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An Overview: Relationship of Geological Condition and Rainfall with Landslide Events at East Malaysia

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Abstract

Tropical country like Malaysia is rich with residual soil and nurtured with high rainfall amount on average 2,550 mm per year. From 2009 until 2018, there are many landslide events reported in the news at Ranau, Sabah and Canada Hill Miri, Sarawak that occurred during rainy season and the landslide recurs within same location over the years. The objective of this study is to determine the relationship of landslide events with geological condition and rainfall at Ranau, Sabah and Canada Hill Miri, Sarawak. Historical landslide data were obtained from local news, previous researchers, and local authorities. Integrated review was conducted to meet the objective. In summary, both areas are prone to landslide due to the high average amount rainfall recorded and the geological properties that are susceptible to landslide occurrence namely shale interbedded with sandstone. Sandstone and shale contact are easily accessible by water weaken the contact surface lead to landslides incidents. Besides, Shale classified as highly plastic soil due to high amount of clay. Clay soil depends on its matric suction to sustain its strength towards sliding. Thus, increasing of pore pressure from rain infiltration reduce the matric suction and eventually reduce the shear strength. Ranau is located at seismically active area compare to Miri and other locations in Sabah crossing Lobou-Lobou fault, Mensaban fault and Mesilou fault. Theoretically, slope instability due to earthquake happened because the cementation of soil may be broken and lead to lesser roughness between soil surfaces resulting in reduction of internal friction angle and cohesion of soil.

Keywords: Rainfall-induced landslide, Earthquake-induced landslide, Unsaturated soil strength

Introduction

Landslide can be described as a variety of processes that resulting in the downward and outward movement of slope-forming materials including rock, soil, artificial fill or combination of these materials either by falling, toppling, sliding, spreading or flowing influenced by gravity [1-3]. It is one of the major hazards that lead to hundreds of deaths and loss of property worldwide including Malaysia every year particularly during rainy season that usually occur due to instability of slopes, distressed slopes and unprotected fill or cut slopes [2-8].

Referring to historical data obtained, there were 8 landslide cases recorded at Ranau, Sabah and 8 landslide cases recorded at Miri, Sarawak between year 2009 to 2018. Ranau, Sabah and Canada Hill, Miri, Sarawak having repetitive landslide cases at the same location throughout the year and predicted to reoccur in the future. One similarity can be captured from the landslide cases which is all events occurred during rainy season as per reported in the news [9-16]. Based on study conducted by previous researchers, rainfall has been identified as major triggering factors of landslide events in Malaysia due to the atmospheric condition which causing average annual rainfall in Malaysia reaching about 2,550 mm and steamy climate causing hot and humid atmosphere throughout the year with yearly monsoons from southwest on April to October and northwest from October to February [2,7,17].

Rainwater that infiltrates into ground cause increase of pore water pressure within the slope body. Due to this, the active pressure of slope eventually increases due to increase of pore water pressure that act as lateral pressure. Besides, the infiltrated rainwater also acts as softening agent or lubricated the sliding surface which promote slope instability [50,78]. In the other hand, increase of pore pressure also means reduction of negative pore pressure that reflect the soil suction in unsaturated soil condition and consequently reduce shear strength of slope especially for highly clay soil [18-21].

However, the major causal factors of landslide occurrence in Malaysia is due to design errors. Industrial expert has claimed that the shortage in design is usually affected by lack of understanding in subsoil conditions and geotechnical issues such as the geological characteristics [2,3,7,22,23,]. In other words, the geological information and soil engineering parameters are the key input prior to further develop the detail engineering design for slope mitigations.

This is also agreed by Roslee *et al.* (2010) that mentioned human ignorance and negligence to include and understand geological inputs in slopes design cause landslide occurrence [24]. Thus, the best solution to prevent slope from failure is to understand the geological conditions to ascertain the selection of slope protection. Other than that, understanding rainfall event also important to dictate worst condition in analysis and for drainage system design purposes. With regards to the causal factors and triggering factors discussed, this paper aims to study the relationship of geological condition and rainfall with landslide events at Ranau, Sabah and Miri, Sarawak that causing repetitive occurrence between year 2009 to 2018.

Study area

Sabah and Sarawak are located at East of Malaysia and part of Borneo Island adjoining Indonesia and Brunei [2]. Sabah occupying area of 73,371 km^2 which about one 10th of the island of Borneo [25]. Sabah has a tropical climate with uniform temperature and high humidity throughout the year. The annual rainfall ranges from 1,920 to 3,190 mm [26]. While, Sarawak occupying area of 124,450 km^2 with over some 700 km along the northwestern coast of Island of Borneo. Sarawak has an equatorial climate conditions which are uniform temperature, high humidity and copious rainfall. The annual rainfall for Sarawak is between 3,300 mm near the coastland to 4,600 mm as it further inland [27].

Based on National Slope Master Plan (NSMP), landslide distribution for year 1973 - 2007 have indicate that Sabah is having around 6 % compare to other state in Malaysia. It is reported that landslides in Sabah occurred due to human activities such as uncontrolled cutting and burning of vegetation causing slope disturbances. For Ranau, Sabah, the slope instability caused by the geological factors which is the tectonic movement and the geological formation itself. Meanwhile, Sarawak contribute around 4 % of landslide distribution for year 1973 - 2007 [28]. **Figure 1** shows the landslide prone locations of Sabah and Sarawak.

Ranau, Sabah is a well-known touristic location area with beautiful mountainous view of Mount Kinabalu. It is located between 500 to 2,000 m above mean sea level on the southern flank of Mount Kinabalu [17,29]. Ranau is surrounded by Kota Marudu to the north, Kota Belud to the northeast, Tuaran to the west, Tambunan to the southwest, Keningau to the south, Tongod to the southeast and Beluran to the east [17]. While Canada Hill is known as the 1st oil well drilled in Malaysia which called The Grand Old Lady. It is located at Miri, the 2nd largest city in state of Sarawak. Canada Hill is around 200 m high ridge that located along Miri from north east to south west [12].

Figure 1 Landslide prone locations at Sabah and Sarawak extracted from National Slope Master Plan 2009 until 2023.

Ranau, Sabah and Canada Hill, Miri, Sarawak are chosen for this study due to the heat map indication of landslide prone area as shown in **Figure 1**. This has been confirmed with the landslide historical data obtained from news which has reported that these locations are having repetitive landslide events in total 16 occurrences between year 2009 - 2018 as shown in **Table 1**. These have shown the severity and criticality to conduct study to find out the root cause of the landslide issue at these areas for the usage of future development as lesson learn.

