# EVALUATION OF SLOPE STABILITY DUE TO EARTHQUAKE AND RAINFALL OCCURRENCES

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# ABSTRAK

Malaysia adalah sebuah negara tropika yang mempunyai kelembapan yang tinggi dan hujan lebat. Purata hujan tahunan bagi Semenanjung Malaysia adalah 2,300 mm. Dari perspektif lain, gempa bumi adalah bencana alam yang kurang berlaku di Malaysia. Walau bagaimanapun, kes gempa bumi tempatan semakin meningkat. Selain itu, penduduk Malaysia sering merasakan gegaran gempa bumi dari kawasan jiran seperti Sumatera. Kajian ini menggunakan perisian GeoStudio untuk membentangkan kestabilan cerun di Pulau Pinang selepas kesan hujan dan gempa bumi. Kehasilan menunjukkan bahawa hujan dengan tempoh yang lebih panjang dan intensiti hujan yang lebih tinggi akan merendahkan kestabilan cerun. Kegagalan cerun yang disebabkan oleh hujan sering berkaitan dengan kenaikan paras air bawah tanah. “Factor of safety” lebih rendah apabila mengambil kedua-dua kesan hujan dan gempa bumi. Deformasi adalah satu lagi parameter yang boleh digunakan untuk menilai kestabilan cerun yang terjejas oleh gelombang seismik. Kehasilan menunjukkan bahawa deformasi yang lebih tinggi direkodkan untuk geometri cerun yang mempunyai sudut cerun yang lebih besar dan ketinggian cerun yang lebih tinggi. Pengukuhan adalah penting untuk meningkatkan kestabilan cerun supaya menghasilkan “factor of safety” yang lebih besar daripada 1.0 dan deformasi dapat dikurangkan pada masa yang sama. Tembok penahan digunakan dalam kajian ini untuk menahan jisim tanah dalam cerun kritikal. Dari kehasilan dapat dilihat dengan jelas bahawa tembok penahan boleh mengurangkan kesan hujan dan gempa bumi dengan berkesan. Pengukuhan lain yang dibincangkan dalam tesis ini termasuk paku tanah dan sistem perparitan. Paku tanah juga dapat mengurangkan kesan hujan kerana meminimumkan perpindahan tanah melalui ikatan dengan tanah sekitarnya. Kepentingan sistem perparitan yang betul termasuk saliran permukaan dan saliran tanah bawah tanah juga dipelajari.

# ABSTRACT

Malaysia is a tropical country which has high humidity and heavy rainfall. The annual average rainfall for Peninsular Malaysia is 2,300 mm. In other aspect, earthquake is not a frequent natural disaster happened in Malaysia. However, the case of local earthquake displays a slightly increasing trend. Besides, residents often felt tremors of earthquake from neighbouring region such as Sumatra. The 2004 Sumatera earthquake even caused 68 people killed in Penang, Langkawi, and Kedah. It is unknown for the combined effect of rainfall and earthquake to the existing slope structures in Penang Island. This dissertation presents the results on slope stability after the impact of rainfall and earthquake using the GeoStudio software. When considering the single effect of rainfall only, the results show that rainfall with longer duration and higher rainfall intensity will adversely affect the slope stability. The rainfall-induced slope instability often related to the rise of groundwater table level. On the other hand, the factor of safety for selected slope are even lower when both effect of rainfall and earthquake are considered in the analysis since the seismic waves will be imposed as secondary damage to the slope. Deformation is another parameter that can be used to evaluate the stability of slope affected by seismic waves. The results show that a higher deformation is recorded for slope geometry which has bigger slope angle and higher slope height. Reinforcement is essential to improve the slope stability so the factor of safety greater than 1.0 and deformation can be reduced at the same time. One of the reinforcements applied in this research is retaining wall which can improve the slope stability under the effect of rainfall and earthquake. Soil nailing is another reinforcement that can reduce the effect of rainfall since it minimizes the soil displacements through bonding to the surrounding soil. The importance of proper drainage system including surface drainage and subsoil drainage was studied as well.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| DID | Department of Irrigation and Drainage |
| FOS | Factor of safety |
| FHWA | Federal Highway Administration |
| GIS | Geographical information systems |
| GPS | Global Positioning System |
| MMD | Malaysian Meteorological Department |
| NEM | Northeast monsoon |
| REAM | Road Engineering Association of Malaysia |
| SWM | Southwest monsoon |
| USGS | U.S. Geological Survey |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of the Study

In today's globalized world, property developing and building construction are common to fulfill the community's demand. However, the lack of land resources had become an issue due to rapid population growth. As a result, many construction projects had to be carried out on hillslope due to limited land resources. Therefore, the phenomenon of slope failure can happen unexpectedly without proper preventive measures.

Landslide hazard is one of the common types of slope failure which appeared to occur more frequently. In general term, a landslide is defined as the downward movement of soil and rock under the influence of gravity (U.S. Geological Survey (USGS), n.d.). A landslide can also be induced by natural disasters or human activities. The formation of landslides will subsequently cause destructive outcomes such as damage to properties, financial loss, and fatalities. The landslide hazard can happen in different forms such as mudflows, debris flow, and rockfalls. In these cases, slope stability analysis is essential to avoid the evolution of slope failure and landslide. Slope stability analysis is mainly used to analyse the slope's stability and sliding resistance. It is vital to understand the effect of driving force and resisting force acted on slope faces. The key determination for slope stability is the equilibrium of shear stress and shear strength. If the shear stress applied is larger than soil shear strength, the landslide has a greater chance to take place.

### 1.1.1 Slope Instability

Understanding the slope failure mechanism and the causes of slope instability is critical to prevent landslides from happening. However, it is unlikely for a slope failure to be triggered by a single definite reason. Slope instability is a complicated issue related to various geotechnical principles, which needed site inspection and professional engineers' experiences. Commonly, slope failure can be caused by internal factors and triggering factors. The internal factor includes the slope geometry, strength of soil materials and groundwater. In contrast, the triggering factor includes natural phenomenon such as volcanic eruptions, earthquakes, and heavy rainfall. It can be said that earthquake-induced landslide and rainfall-induced landslide are two common types of slope failure.

