contrast, ARI 100 experienced a significant drop to 2.058, showcasing a pronounced sensitivity to applied stress. Similarly, intermediate ARI levels such as ARI 10 and ARI 20 exhibited moderate declines, with FOS values reducing to 2.322 and 2.283, respectively. This phase underscored the heightened impact of stress on scenarios with higher ARI values, which experienced steeper declines in stability. After 2 hours, the FOS value gradually increased. By hour 12 hours, however, the FOS for all ARI values reached their respective minimum recovery points, with ARI 0 maintaining a relatively high value of 2.569 and ARI 100 stabilizing at a notably lower level, 1.911. Other ARI levels such as ARI 25 and ARI 50 also exhibited moderate stabilization, with FOS values at 1.983 and 1.941, respectively. By 24 hours, the FOS value for ARI 0 recorded the highest FOS at 2.572. On the other hand, ARI 100 concluded with the lowest FOS of 2.379. Intermediate ARI levels such as ARI 5, ARI 10, and ARI 20 stabilized at FOS values of 2.456, 2.428, and 2.415, respectively.

Malla & Dahal (2021) [31] confirms that higher rainfall intensities lead to more rapid FOS reductions due to increased pore water pressure and reduced shear strength. The initial uniform FOS values across ARI levels, followed by differentiated declines and recoveries, reflect the effects of rainfall infiltration, soil permeability, and precipitation characteristics, emphasizing the critical impact of rainfall intensity and duration on slope stability. The results are consistent with findings from other tropical regions. In Indonesia, prolonged rainfall has been identified as a dominant trigger for slope failures in volcanic terrains [32]. Similarly, in the Philippines, monsoon-driven rainfall frequently causes large-scale slope collapses in mountainous areas [33]. These comparisons broaden the relevance of this study and reinforce the role of rainfall as a universal driver of slope instability in humid tropical climates.

5. Conclusion

The first objective of this study was to determine the soil characteristics and properties of the selected areas, as these parameters form the foundation for understanding slope behavior. Soil investigations revealed marked variability between Ranau and Kota Belud, reflecting the influence of their differing geological settings. In Ranau, soil samples contained up to 40 percent silt and as much as 60 percent sand, with smaller proportions of clay and gravel. In contrast, Kota Belud soils were dominated by coarse-grained materials, with sand content ranging from 7 to 72 percent, suggesting higher permeability and lower cohesion. The Atterberg limits further highlighted these differences, with liquid limit values ranging from 28 to 54 percent and plasticity index values between 9 and 28 percent. These results indicate that soils in both districts possess moderate to high water retention capacity, which strongly influences their strength and deformation under stress. Such properties are critical for slope stability assessments, since changes in pore-water conditions during rainfall can significantly reduce shear strength. Overall, these findings reinforce the importance of carefully evaluating key soil parameters, particularly cohesion and friction angle, when predicting slope instability in vulnerable regions.

The second objective was to examine the impact of rainfall intensity on slope stability using rainfall records from the Malaysian Meteorological Department spanning 2013 to 2023. Intensity-Duration-Frequency (IDF) curves were developed for recurrence intervals of 2, 5, 10, 20, 50, and 100 years. For short-duration rainfall events of one hour, the factor of safety (FOS) at both Ranau and Kota Belud remained largely unaffected by variations in recurrence interval, showing steady increases before stabilizing. By contrast, extended 24-hour rainfall events produced a sharp initial decline in FOS, particularly at higher recurrence intervals. During a 100-year event with a 24-hour duration, rainfall intensity peaked at 2.18 mm/hr, reducing FOS from 2.481 to 2.369. Although stability later recovered to 2.565 as pore pressure dissipated, this demonstrated the transient yet critical influence of rainfall on slope performance. The Ranau slope remained consistently stable across scenarios, while Kota Belud exhibited greater sensitivity, with modest but clear reductions in stability under prolonged rainfall. These results demonstrate the strong role of rainfall as a trigger for slope failures and provide valuable insights into the interactions between soil properties, rainfall intensity, and slope safety. Projected increases in extreme rainfall intensity under climate change scenarios are expected to further elevate slope susceptibility in Sabah. Walsh et al. (2013) [18] reported a rising frequency of daily rainfall events exceeding 100 mm in Sabah, trends that could shift present ARI-50 or ARI-100 thresholds into more frequent events, thereby intensifying the risk of slope failures in Ranau and Kota Belud.

In conclusion, this study highlights the urgent need for effective mitigation measures to reduce landslide risks in vulnerable regions such as Ranau and Kota Belud. Advanced drainage systems, slope reinforcements, and rainfall-based early warning mechanisms are essential to safeguarding communities and critical infrastructure. By integrating a decade of rainfall records with detailed soil investigations and numerical modelling, the research fills an important knowledge gap in Sabah and offers new perspectives on rainfall-induced slope instability in tropical environments. The findings provide practical and actionable insights for local authorities, including JKR Sabah and municipal councils, by guiding the prioritization of slope reinforcement projects, supporting the design of drainage systems calibrated with Intensity-Duration-Frequency (IDF) curves, and strengthening disaster preparedness through early warning systems. Collectively, these contributions not only advance scientific understanding but also serve as a foundation for geotechnical planning and policy development aimed at protecting lives, property, and livelihoods in landslide-prone districts.

This study is subject to several limitations. Soil sampling was limited to selected sites, which may not capture all micro-scale heterogeneity. In addition, numerical models assumed homogeneous soil profiles and simplified hydrological conditions, which may not fully reflect field complexities. Future research should expand sampling coverage, integrate climate projection datasets, and apply fully coupled hydro-geotechnical modelling for greater accuracy.

6. Declarations

6.1. Author Contributions

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

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

7. References

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