Table 1 Landslide Events at Ranau, Sabah and Canada Hill, Miri, Sarawak Recorded in News from 2009 until 2018.

Date	Location	Description	Reference
7 May 12	Ranau KM83.9 Tamparuli	Continuous heavy rain causing thick mud as high as 5 meters blocking the road around 50-meters length	"Bundu Tuhan Landslip," (2012) [9]
26 Dec 13	Ranau Ranau-Tamparuli Road	Tones of earth and rock material burying road	"Landslip Hit Ranau-Tamparuli," (2013) [11]
23 Jan 14	Canada Hill Kampung Lereng Bukit	Tones of earth and sand washed down by heavy rain	Chung and Loo (2019) [12]
5 Jun 15	Ranau Kundasang	5.9 Richter scale earthquake causing 2 mudslide incidents which drifted big rubbles, trees and destroyed the banks of rivers in Kundasang.	Abdullah (2015) [13]
13 Nov 17	Canada Hill Kampung Lereng Bukit	Houses and vehicles were damaged. Roads cracked due to soil erosion	Chung and Loo (2019) [12]
15 Nov 17	Canada Hill Top of Canada Hil	A big chunk of a deep slope collapsed and half of the road links	Chung and Loo (2019) [12]
6 Jan 18	Canada Hill Kampung Lereng Bukit	Hillslope collapsed; mudslide moved down	Chung and Loo (2019) [12]
8 Mar 18	Ranau, Kundasang and Kota Kinabalu	Several rubbles falling from mountain would possibly cause mudslide if there is continuous heavy downpour following 5.2 Richter scale earthquake	Abdullah (2015) [13]
22 Sep 18	Ranau Kg. Kinasaraban	30m depth and 18m width landslide cut-off road link between Ranau and Kota Kinabalu during heavy downpour	Lee (2018) [15]

Geological condition at Ranau, Sabah and Canada Hill Miri, Sarawak

Gue and Tan (2016) conclude that geological features such as discontinuities rarely detected during design stage even though extensive subsurface investigation is conducted. Most of the features are found during the execution stage. Thus, it is encouraged to carry out detail geological study such as slope mapping to detect any geological discontinuities before proceeding with geotechnical construction works into further stage [22]. Roslee *et al.* (2010) believes that geological inputs are required for mitigation measures as ground idealization and shall be considered as guideline for landslide investigation [24].

Ranau is located within Trusmadi Formation, Crocker Formation and Quaternary Alluvium Deposits. Trusmadi Formation consists of dark grey shale with thin bedded sandstones. The fresh shale is in dark grey color. However, the color changes into light grey to brownish when weathered [30,31]. Crocker formation is formed from sequence of interlaying of permeable sandstone with impermeable shale with highly fractured to fine-grained sandstone while shale layers are sheared [30,32,65].

Quaternary Alluvium deposits can be found in lowland area [30,32]. It is mainly representing the unconsolidated alluvial sediment on river terraces and weathered product materials that are composed of unsorted to well-sorted, sand, silt and clay of varying proportions which were derived from the bed rocks.

Alluvium deposits occur in irregular lenses with various of form and thickness. Alluvium may consist very thin layer of organic matter and categorized as soft, compressible and prone to settlement [31]. Trusmadi Formation and Crocker Formation are well known for their instability [30,32]. **Figure 2** shows the geological map of Ranau, Sabah.

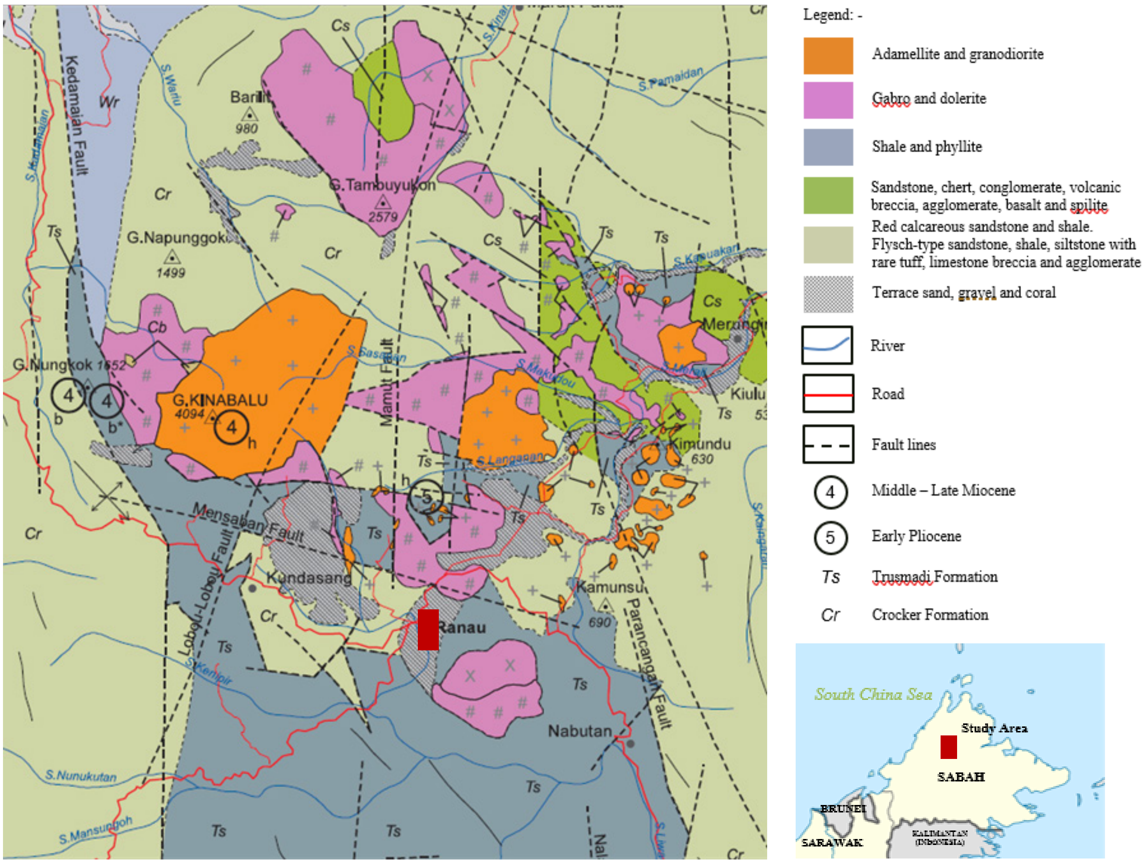

Figure 2 Geological Map 2015 of Ranau, Sabah from Department of Mineral and Geoscience Malaysia.