Earthquake-induced landslide is often related to the magnitude of an earthquake, distance from the epicenter, and geological condition. In general, earthquake involves a series of ground movement which can cause destructive disasters such as landslide and tsunami. When an earthquake happens, the ground acceleration will act as dynamic loading applied to the slope. Then, the driving force and sliding force will be increased along the potential slip surface. Subsequently, the sliding surface will transform into plastic state and reduce the sliding resistance. Thus, slope failure occurs.

From other aspect, a landslide can also trigger by rainfall with certain rainfall intensity and duration. However, the formation of landslide depends on geological conditions as well. Loose soil and weathered rock are more prone to rainfall-induced landslide. When rainfall takes place, the water will infiltrate into the ground and increase the groundwater table level. The groundwater level fluctuation will lead to a drop in soil matric suction and increase the pore water pressure. The decline in soil matric suction will weaken the soil shear strength. When the soil is nearly saturated, the soil matric suction will decrease drastically. These mechanisms will lead to slope instability and eventually trigger the landslide.

### 1.1.2 Malaysia Seismic Condition

Malaysia is part of the Sundaland Block, covering a major part of Southeast Asia (Simons et al., 2007). It is mainly surrounded by several plates tectonic, including Australian Plates and the Philippines Plate. Malaysia was categorized as tectonically stable since it is located far from plate tectonics boundaries and the Ring of Fire region. Hence, natural disasters like volcanic eruptions and major earthquakes caused by plate tectonics movement seldom take place. However, it is necessary to point out that the assumption that Malaysia had a low seismicity profile is unconvincing, especially after the 9.1 M Sumatra-Andaman earthquake. Malaysia experienced a significant change in direction and rate of tectonic motion after the 2004 mega-earthquake (Marto et al., 2013). This statement had been proven by observation using Global Positioning System (GPS): a co-seismic displacement of 17cm in Langkawi Island, Malaysia (Vigny et al., 2005). As a result, researchers must understand and consider the impact of seismic waves when assessing slope stability since Malaysia is no longer earthquake-free.

### 1.1.3 Malaysia Climate

Malaysia is recognized as a tropical country since it is located close to the equator. Malaysia's climate is classified as equatorial, which has high temperatures and heavy rainfall. The annual average rainfall for Peninsular Malaysia is 2,300 mm (Suhaila et al., 2010). According to the Department of Irrigation and Drainage (1988), Penang's mean annual rainfall is around 2,250mm to 3,250mm. Generally, Malaysia undergoes two types of monsoons: Southwest Monsoon and Northeast Monsoon. Both monsoon seasons recorded two different types of rainfall patterns in Malaysia.

According to the Malaysian Meteorological Department, the local weather condition was hot and dry during Southwest Monsoon from May to September (Malaysian Meteorological Department, 2019). The hot climate could lead to drought and haze issues occasionally. The disaster of drought often affected the community's livelihood, including the reduction of crop yields and water shortage.

On the other hand, the local areas experienced a higher rainfall intensity during Northeast Monsoon from October to March. For instance, seven episodes of heavy rainfall occurred in November and December 2019 during Northeast Monsoon 2019/2020 resulting in flooding. It can be said that flood disaster had become part of Malaysian life during Northeast Monsoon.

## 1.2 Problem Statement

Landslide had been a problematic disaster that happened for the past decades in Malaysia. In common, the formation of landslide can be blamed on human activities or natural disasters. It is significant for scholars to figure out the mechanism of landslide formation. The research outcomes can often provide useful information for government and land developers to monitor the slope movement. Hence, the risks for residents exposing to landslide hazard can be minimized.

The effect of an earthquake is still considered tolerable since major earthquake did not occur in Malaysia. Thus, the effect of seismic waves seldom taken into consideration when evaluating slope stability. Most of the local earthquakes hit Malaysia in Ranau, Sabah. For example, the strongest earthquakes, the 6.0 $M_w$ Ranau earthquake took place in 2015. In general, the phenomenon of earthquake always related to losses in lives and properties. In Malaysia, the first recorded landslide triggered by earthquake was in Ranau, Sabah dated back to 26 May 1991 with magnitude 5.3$M_w$ (Marto et al., 2013). With the first case of earthquake-induced landslide, the awareness was raised among the residents. The devastating effect of the earthquakes is not only social economics but will also impact the geotechnical field. Yet, there were not much preventive actions taken by government to study and take some preventive measures. It is important and necessary to study the destructive effects of earthquake especially after the 9.1M Sumatra-Andaman mega-earthquake. The mega earthquake had altered the direction and rate of tectonic motion and reveal the need of considering the effect of seismic waves in slope stability analysis.

In other aspects, local climate conditions need to be considered for a more accurate evaluation to slope stability. Malaysia's climate is hot and rainy throughout the year since it is located near the equator. Due to global warming, more extreme weather events such as heavy rainfall and thunderstorm frequently happened worldwide. Malaysia was not spared from the negative effects caused by global climate change. During Northeast Monsoon, a noticeable number of heavy rainfall events were frequently occurred which increase the volume of surface runoff. This excess runoff on the surface can affect the flow of seepage in the water circulation system. Besides, the occurrence of extreme weather events such as Typhoon Damrey which recorded 315mm of rainfall intensity in four days had induced slope failure in Penang Island due to the overflowing water carrying the soil down the hillslope (Ahmad et al., 2020). In other words, the change in rainfall intensity might be a possible cause of slope failure. Thus, the variation in rainfall patterns should be given attention when evaluating slope stability.

Comprehensive studies on the impact of earthquake and rainfall on slope stability should be carried out promptly by considering the effects of both the triggering factors. The ground-shaking induced by seismic waves, combined with rainfall patterns in Penang area, might have a greater impact on slope stability and result in irreversible disaster.

## 1.3 Objectives

The objectives of the research project are stated below:

i. To determine the effect of rainfall intensity and rainfall duration on slope stability
ii. To determine the combining effect of earthquake and rainfall on slope stability
iii. To propose solutions for slope instability due to rainfall and earthquake effect

## 1.4 Scope of Works

The work scope will be focused on slope structure modelling using GeoStudio software including SEEP/W, QUAKE/W and SLOPE/W. The deformation of slope structure will be analysed considering ground shaking induced by earthquake and rainfall intensity. The secondary data for the earthquake are taken from historical earthquake event in Indonesia. In contrast, local weather conditions will be stimulated using two different rainfall intensities, which is 80mm/hr and 120mm/hr. The slope stability affected by rainfall and seismic waves will be compared with guideline. Slope reinforcement will then applied to the unstable slope to improve the safety factor and reduce deformation.