The geomorphological of Ranau is generally steep and hummocky terrain, with regional and unstable local geology together with existence of old landslide areas [33]. Apart from the geological formation, Sabah also known as the most tectonically active area in Malaysia. This is due to its proximity to the major plate boundary faults in Philippines and Sulawesi [34]. Sabah experienced local earthquakes events and earthquakes originating from nearby area over southern Philippines, straits of Macassar, Sulu Sea and Celebes Sea. Earthquake motion generates movement of natural, manmade slopes or earth structures which further become landslide when the slope fails to sustain the force of gravity [35].

Active faults defined as linear areas where ground movement that occurs systematically and continuously over a large area and describing that the region is still under active tectonic stress. Any faults considered as active when there is seismic activity observed or recorded for the past 10,000 years [34]. Tjia (2007) conclude that there is presence of 2 regional fault named Crocker Fault Zone (CFZ) and Mensaban Fault Zone (MFZ) within Ranau and Kundasang. CFZ is more than 170 km long and several kilometers wide contains Tenom, Keningau and Tambunan with the northern segment. Meanwhile, MFZ can be traced over 110 km from Tuaran toward east into the interior of Sabah along with Kundasang [36]. Local faults that presence nearby study area are Lobou-Lobou fault and Mesilau fault [34,36]. It is believed that the road subsidence and displacement within Ranau and Kundasang region are related to these active faults [34].

Based on historical data, 4 earthquakes had occurred in Ranau since 1989. First earthquake occurred in 1989 with 5.6 Richter scale. Followed with 5.1 Richter scale on 1991. Then, 4.1 Richter scale on March 2005 and the 4th in February 2010 with magnitude of 2.6 Richter scale. Other than Ranau, there are other districts in Sabah that are prone to seismic activity which are Pitas, Lahad Datu, Kunak and Tawau [72]. This is because the seismic activity was origin from nearby area such as southern of Philippines, Straits of Macassar, Sulu Sea and Celebes Sea [35]. **Table 2** below shows the number of earthquake occurrence obtained from Department of Meteorology of Malaysia from 2009 until 2018 that show Ranau is the most seismically active area compare to other locations in Sabah.

Table 2 Number of Earthquake Occurrence for Ranau, Lahad Datu and Tawau from 2009 until 2018.

Years	Ranau	Lahad Datu	Tawau
2009	-	1	-
2010	2	2	2
2011	2	1	1
2012	-	1	-
2013	13	-	2
2014	11	-	-
2015	152	2	-
2016	67	93	8
2017	108	38	9
2018	605	6	7
Total	**960**	**144**	**29**

Canada Hill, Miri, Sarawak is located at Miri Formation. Miri is considered as narrow coastal region with total thickness of Miri Formation estimated exceeding 1,830 m. Lower part of Miri soil profile consist of interbedded shales and sandstones. Meanwhile, the upper part of soil is consisting of rapidly recurrent and irregular sandstone-shale alternations, with the sandstone beds passing gradually into clayey sandstone and sandy or silty shale [12,37]. Canada hill was initially formed due to strike-slip deformation subsiding western portion of Baram Delta Block which is offset against the stable network of faults called Baram Line.

The strike-slip deformation can be explained by hydraulic pressure onto a semi-liquid pressure onto a pillow of Setap Formation triggered remobilization of mobile clay pillow beneath causing parts of Miri Formation uplifted and forming Canada Hill [38]. **Figure 3** shows the geological map of Canada Hill, Miri, Sarawak. **Figure 5** shows the absence of fault lines at Miri, Sarawak. Thus, it can be concluded that earthquake activities at Canada Hill is not affected by seismic activity. **Table 3** shows the physical and engineering properties of soils and rocks at Ranau, Sabah and Canada Hill, Miri, Sarawak based on data recorded by previous researchers [12,63,65].

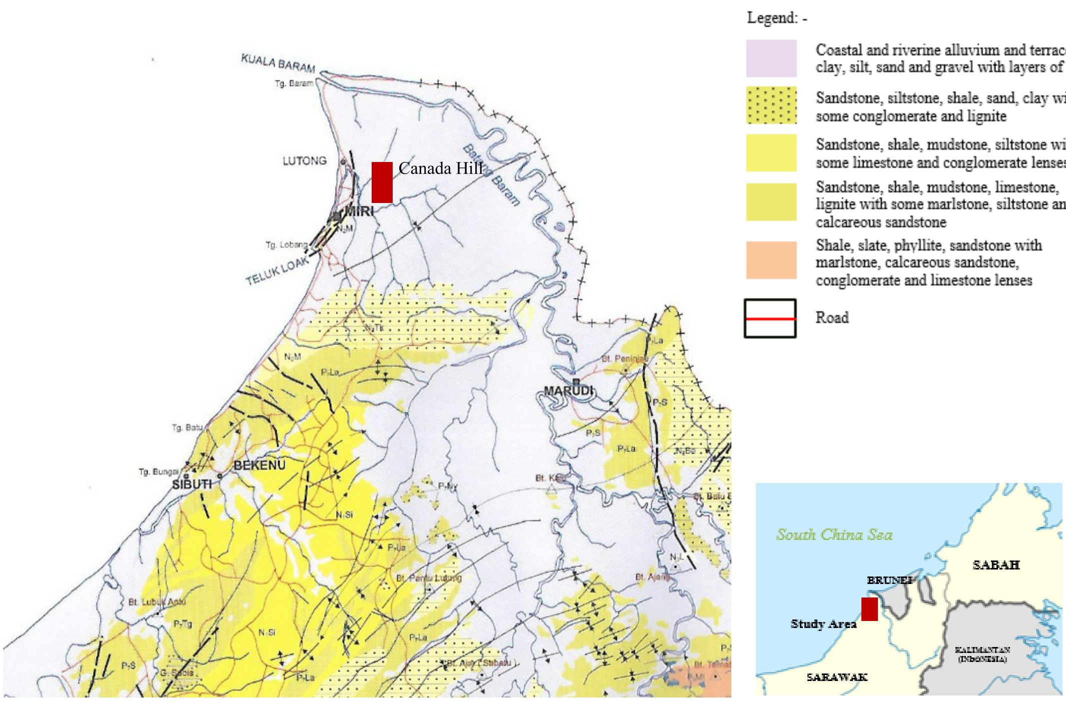

Figure 3 Geological map 2013 of Miri, Sarawak from Department of Mineral and Geoscience Malaysia.

Table 3 shows the soil properties obtained from previous researchers for Trusmadi Formation, Crocker Formation and Miri Formation compared nearby countries which are Singapore and Indonesia. Based on the data obtained, permeability value shows that Singapore has the lowest range compare to other locations and Indonesia has the highest permeability. For cohesion, Miri Formation shows that the value can reach as low as zero indicate that some area may consist of only sand. Trusmadi Formation has the lowest friction angle value compare to other locations. This illustrate that the area within Trusmadi Formation may prone to landslide due to low friction angle value translated to lower shear strength of soil.

Table 3 Soil properties of Trusmadi Formation, Crocker Formation, Miri Formation, Singapore and Indonesia.

Properties	Trusmadi	Crocker	Miri	Singapore	Indonesia
Permeability (cm/s) ($\times 10^{-3}$)	3.28	4.25 - 9.15	0.5 - 1.0	0.01 - 10	2060
Cohesion, C (kN/m^2)	5.11	6.27 - 24.44	0 - 10	10 - 16.5	17.2 - 20.8
Friction Angle (°)	7.72	11.70 - 28.9	20 - 38	26	29.8
Reference	Erfen, Gansaur and Henry (2016) [37] and Roslee and Tongkul (2018) [70]		Chung and Loo (2019) [52]	Rahimi, Rahardjo and Leong (2011) [3] and Rahardjo, Santyaga and Leong (2016) [32]	Setiawan *et al.* (2019) [34]

Rainfall intensity at Ranau, Sabah and Miri, Sarawak

Rainfall have been identified as the major contributors to landslide event in Malaysia. Malaysia is having around 2,550 mm of rainfall per year because of the presence of yearly monsoon seasons which are from southwest starting April until October and from northeast starting October until February. In peak monsoon season, the pore water pressure of soil will increase that causing the effective stress of soil decrease, after that lowers down the shearing resistance at the slip surface which lead to slope failures after heavy downpour [5].

Landslide are commonly occurred after a period of heavy rainfall. Intense rainfall will affect the active force that drives the slope to fail due to the weight of soil after rainfall increased because rainwater infiltrate and retained in slope body and reduce the soil suction and eventually shear strength [12,43]. Gue and Tan (2006) have recommended that slope should be verified according to their sensitivity of water levels with the stability and this input is required to predict the worst groundwater conditions to be used as feed during design stage [22].

Figure 4 shows the monthly rainfall amount for Ranau, Sabah from 2009 to 2018. The highest annual average rainfall recorded on 2017 with amount of 585.31 mm and the lowest annual average rainfall recorded on 2014 with amount of 197.32 mm as per shown in orange dashed line.

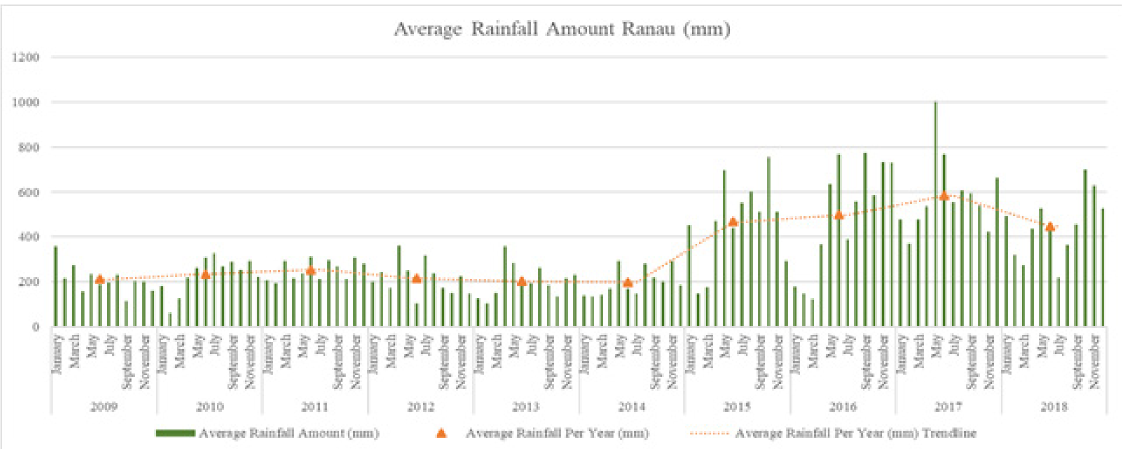

Figure 4 Monthly rainfall amount of Ranau, Sabah from 2009 until 2018.

Figure 5 shows the average rainfall amount for Miri, Sarawak from 2009 - 2018. The highest annual average rainfall recorded on 2010 with amount of 148.31 mm and the lowest annual average rainfall recorded on 2016 with amount of 32.27 mm as per shown in blue dashed line.

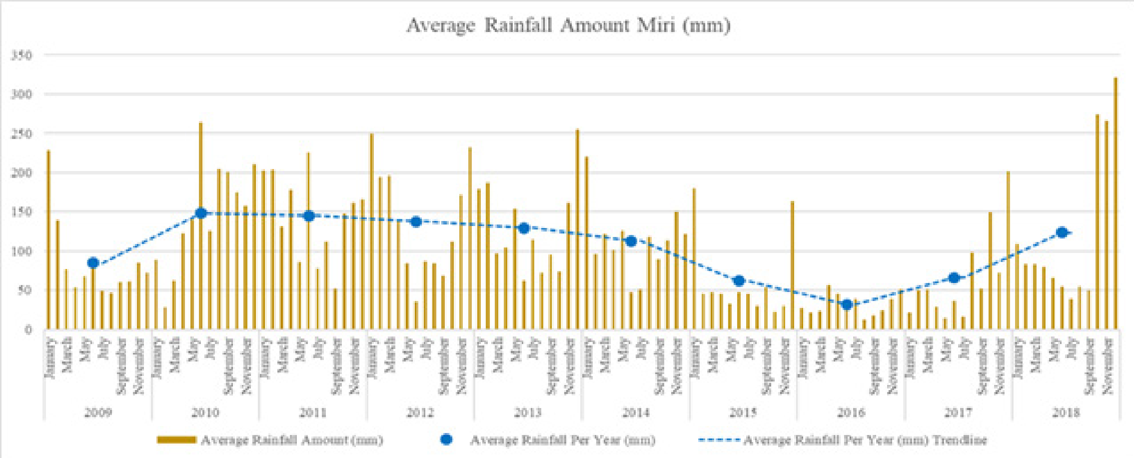

Figure 5 Monthly rainfall amount of Miri, Sabah from 2009 until 2018.