## 1.5 Structure of Dissertation

The dissertation consists of five main chapters. Chapter 1 mainly introduces this research project's background, problem statement, objectives, and scope of work. Chapter 2 reviews the literature and discusses Malaysia’s seismic condition, Malaysia climate, slope failure, and other relevant topics. Chapter 3 discusses the research methodology in different stages, including slope structures and secondary data analysis. In Chapter 4, the research results are presented in tables, figures, and graphs. The discussion is further made by using the result obtained. Lastly, Chapter 5 contains the conclusions made for this research will be stated and recommendations proposed for future research.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Overview

A significant proportion of studies have been conducted to determine the impact of earthquake and rainfall intensities on slope stability (Chen et al., 2020; Tang et al., 2011). In Malaysia, most of the previous research mainly focused on the vulnerability of rainfall-induced landslide (Huat et al., 2012; Lee et al., 2013; Mukhlisin et al., 2015). The effects of earthquakes on slope stability received the least attention when discussing the topic of slope stability. However, ground shaking is important in evaluating slope stability, considering the seismic condition in Malaysia.

The combined effects of the two natural phenomena can negatively impact to most of the slope in Malaysia. However, the research on slope instability in Malaysia seldom related to the combined effects of an earthquake with rainfall. The combined effect of ground shaking induced by earthquake and variation of rainfall pattern is worth studying and should be given attention when analyzing the slope stability.

## 2.2 Slope failure

Landslide is one of the natural phenomena that will change the shape of the ground surface on the Earth. Landslide can be defined as a physical structure that evolves over time (Hungr et al., 2013). Petley (2012) studied the occurrence of landslide worldwide from the year 2004 to 2010. The research stated that 2620 major landslide that led to catastrophic consequences were reported in the studied duration, resulting in 32,322 deaths. The disastrous impacts caused by landslide hazard had revealed the importance to study the mechanism of landslide.

The classification and types of landslides had been evaluated in many previous studies (Hungr et al., 2013; Highland and Bobrowsky, 2008; Niroumand et al., 2012). The landslides can divide according to their motion: fall, slide, flow, topple, and spread. Different types of landslides occurrences often related to the geologic material (Akter et al., 2019). Hungr et al. (2013) summarized all the 29 landslide type names as shown in Table 2.1 and described in more detail for each type of landslides.

Table 2.1 Summary of Varnes' classification (Hungr et al., 2013)

| Movement Type | Rock | Debris | Earth |
|---|---|---|---|
| Fall | 1. Rock fall | 2. Debris fall | 3. Earth fall |
| Topple | 4. Rock topple | 5. Debris topple | 6. Earth topple |
| Rotational sliding | 7. Rock slump | 8. Debris slump | 9. Earth slump |
| Transitional sliding | 10. Block slide | 11. Debris slide | 12. Earth slide |
| Lateral spreading | 13. Rock spread | - | 14. Earth spread |
| Flow | 15. Rock creep | 16. Talus flow<br>17. Debris flow<br>18. Debris avalanche<br>19. Solifluction<br>20. Soil creep | 21. Dry sand flow<br>22. Wet sand flow<br>23. Quick clay flow<br>24. Earth flow<br>25. Rapid earth<br>26. Loess flow |
| Complex | 27. Rock slide-debris avalanche | 28. Cambering, valley bulging | 29. Earth slump-earth flow |

Highland and Bobrowsky (2008) mentioned that natural disasters or human activities could either cause a landslide. In general, landslides are often triggered by natural disasters such as heavy rainfall, earthquakes, and volcanic eruptions. Haliza and Jabil (2017) stated that rainfall and poor slope management were the triggering factors that induced landslides at most construction sites in hilly areas. Landslides might also be caused by the insufficient analysis of previous slope failures and the misuse of prescriptive procedures.

In other aspects, many studies were researching the mechanism of landslide. Huat et al. (2012) used the Terrestrial LiDAR survey (TLS) to illustrate the failure area in the landslide. Then, back analysis was carried out to discuss the failure mechanism.

While Lee et al. (2013) analysed the correlation of landslide with rainfall intensities and conducted numerical stimulation on the mechanism of landslide induced by rainfall. Mukhlisin et al. (2015) mainly investigated the correlation between rainfall and soil quality with soil water index (SWI) as an indicator.

### 2.2.1 Overview of Landslide in Malaysia

Although mountain and hill areas in Malaysia are occupy less than 25% of topography, landslide still occurred regularly in the country (Haliza and Jabil, 2017). The study of Haliza and Jabil (2017) stated that approximately 28 major landslides were recorded in Malaysia throughout 1993 and 2011, causing the deaths of over 100 people. Furthermore, the gross financial loss in Malaysia attributable to landslides was reported to be around $1 billion from 1973 to 2007. It is worth mentioning that the very earliest failure of high rise building on hillslope side, Highland Tower Block 1 on 11 December 1993 in Selangor (Niroumand et al., 2012). The incident had successfully raised the awareness of public and private sector towards the importance of slope stability in construction site. Singh et al. (2008) had tabulated all the major landslide incidents occurred in Malaysia with casualties' toll recorded.

Table 2.2 Historical landslide occurrence from 1993 to 2004 (Singh et al., 2008)

| No | Location | Date | Types of landslides | Casualties |
|---|---|---|---|---|
| 1 | Ulu Klang, Selangor | December 1993 | Shallow rotational slide | 48 |
| 2 | Karak Highway, Genting Highland | June 1995 | Debris Flow | 22 |
| 3 | Gunung Tempurung, Kampar | January 1996 | Deep-seated rotational slide | 1 |
| 4 | Kampar, Perak | August 1996 | Debris Flow | 44 |
| 5 | Sandakan, Sabah | January 1999 | Shallow rotational slide | 13 |
| 6 | Cameron Highlands, Pahang | January 2000 | Debris flow | 6 |
| 7 | Simunjan, Sarawak | January 2001 | Shallow rotational slide | 16 |
| 8 | Ulu Kelang, Selangor | November 2002 | Debris flow | 8 |

Limited land in Penang area increased the frequency of hill development. Theoretically, hilly sites with dangerous slopes (20-30 degrees of gradient) and critical slopes (greater than 30 degrees of gradient) would not be appropriate to develop (Haliza and Jabil, 2017). However, earthworks can still be carried out at slope with gradient 50 to 70 degree for housing project at Paya Terubong (Ngai, 1997). Hence, slope failure can be occurred easily without proper reinforcement approaches and maintenance.