Discussion

Rainfall and earthquake are the most common triggering landslide mechanism worldwide. The significant long-term impact of earthquake event can be seen on the slope stability during rainy season because the landslide scars and debris were easier to reactivate during rainy season. Thus, it is expected that rainfall-induced landslide will continue to occur at seismically active location in the future [44-46,48]. Combined charts have been developed between annual rainfall amount and the landslide events to confirm the landslide events were happened during heavy downpour. **Figure 6** shows the combined chart of annual rainfall amount and landslide event at Ranau, Sabah from year 2009 to 2018 and **Figure 7** shows the combined chart of annual rainfall amount and landslide event at Canada Hill, Miri, Sarawak from year 2009 to 2018.

Based on **Figure 6**, it can be concluded the average annual rainfall amount in Ranau, Sabah from 2009 to 2014 is below 300 mm. However, it jumps to above 400 mm from 2015 to 2018. There were 5 landslide events happened between 2009 to 2014 even though the average rainfall amount considered on lower side compare to the latest year on 2015 to 2018. While the remaining 3 landslide events were recorded occurred on 2015 to 2018. There were 2 landslide events occurred below average annual rainfall amount trendline which are landslide event on December 2009 and April 2011. However, both landslide events were occurred right after heavy downpour on the previous month. Meanwhile, the rest were occurred above annual average rainfall amount trendline.

Based on **Figure 7**, the average annual rainfall trendline Canada Hill, Miri is above 50 mm except on year 2016. The overall pattern shows a wavy shape compare to Ranau, Sabah that having consistent magnitude initially and spike up on 2015 to 2018. Canada Hill was also having landslide case that occurred below average annual rainfall amount trendline which is landslide event on November 2017. But the landslide event was also occurred right after heavy downpour on the previous month, likewise Ranau. These situations matched with a study conducted by previous researchers which is referred to as landslide induced by antecedent rainfall [7,40,47,49,50]. The other landslide events occurred above annual average rainfall amount trendline.

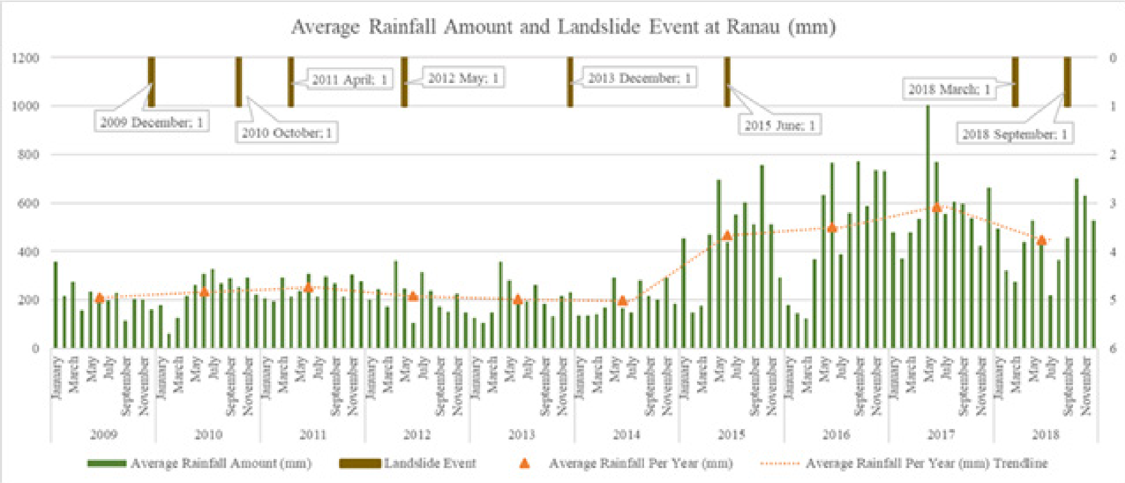

Figure 6 Combined chart of annual rainfall amount and landslide event at Ranau, Sabah from year 2009 until 2018.

Since Ranau located at mountainous area with high rainfall amount and active seismic activity, **Figure 8** is developed to combine the landslide incidents that happen from 2009 until 2018 together with number of landslide event recorded annually to assess the relationship of landslide with rainfall and earthquake event. Based on **Figure 8**, it can be concluded that the landslide incidents at Ranau have been active even before seismic event increase drastically starting on 2015 which were heavily impacted from rainfall. Meanwhile, landslide on 2015 was a combination of rainfall and earthquake by looking on the spike of rainfall amount and earthquake event. This situation has cause Ranau to become the most landslide-prone area compare to Miri because of the exponential trending of rainfall and seismic as per recorded by Department of Meteorology Malaysia and previous researchers. The theoretical reason will be explained in the following section.

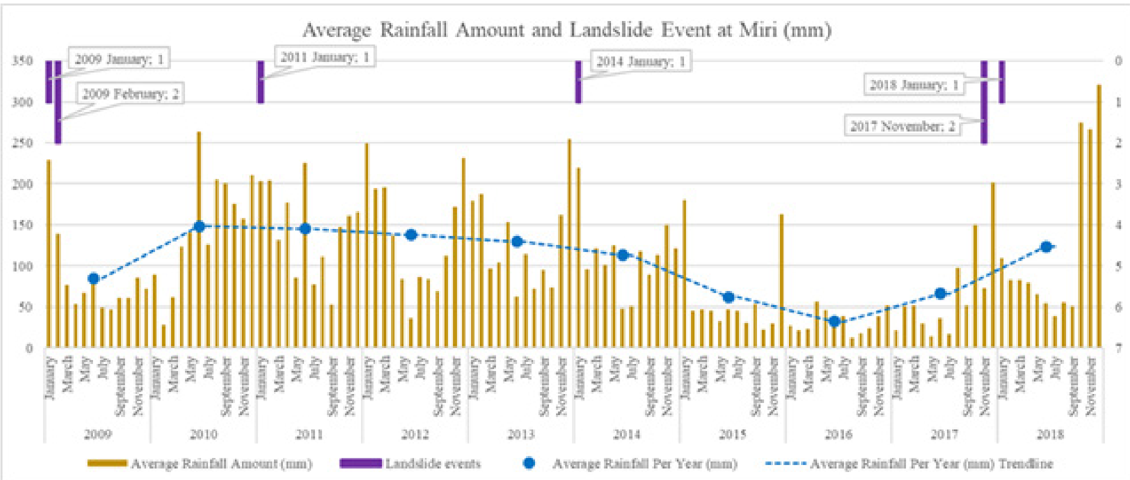

Figure 7 Combined chart of annual rainfall amount and landslide event at Miri, Sarawak from year 2009 until 2018.

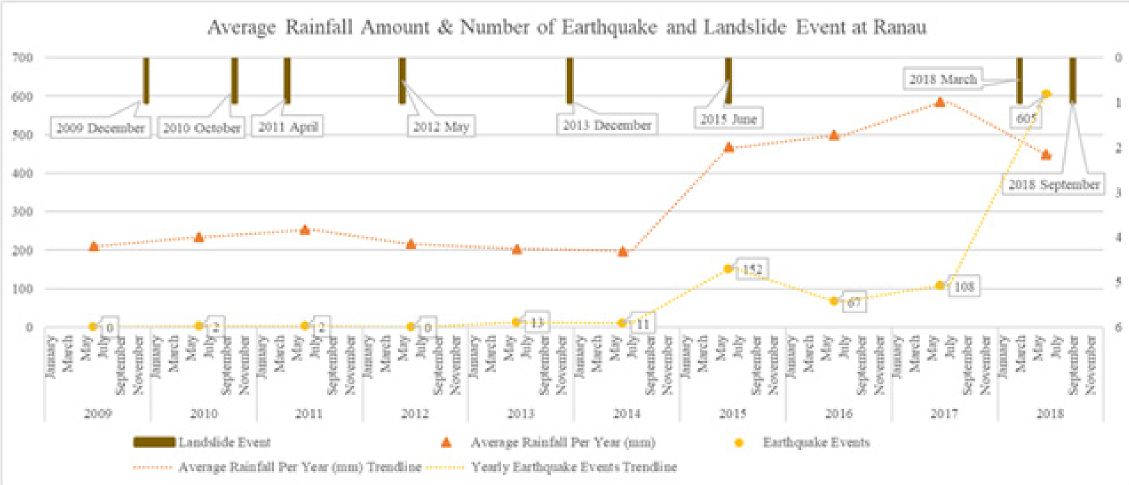

Figure 8 Average rainfall amount & number of earthquake and landslide event at Ranau from 2009 until 2018.

Rainfall-induced landslide

Rainfall-induced landslide is not uncommon in tropical country like Malaysia that mainly consist of residual soils [4,7,40,42,44,51-53]. However, Other than Malaysia, other countries are also exposed to the similar landslide threat induced by rainfall. Chien-Yuan *et al.* (2005) have concluded that the effects from rainfall infiltration and surface water runoff should be considered as 2 important factors for slope failure. Besides, other factors that required to be attained are topography, geological structures, material properties and vegetation cover. These factors may affect the landslide mechanism [54]. Landslide triggered by rainfall is also famous in mountainous landscape areas [55,56]. Rainfall-induced landslide normally caused by the increase of pore pressure and seepage forces during intense rainfall [52,55,57,58].

Rainfall impact on geological feature

Ranau and Canada Hill are having almost similar subsoil profile which are both resided on shale bedded or interbedded with sandstones. Ranau is located at Trusmadi Formation, Crocker Formation and Quaternary Alluvium Deposits. Trusmadi Formation and Crocker Formation are mostly formed with shale bedded with sandstones [30,31]. Meanwhile, Canada Hill is resided at Miri Formation that formed from Setap Shale Formation that consist of shale and sandstone [12,38]. Technically, both study areas are having similar subsoil profile which the profile were formed from shale and sandstone. Previous researchers have proven that shale possess weaknesses that can cause landslide to occur with the presence of moisture especially when in contact with sandstone.

Gutierrez *et al.* (2008) and Ekeocha (2014) have defined shale is a soil or rock with high clay mineral content that filling intermediate position between soils and rocks. Shale contains between 50 to 100 % clay sized particles with clay mineral constituting at least 25 % of the total of rock origin volume [59,60]. Fine grain soil become low plasticity and slurry when high percentage of water introduced therefore triggering landslide to occur [61].

Shale is flawed with its nature of deterioration when exposed to variation of moisture which attribute to cation exchange of the clay minerals which increased water absorption and subsequently reduce strength properties of clay. Besides, shale is weathered and eroded quickly than other rocks like limestone and sandstone [60]. Shale also known as expansive soil which defined as any soil or rock material that has a potential for swelling or shrinking under changing of moisture content. Such behavior may cause damage to foundations of building substructures or potentially induced landslides [18].

Meanwhile, sandstone is formed from cemented grins that either be fragments of a pre-existing rock or mono-minerallic crystals [62]. Theoretically, sandstone is easily accessible by water through fractured rock weaken the shale surface and causing landslides and falls within the formation and lead to landslides. Interbedded sandstone and shale may also cause problems as it can lead to settlement and rebound [31,63-65].

Hasbollah *et al.* (2019) have explained that the reduction of shear strength with increase of moisture content is due to reduction of internal friction angle and the surface energy. Presence of water also soften the bonds or interaction or grease with mineral surfaces consequently alter their properties especially the strength of the material. The study conducted have conclude that presence of water has affected strength index of shale more than sandstone [62].

Various study has been conducted to identify the effect of moisture variation induced landslide. Chen *et al.* (2009) conclude that slope stability analysis has shown that the rainfall-time history is the most significant influence factor for landslide occurrence induced by rainfall. Thus, it means that landslide event occurred by rainfall will not happen in short period of time instead it took a period of duration in order to trigger slope failure [66].

Rainfall impact on soil strength

Previous researchers also mentioned that rainfall induced landslides due to changes of pore pressure, soil suction and shear strength of soil caused by rainwater infiltration [40,44,66,67]. Rainwater infiltration is a gravity-driven process with uniform water content and zero pore water pressure behind the wetting front [56]. Soehady *et al.* (2018) and Setiawan *et al.* (2019) have concluded that increasing of soil moisture will decrease the soil strength which contribute into landslide occurrence [4,68].

Figure 9 explains the condition of soil particles according to its saturation or also known as volumetric water content in graph while **Figure 10** is showing the illustration of soil particles in different saturation. When the porosity of soil has been filled with water and has achieve saturated condition (Ksat) and illustrated in **Figure 10(a)**. However, when the water volume in soil is reducing, it allows air to enter between the porosity that represent as Air Entry Value (AEV) and is shown in **Figure 10(b)**. This point indicates that the soil is experiencing negative pore pressure and matric suction. As the negative pore pressure increase, the soil eventually achieves fully drained condition with residual water content as shown in **Figure 10(c)**.