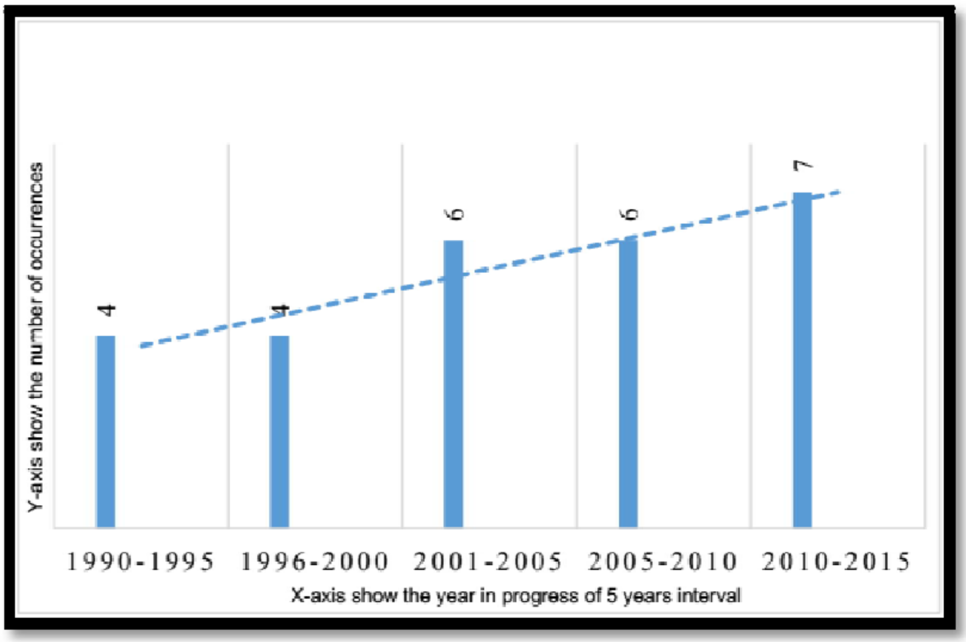


Figure 2.1 The trend of occurrence of landslide with years (Akter et al., 2019)

In the study of (Akter et al., 2019), the landslide cases in Malaysia showing a slightly increasing trend as shown in Figure 2.1. The increase in population had caused over developed on hillslope. The rate of development in slope areas should be given attention by researchers and more mitigation measures should be proposed to reduce the probability of landslide hazard.

### 2.2.2 Landslide hazard assessment

Landslide hazard assessment is of utmost vital since it functions as a precautionary step for engineers monitoring and preparing effective countermeasures to reduce the risk for the occurrence of landslide. In general, there are many landslide mapping techniques can be used to produce landslide hazard map. Aleotti and Chowdhury (1999) stated that landslide hazard assessment could be conducted in term of qualitative or quantitative.

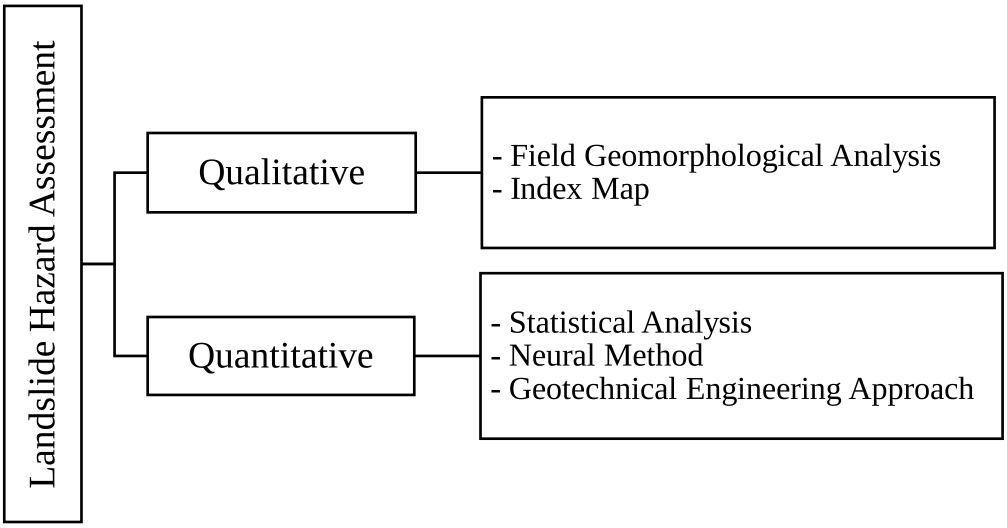


Figure 2.2 Different approaches of landslide hazard assessment

One of the qualitative methods is field geomorphological analysis which is a map that provide all the relevant data to evaluate the stability of slope. The use of index map is another method which weighting the topographic maps. Begueria and Lorente (1999) expressed the view on the complexity for the qualitative methods since subjective judgements involved. This mean the outcomes and results from multiple studies could be entirely different.

In contrast, quantitative method included statistical analysis, neural method, and geotechnical engineering approaches. Statistical analysis included bivariate analysis and multivariate analysis which study the relationship of landslide and various variables. Neural network analysis can be described as a black box model which can function as a device that able to iteration with certain parameters and calculate the output (Aleotti and Chowdhury, 1999). Geotechnical approach can divide to deterministic approach and probabilistic approach. Deterministic approach often conducted to determine the factor of safety (FOS) while probabilistic approach can used to evaluate the possibility for landslide event occur.

With development of technologies, geographical information systems (GIS) often used as deterministic approach and probabilistic approach to analyse landslide hazard (Van Westen and Terlien, 1996; Carrara et al., 1999; Ohlmacher and Davis, 2003). Landslide hazard map often used to show the historical landslides and to indicate the probability for landslide to occur in future, providing geological condition of the slope (Highland and Bobrowsky, 2008). In the study of Ohlmacher and Davis (2003), a landslide hazard map was produced using ArcView GIS after interpretation of all the data and previous geology map. In addition, probabilistic approach and linear regression were developed to generate equation to predict the landslide event. With the reference of index map using GIS, Van Westen and Terlien (1996) created a data base, calculated factor of safety, and produced a landslide hazard map.