Saturation zone of slope will not be formed when the infiltration rate is less than coefficient of permeability especially for fine grained soils which more likely cause deeper failure due to reduction of shear strength caused by loss of suction. This condition is referred to as unsaturated soil. Unsaturated soil will remain stable due to its matric suction which contribute to higher shear strength. The pore water pressure of unsaturated soil will accumulate within the wetting zone since the water cannot infiltrate easily into deeper layer [42,52,66,69]. However, the rainwater that percolated down in the slope will cause matric suction to decrease at deeper depth and increase the depth of wetting front [40].

Previous researchers have mentioned that the shear strength of unsaturated soil is controlled by matric suction which also known as soil suction. The reduction of pore water pressure is due to evaporation, vapor pressure, suction and cavitation of soil mass and oppose with negative pore pressure value or matric suction [19,20,70,88]. Yoshida and Kuwano (1991) and Cai *et al.* (2018) have confirmed via laboratory experiment that the shear strength of unsaturated soil decreases due to the reduction of soil suction which contribute to lower factor of safety [58,71]. Soil suction refers to the inter-particle forced produced by the negative pore pressure. The force depends on particle size and found to be higher in fine grained soil such as clay compare to silt and sand.

The contribution of matric suction to shear strength is related to the rate of soil distortion which is a function of water content. When the matric suction is small that Air Entry Value (AEV), shear strength of soil increases as matric suction increases and the increment appeared to be linear because the soil is in saturated condition [20]. Based on laboratory test conducted by Cai *et al.* (2018), the result shows that coarser soils particle has lower matric suction and AEV value compare to finer soils particle [71].

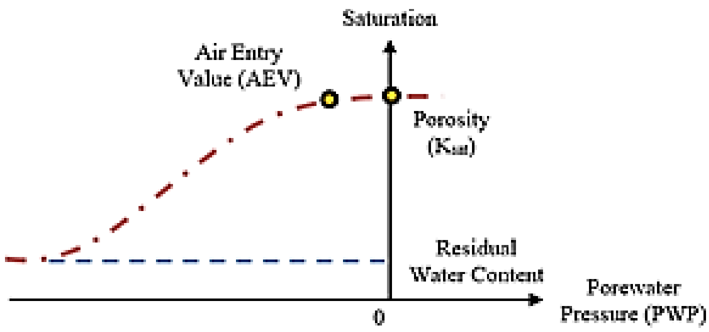

Figure 9 Volumetric water content of soil.

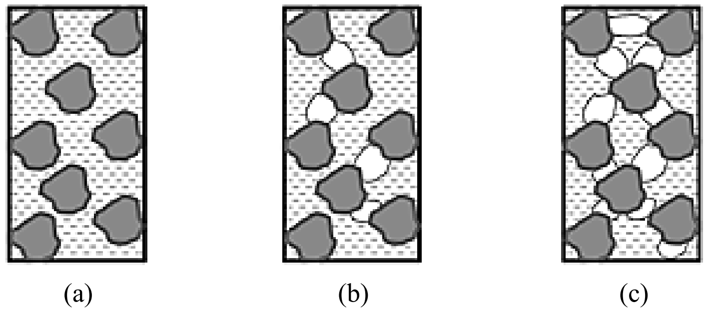

Figure 10 Soil particles, water and air during suction a) saturated; b) unsaturated; c) fully drained (residual water content).

Based on study conducted by Pujiastuti *et al.* (2017), it was recorded that soil cohesion and internal friction angle increase as matric suction increases. However, the increment was found nonlinear. They conclude that the matric suction has cause the shear strength to be increased is a result of increase in soil cohesion and internal friction angle for sandy clay type. Besides, they also stressed that high matric suction create stable relationship between shear strength and matric suction in a low moisture content.

Table 3 has shown the cohesion and friction angle value for each study area. Both values for all locations are lower than other countries which are Singapore and Indonesia. When reduction of soil suction occurs, the value of cohesion and friction angle become lesser and eventually reduce the shear strength of soil and slope failure will occur. However, the matric suction is not transmitted effectively to the contact point of soil particles and large increase of matric suction does not significantly increase shear strength [20].

Earthquake-induced landslide

Ranau has experienced landslide occurrence induced by seismic activity on 5th June 2015 and 8th March 2018 inducing induced several land instabilities at Tambunan, Tuaran, Kota Kinabalu and Kota Belud [35,72]. It was recorded the earthquake on 5th June 2015 was 5.9 on the Richter scale and classified as the most powerful earthquake occurrence happened in Malaysia for the last 39 years since 1976. Meanwhile, the earthquake on 8th March 2018 was 5.2 Richter scale. The tremor at Ranau has surpassed the previous records that occurred in 1976 which was 5.8 on the Richter scale at Lahad Datu. **Figure 11** shows the percentage of seismic activities at Ranau, Lahad Datu and Tawau, Sabah between year 2009 until 2018 has confirmed that Ranau is the most seismically active location with 85 % occurrences compare to Lahad Datu with 13 % occurrences and Tawau 2 % occurrences of total recorded earthquake events by Department of Meteorology Malaysia.

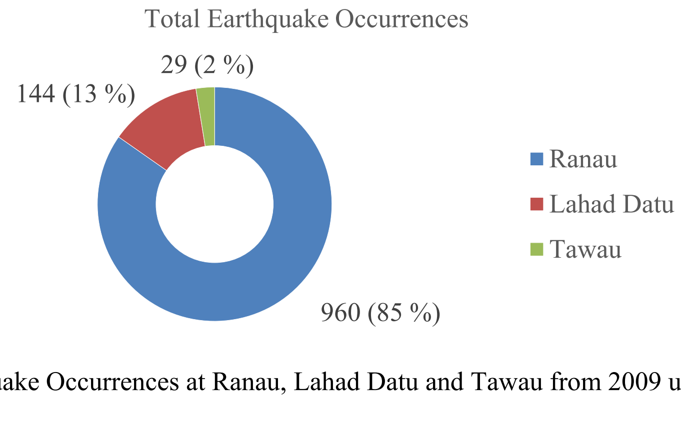

Figure 11 Total Earthquake Occurrences at Ranau, Lahad Datu and Tawau from 2009 until 2018.

Tongkul (2015) has interpreted that Ranau earthquake on 5th June 2015 originated from the fault plane that generate the main shock was normal fault. The suspected normal fault was extended from Lobou-Lobou Fault zone which appear to be undercutting Mount Kinabalu. This also has explained the reason Mount Kinabalu was shaking aggressively during the main shock and aftershocks. The main shocks and aftershocks have caused rockfalls and landslides around Mount Kinabalu especially around Mesilau, Ranau area. The loose materials have accumulated on the slopes, in gullies and river valleys provided source for debris flow during heavy rain and affecting flow of water [73].

This finding matched with a study conducted by Faris and Wang (2014) that conclude the rainfall has saturate the landslide mass before the earthquake shock triggered the liquefaction and decrease the stability dramatically [74]. Bommer *et al.* (2001) stated that neither saturation of slope due to rain nor the earthquake event alone would develop extensive damage, but it was the combination of both factors that creating disastrous widespread landslide [86]. This is agreed by Nomura *et al.* (2014), they mentioned that rainfall intensity is the primary meteorological factor associated with earthquake while antecedent rainfall comes second [75]. Havenith *et al.* (2003) believe that other factors that such as weathered rock material or colluvium act as the soft layers on the earthquake-induced landslide [76].

Earthquake impact on soil properties

The earthquake induced landslide is famous worldwide. Based on Hack *et al.* (2006) and Faris and Wang (2014), horizontal acceleration during earthquake generates oriented force that cause slope instability. The acceleration also causes reduction of normal stress on the contact plane and shear strength along the plane. Besides, cementation of soil may be broken and lead to less-roughness surface resulting in reduction of cohesion and friction angle of slope mass. Other than that, the earthquake creates cyclic loading effect on the soil. This may lead to reduction of pore volume in loose soils which further disallowed pore water to drain fast enough. Pore pressure will increase and decrease the effective stress between soil particles hence reduce the shear strength of soil [74,77].

The increase in seismic loadings or acceleration will reduce the soil friction angle and soil cohesion. This eventually increase the soil displacement and further develop into earthquake-induced landslide event [78]. In other terms, Erken *et al.* (2016) and Huang and Peng (2018) mentioned that the landslide mass start to sliding when the seismic acceleration exceeds yield acceleration of the slope mass [79]. Not only that, they believe the dynamic pore pressure during earthquake event plays significant role affecting landslide. This has been agreed by Sigaran-loria, Kaynia and Hack (2007) that mention seismically induced pore water pressure rise was a major controlling parameter in spatial landslide occurrence [80].

The effect of earthquake has been confirmed from laboratory tests conducted by Nakamura *et al.* (2013). The cyclic and triaxial tests using clayey soil obtained from the slip surface from earthquake location have shown shear strength reduction due to the destruction of clay particle originated from sedimentation. The skeleton of the soil structure was destructed. Nakamura and team were also performing finite element analysis that further support the soil resistance was greatly reduce due to stress concentration in the clayey soil [81].

Earthquake impact on slope mass equilibrium

Bhat, Saxena and Prasad (2010) conclude that earthquake movement can induce significant inertia forces on slope. The inertia force cause instability that produce shearing stress to the soil mass. This force alternate in direction and magnitude for numerous times. The inertial force that exceed failure limit of slope will induce further displacement. The earthquake shakings generate loss of strength which drop below the soil strength that required to maintain the slope equilibrium. These failures may happen under static conditions after earthquake event was ceased and usually produce large deformations which occur without warning [82].

Kokusho *et al.* (2007) believe that earthquake-induced slope failures can be explain using energy approach instead of equilibrium force. They conclude that earthquake energy plays a major role as initiator for landslide by supplying extra energy for the slope destabilization and reducing its shear resistance which disrupting the energy-balance in the failure of large soil mass [83].

Earthquake impact on geological feature

Meanwhile, Towhata (2013) stated that seismic slope failure is not only the product of natural disaster. It is also known as the starting point of a long-term catastrophic in which the compound effects of preceding earthquakes and followed by heavy rain play significant roles. It is found that cracks were developed after earthquake event will allow rainwater to percolate into the slope and affecting the long-term stability [84].

This can be seen on slope failure that occur at Ranau, Sabah post-earthquake event on 5th June 2015. It was assumed that the slope that failed during the earthquake might have developed some slope failure indications such as tension cracks that allow water to flow into the slope mass and eventually fail after certain period. This is similar with landslide findings by Erken *et al.* (2016) that conclude there are development of tension cracks and settlement induced shear cracks during earthquake occurrence [85].

Conclusions

This paper demonstrates the relationship of geological condition and rainfall event with landslide events occurrence at Ranau, Sabah and Miri, Sarawak. By referring to the rainfall data, seismic reading, and landslide historical events, below summaries can be concluded:

i. Ranau, Sabah and Canada Hill Miri Sarawak are mainly formed from shale interbedded with sandstone. Previous researchers have proven that shale possess weaknesses especially when exposed to moisture. Shale is mainly consisting of clay materials and shale also possess nature of deterioration and tend to swell or shrink when exposed to water. Interbedded with sandstone have promote water seepage from surface towards shale through the fractured rocks.

ii. All landslide events at Ranau, Sabah and Canada Hill Miri, Sarawak discussed in this study occurred during rainy seasons and considered as rainfall-induced landslide. Rainwater infiltrated into the slope mass and reduce the shear strength of soil due to increasing of pore pressure. This eventually reduce the matric suction of soil that act as inter-particle force that holds the soil particles together especially for fine grained soils such as clay. Laboratory experiments also shown that increasing of soil moisture causing reduction of internal friction angle and cohesion of soil.

iii. Based on previous researchers and data from Department of Meteorology Malaysia, Sabah is classified as seismically active area compare to Sarawak. Data obtained from Department of Meteorology Malaysia shown that Ranau is the most seismically active area with 85 % earthquake occurrences compare to Lahad Datu with 13 % and Tawau with 2 % from year 2009 until 2018.

iv. Earthquake affecting landslide events occurred due the horizontal acceleration acting on slope mass within the area of impact resulting slope instability. The cementation of soil may be broken and lead to lesser roughness between soil surfaces resulting in reduction of internal friction angle and cohesion of soil. Besides, the earthquake movement generate inertia and develop shearing stress that disrupt the slope mass equilibrium.

v. The landslide event that occurred post-earthquake is due to the seepage of rainwater into cracks that developed during the earthquake event. This explain some slope mass not failing during the seismic event but eventually failed after certain period followed by heavy rain.

Therefore, the understanding of geological condition and rainfall data is very important to study any landslide events forensic work to identify the exact root cause of the failure. In addition, the geological and rainfall data are also required to be include in any geotechnical design for any slope related works to avoid lack of understanding on the potential cause of failure that might happen in the future.

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