For Penang area, the landslide hazard map was produced using different method in previous studies (Lee and Pradhan, 2006; Tay et al., n.d.). Tay et al. (n.d.) generated the landslide hazard map using three methods including frequency ratio, landslide nominal susceptibility factor and statistical index. While in the research of Lee and Pradhan (2006), a landslide distribution map was combined with frequency ratio values to understand the probability for landslide to occur in Penang Island area. A landslide susceptibility map was produced after correlating the occurrence of landslides with all the possible factors. Then, a landslide hazard map was generated by overlapping the landslide susceptibility map with precipitation map as shown in Figure 2.3.

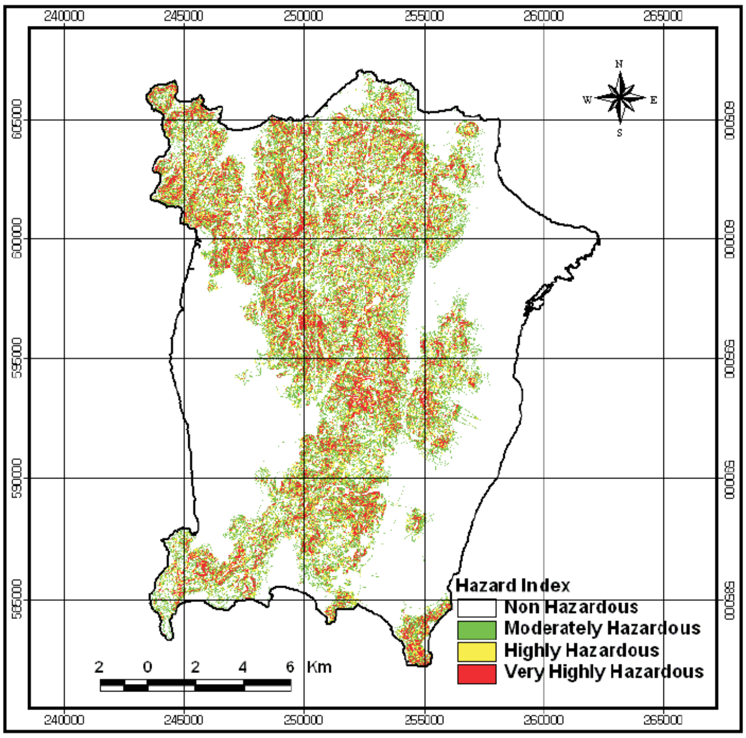


Figure 2.3 Landslide hazard map for Penang Island (Lee and Pradhan, 2006)

### 2.2.3 Earthquake-induced slope failure

Landslide triggered by earthquake had raised a lot of attention since it is a common phenomenon around the world. Serey et al. (2019) studied the area of Chile, South America and pointed out that magnitude of 8.8 $M_w$ Maule earthquakes had triggered a total number of 1226 landslides in 2010. In the finding of Wartman et al. (2013), Tohoku earthquake with magnitude 9.0$M_w$ jolted the country of Japan and inducing a total number of 3477 landslides in the area.

Highland and Bobrowsky (2008) pointed out that a big portion of hillslope area that susceptible to landslide had experienced seismic activities. The statement was proven by several cases such as massive landslide induced by the 1964 Great Alaskan earthquake with magnitude 9.2 $M_w$ in the United States. After seismic activities, loosening of rock and reduction of soil shear strength had a greater chance causing rockfalls or rock topple.

In Malaysia, the first recorded landslide triggered by earthquake was in Ranau, Sabah dated back to 26 May 1991 with magnitude 5.3$M_w$ (Marto et al., 2013). In contrast to landslides caused by heavy rainfall, landslides triggered by earthquake have distinct characteristics and owning more complex mechanisms. When an earthquake happens, cyclic loading of high shear stress can cause substantial shear strength loses along the sliding surface. Marui (2017) discussed several factors that are believed to be crucial in causing such a drastic drop in shear strength. One of the factors was the devastation of consolidated soil structure. In unsaturated conditions, cyclic loading induced by massive earthquake shaking would cause the destructive of consolidated soil structure, followed by reduction of soil shear strength.

In other aspects, the reduction in effective stress caused by increased pore-pressure could decrease the soil shear strength as well. The increase of pore water pressure was attributed to the earthquake liquefaction.

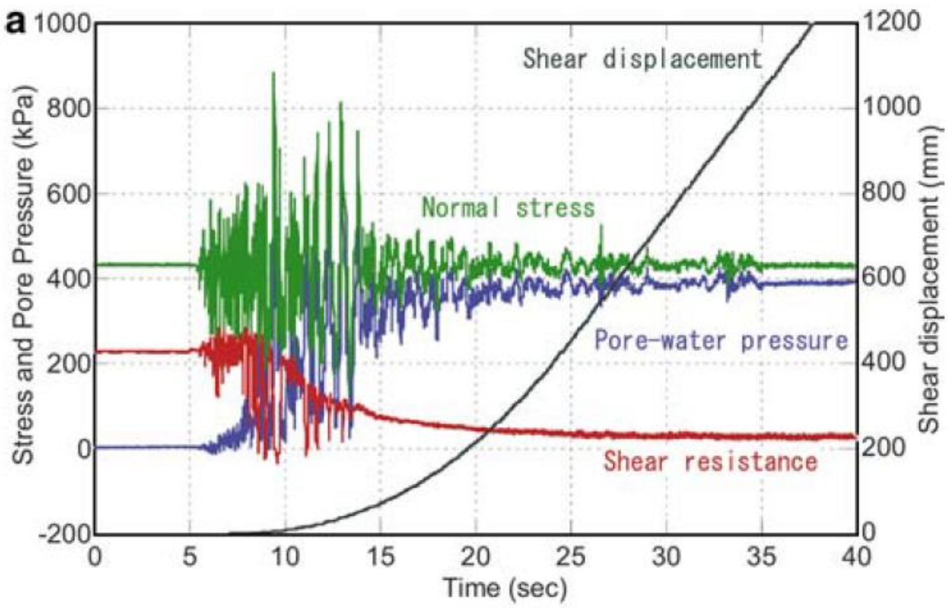


Figure 2.4 Undrained earthquake loading test (Sassa et al., 2005)

Under undrained condition, liquefaction took place which part of the loose soil will collapse, accompanied by a rise in pore water pressure and weakening of shear strength, causing shear displacement to occur. The mechanism had proven by the finding by Sassa et al. (2005) as shown in Figure 2.4.

### 2.2.4 Rainfall-induced slope failure

The effect of rainfall precipitation to slope stability was previously addressed in several studies (Niroumand et al., 2012; Chen et al., 2020; Kazmi et al.,2017). There were many cases of rainfall-induced landslide took place around the world. For example, a rockfall-type landslide had destroyed 75 houses and buried 40 people at Sadal village after two days heavy downpour on September 2014. This event had motivated Kumar et al. (2017) to analyse the relationship of rainfall distribution with formation of landslides in Indian Himalaya region. The research had concluded an amount of 290mm rainfall was capable to trigger a landslide, considering the geological conditions in the study area. Kazmi et al. (2017) focused on the landslide case study of Highland Tower on December 1993 in Selangor, Malaysia. The cumulative precipitation on the landslide hazard day was around 900mm which were around 35% of the annual rainfall 2604mm. The rainfall water had affected the flow of seepage and promote the rotational slope failure. LaHusen et al. (2020) had researched the occurrence of deep-seated landslides in Oregon Coast Range, United States, with finding the frequency of landslide hazard proportional with average rainfall intensity.

Highland and Bobrowsky (2008) mentioned that water is one of the major triggering factors of landslide. An increase of soil saturation by water such as snowmelt, canals, and intense rainfall can lead to slope failure. Figure 2.5 shows the effect of water to stability of slope in slip surface.

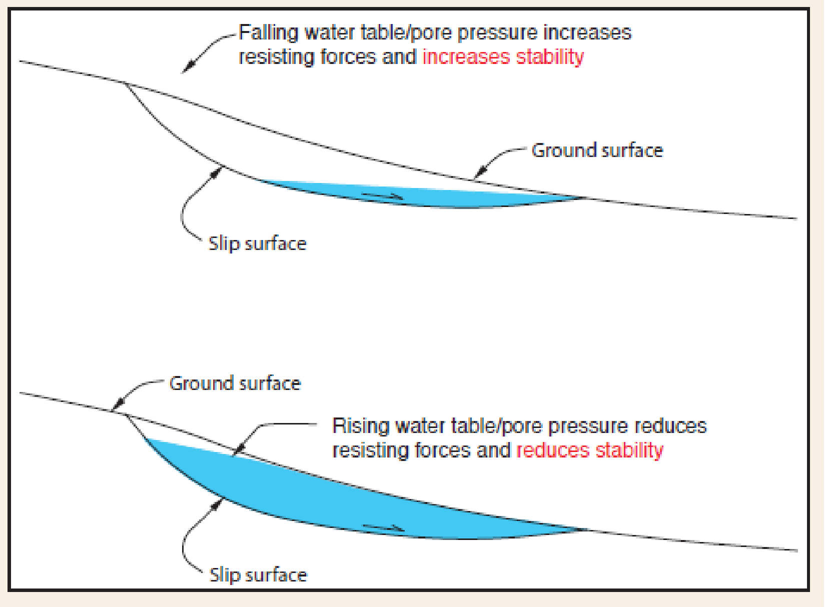


Figure 2.5 The general impact of water to slope stability (Highland and Bobrowsky, 2008)

The elevation of water table will lead to a reduction in pore pressure as shown in Figure 2.5. This will weaken the resisting force and eventually causing slope failure. In other words, heavy rainfall or cumulative precipitation that can affect the flow of seepage have a great effect to slope stability.

A conceptual idea of the slope instability induced by rainfall is shown as Figure 2.6. The heavy rainfall will increase the volume of surface runoff, causing surface erosion indirectly. When the soil permeability is high, it can contribute to a large volume of infiltration into the ground surface. This will cause a rise in groundwater table level which can reduce the soil suction (Niroumand et al., 2012). Eventually, it will lead to a reduction to soil shear strength. Chen et al. (2020) added on that the raise of groundwater table level will weaken the soil in potential surface and thus reduce the slope stability.

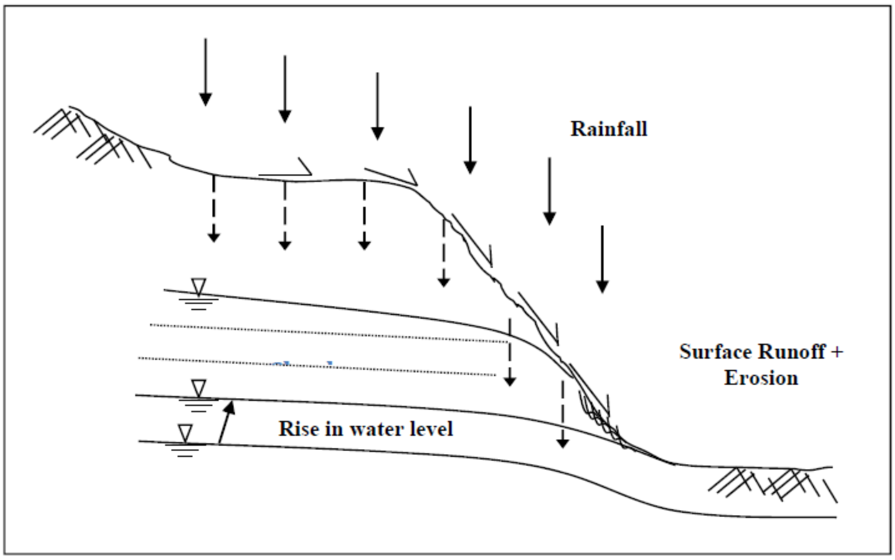


Figure 2.6 Effects of rainfall on slope (Niroumand et al., 2012)

## 2.3 Malaysia's seismic condition

Malaysia is located at Sunda plate and is mainly enclosed by extremely active subduction zones including the Philippine, Australian, and Indian plates. (Simons et al., 2007) Although most of the seismic activities appeared in the adjacent plate subduction, it was a great fortune for interior part of Sundaland to experience low seismic activities. To date, Malaysia has not suffered from any major earthquake. However, the 2004 Sumatera earthquake had caused disturbance to surrounding tectonic plates, including the deformation of core in Sunda plate. Marto et al. (2013) elaborated that Malaysia experienced a displacement in the direction of west-southwest, which is nearer to the epicenter. The frequency and magnitude of earthquakes took place in Malaysia were expected increase in the future.

Besides, Peninsular Malaysia had experienced the tremors of local earthquakes such as Bukit Tinggi Earthquakes, Manjung Earthquake, and Terengganu Earthquake (Malaysian Meteorological Department, 2011). The tremors of earthquakes from another region will hit Peninsular Malaysia occasionally as well. Table 2.3 listed the frequency and maximum intensity felt according to the state in Malaysia.

Table 2.3 Frequency and earthquake intensities recorded (Malaysian Meteorological Department, 2011)

| State | Frequency | Maximum Intensity (Modified Mercalli Scale) |
|---|---|---|
| Peninsular Malaysia (1909-2010) | | |
| Perlis | 3 | V |
| Kedah | 18 | V |
| Penang | 41 | VI |
| Perak | 24 | VI |
| Selangor | 52 | VI |
| Negeri Sembilan | 14 | V |
| Melaka | 19 | V |
| Johor | 32 | VI |
| Pahang | 35 | III |
| Terengganu | 2 | IV |
| Kelantan | 3 | IV |
| Kuala Lumpur/ Putrajaya | 38 | VI |
| Sabah (1897-2010) | | |
| Sabah | 41 | VII |
| Sarawak (1874-2010) | | |
| Sarawak | 17 | VI |

It can be said that Malaysia had greater chances to experience the tremors of earthquakes since a considerable number of earthquakes happened near to Malaysia. With the record of database in USGS website, a total number of 2454 earthquake events took place near to Malaysia from the year 1970 to 2021 as shown in Figure 2.7. The magnitude of the earthquake ranging from the smallest M4.0 to the largest M8.6.

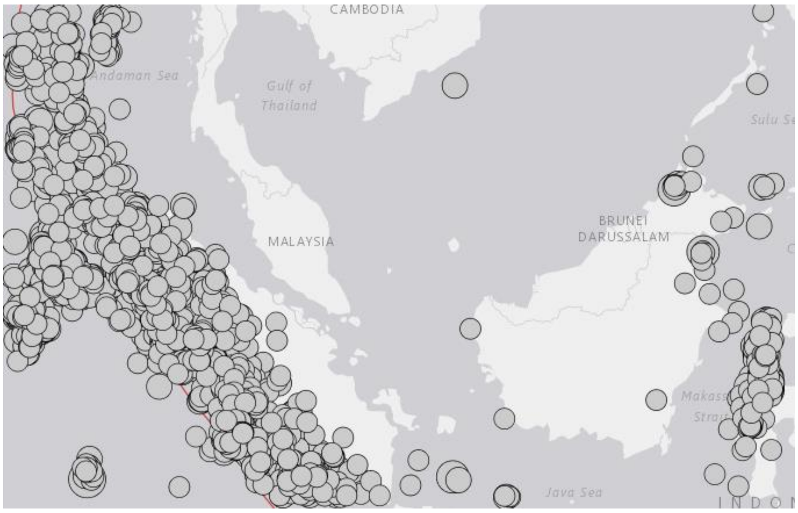


Figure 2.7 Earthquakes happened near to Malaysia from the year 1970 to 2021 (USGS)

Generally, the residents in west coast of Peninsular Malaysia often felt the tremors of earthquake from Sumatra, Indonesia. As an example, tremors of Sumatra earthquake hit Penang and Selangor area on 2 November 2002, terrifying residents in the affected area and causing cracks in the buildings (Azlan and Masyhur, 2002). Sumatra is one of the regions in Indonesia where earthquakes occur regularly. Azlan and Masyhur (2002) interpreted the data from National Earthquake Information Centre (USGS-NEIC) and mentioned that the occurrence of around 1000 earthquake cases with magnitudes greater than 5.0 $M_s$ in the region of Sumatra from year 1900 to 2002. Also, (Vigny et al., 2005) stated that the 2004 mega Sumatra-Andaman earthquake had causing irreversible impacts in many regions. The statement was supported with the fact of co-seismic jump that can recorded clearly even in region where 3000km away from the epicenter of earthquake. Displacements of 10 cm or more have been observed at the closest locations, which are still over 400 km away. It can be said that Malaysia had a greater chance to experience the effects caused by earthquakes since the nearest epicenter of earthquake was about 350km from Malaysia (Marto et al., 2013; Azlan and Masyhur, 2002).

### 2.3.1 Historical event

The impact of earthquake to the world had been studied by Cannon and Schipper (2014). The report of World Disaster 2014 had recorded a total of 650,321 losses of lives around the world in historical earthquakes event from the year 2004 to 2013. Several significant historical earthquakes also mentioned by Cannon and Schipper (2014) such as 2010 Haiti earthquake which causing 222,570 deaths, Kashmir earthquake in 2005 which led to 74,648 and China Sichuan earthquake in 2004 resulting in 87,476 deaths. In short, the earthquake cases in the 10 years duration had cost an estimated loss of 507,484 million of US dollar.

Table 2.4 tabulated all the historical earthquake events that significantly affected Malaysia. All the earthquake listed are not originated from Malaysia, but the earthquake had greatly affected citizens in Malaysia. From Table 2.4, it can be concluded that most of the earthquakes originated from Sumatera had greatly affected the residents in Malaysia.

Table 2.4: Historical earthquake events that affected Malaysia (Marto et al., 2013)

| No | Date | Epicenter | Magnitude | Effect on Malaysia |
|---|---|---|---|---|
| 1 | 27 August 1984 | Northern Sumatera | 5.2 | Kuala Lumpur, Penang |
| 2 | 25 April 1987 | Northern Sumatera | 6.3 | Kuala Lumpur |
| 3 | 15 November 1990 | Northern Sumatera | 6.9 | Ipoh, Kuala Lumpur, Penang, Taiping |
| 4 | 11 October 1994 | Southern Sumatera | 6.5 | Southern Malaysia and Singapore |
| 5 | 20 August 1997 | Northern Sumatera | 6.0 | Alor Setar, Petaling Jaya, Penang |
| 6 | 1 April 1998 | Padang | 6.9 | Kuala Lumpur |
| 7 | 4 May 2000 | Sulawesi | 7.4 | Tawau |
| 8 | 4 June 2000 | Southern Sumatera | 7.7 | Johor Bahru, Kuala Lumpur, Petaling Jaya |
| 9 | 2 November 2002 | Simeulue | 7.4 | Kuala Lumpur, Port Kelang |
| 10 | 25 July 2004 | Southern Sumatera | 7.3 | Southern Johor, Singapore |
| 11 | 26 December 2004 | Northern Sumatera | 9.0 | 68 people killed in Penang, Langkawi, Kedah |
| 12 | 12 February 2005 | Sulawesi | 7.0 | Kota Kinabalu |
| 13 | 28 March 2005 | Northern Sumatera | 8.6 | West coast Peninsular Malaysia |
| 14 | 10 April 2005 | Mentawai | 6.7 | Kuala Lumpur, Singapore |
| 15 | 10 April 2005 | Mentawai | 6.5 | Kuala Lumpur |
| 16 | 24 July 2005 | Nicobar Islands | 7.2 | George Town |
| 17 | 16 August 2009 | Southern Sumatera | 6.3 | Kuala Lumpur, Penang, Johor |
| 18 | 9 May 2010 | Northern Sumatera | 7.2 | Sungai Dua, Penang |
| 19 | 11 April 2012 | Northern Sumatera | 8.2 | Penang, Kuala Lumpur |
| 20 | 25 July 2012 | Northern Sumatera | 6.6 | West Coast Peninsular Malaysia |

Other than earthquake from other regions, local earthquake played an important role in defining the seismic condition in Malaysia. In annual report of Malaysian Meteorological Department, a total number of 451 earthquakes were discovered around the world in 2019 (Malaysian Meteorological Department, 2019). Among them, 183 earthquakes took place in local area which is Sabah and Perak. Ranau, Sabah had recorded the highest number of 119 earthquake in Malaysia. It can be clearly seen that most of the local earthquake had took place in the state of Sabah, Malaysia. Therefore, Sabah was recognized as earthquake-prone area with the existence of at least 13 actives faults. Since 1874, there had been 21 earthquakes in Sarawak and 94 earthquakes in Sabah (Marto et al., 2013). It is worth mentioning that the 2015 earthquake in Ranau is the local earthquake that most influential to Malaysia after the 1976 Sabah earthquake. The 2015 Ranau earthquake with magnitude of 6.0 $M_w$ had took the lives of 18 victims. Other than that, several local earthquake events like Lahad Datu Earthquake in 1976, Ranau Earthquake in 1991 and Miri Earthquake in 2004 had caused damages and destroyed old buildings in affected area. (Malaysian Meteorological Department, 2011)

## 2.4 Malaysia's climate

Due to global warming, climate change is a common occurrence in Malaysia. Malaysia had experienced significant change in climate especially the variation in rainfall, revealing the need to study the changes in climate trend and their consequences. According to Wang et al. (2014), climate change often causes the change in temperature, and thus possibly affecting the magnitudes, frequencies, and intensities of rainfall. Climate change also had potential resulting in uncertainty to geographical distribution of rainfall. Followed Mayowa et al. (2015), the extreme weather event caused by climate change was expected to experience a growing pattern in the future. The statement also coincides with Tang (2019) which stated that extreme weather events such as heavy rainfall, heat waves, and thunderstorm had become more frequent in recent decade. Since 1980s, the frequency of heavy rainfall has climbed. This would directly increase the number of floods occurred in Malaysia. In common, flash flood and monsoonal flood are two main forms of flood. Among both, flash flood always triggered by heavy rainfall and extreme thunderstorm over a timeframe of less than six hours while monsoonal flood happens due to severe heavy rainfall. The heavy rainfall and flood disaster are capable to alter the surface structure and shift the hydrological cycle. For instance, the heavy downpour that start from 8am to 4pm had caused a flash flood incident and triggered a landslide in Balik Pulau, Penang on the 21 November 2018.

From geological aspects, the condition of Malaysia is relatively safe since it was surrounded by Indonesia, Vietnam, and Thailand. Thus, the probability for Malaysia to receive a direct strike from tropical typhoon is minimal. However, the occurrence of tropical typhoon at other region might switch the wind direction and causing heavy rainfall in our country. For instance, Typhoon Lekima strike China in August 2019 and causing the negative impact on Malaysia's weather at the same time. Penang area had to cope with the destructive effects including heavy rainfall and flood disaster bring by the Typhoon Lekima (Malaysian Meteorological Department, 2019). Other than that, Penang Island suffered from heavy rainfall and slope failure due to the occurrence of Typhoon Damrey start from 1$^{st}$ November to 4$^{th}$ November 2017. Ahmad et al. (2020) stated that the recorded rainfall intensity for these four days was 315mm, which cause the water overflowing and carrying the soil down the hillslope. The situation eventually led to slope failure incident in Penang Island.

### 2.4.1 Rainfall Monsoon Season

In Malaysia, rainfall intensities can be affected by two monsoon seasons which is Southwest Monsoon (SWM) and Northeast Monsoon (NEM) (Wong et al., 2009; Malaysian Meteorological Department, 2019). The timeframe for Southwest Monsoon and Northeast Monsoon is generally from May to September and from October to March respectively. Other than these two monsoon seasons, there are another two Inter Monsoon seasons in April and October. Suhaila et al. (2010) agreed and stated that monsoon rainfall contributed around 81% of annual average rainfall in Malaysia. Suhaila et al. (2010) and Khan et al. (2019) had deeply elaborated the rainfall intensities during respective monsoon and their effects in certain zones.

The annual report by Malaysian Meteorological Department (2019) stated that Malaysia will experience hotter weather during Southwest Monsoon (SWM) in overall. However, Suhaila et al. (2010) studied the historical rainfall indices and concluded that the SWM had the greatest influence on the northwest region of Peninsular Malaysia, especially in terms of defining the rainfall pattern. The northwest region including Perlis, Kedah, Perak, Penang and some others states in Peninsular Malaysia can be considered as the wettest region during the monsoon.

In contrast, annual report 2019 by Malaysian Meteorological Department (2019) had concluded that local area will experience higher rainfall intensity during Northeast Monsoon (NEM). However, Suhaila et al. (2010) stated that northwest region in Peninsular Malaysia had experienced lowest rainfall indices during this monsoon. The reason for northwest region receiving least impacts of NEM is due to the Titiwangsa Range. Titiwangsa Range is recognized as backbone of Peninsular Malaysia, formed by several mountains. During NEM, Titiwangsa Range is function as a barrier to reduce the chance for northwest region from receiving heavy rainfall. In