RAINFALL-INDUCED LANDSLIDES IN HULU KELANG AREA, MALAYSIA

NG KIM YEONG

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Bachelor (Hons.) of Civil Engineering

Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature : __________________________

Name : __________________________

ID No. : __________________________

Date : __________________________

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"RAINFALL-INDUCED LANDSLIDES IN HULU KELANG AREA,MALAYSIA"** was prepared by **NG KIM YEONG** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Civil (Hons.) Engineering at Universiti Tunku Abdul Rahman.

Approved by,

Signature : _________________________

Supervisor : Dr. Lee Min Lee

Date : _________________________

Specially dedicated to
my beloved grandmother, mother and father

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In addition, I would like to acknowledge the rainfall and landslide data provided by the Ampang Jaya Municipal Council (MPAJ) and the Slope Engineering Branch of Public Works Department Malaysia (PWD).

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ABSTRACT

Hulu Kelang is known as one of the most landslide prone areas in Malaysia. The area has been constantly hit by landslide hazards since 1990’s. This project provides an insight into the mechanism of rainfall-induced landslide in the Hulu Kelang area. The rainfall patterns prior to the occurrences of five selected case studies were first analyzed. The results showed that daily rainfall could not be used for predicting the landslides in Hulu Kelang. The landslide predictions should incorporate the rainfalls of long durations, i.e. 3 to 30 days prior to the landslides. The numerical simulation on a selected case study demonstrated that both the matric suction and factor of safety decreased steadily over time until they reached the lowest values on the day of landslide occurrence. The redistribution of infiltrated rainwater in the soil mass could be the reason for the slow response of failure mechanism to rainfall. Based on 21 historical rainfall induced landslides that had occurred in the area, three rainfall thresholds were developed as attempts to predict the occurrence of rainfall-induced landslide. The rainfall intensity – duration threshold developed based on the local rainfall conditions provided a reasonably good prediction to the landslide occurrence. The cumulative 3-day versus 30-day rainfall threshold chart was capable of giving the most reliable prediction with the limiting threshold line for major landslide yielded a reliability of 97.5%.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

$CARx_n$	Calibration antecedent rainfall for day x
$(E_{30} - N)$	Cumulative 30-day rainfall – Number of rainy day threshold chart
$(E_3 - E_{30})$	Cumulative 3-day rainfall – Cumulative 30-day rainfall threshold chart
Pn	Daily rainfall for the nth day before day x
D	Duration of the rainfall event (h)
K	Empirical parameter (typical value range between 0.8 and 0.9)
FOS	Factor of Safety
$(I - D)_3$	Intensity – Duration of 3-day rainfall threshold chart
MAP	Mean Annual Precipiration
E_{MAP}	Normalized event rainfall
I	Rainfall intensity, mm/h

ϕ^b	Angle of frictional resistance
c'	Effective cohesion
σ'	Effective normal stress
ϕ'	Effective friction angle
α	Intercept
$(u_a - u_w)$	Matric suction
$(\sigma_n - u_a)$	Net normal stress
k_{sat}	Saturated permeability
τ_f	Shear stress at failure
β	Slope of the power low curve
γ'	Soil unit weight
σ^s	Suction stress
q	Unit flux

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Massive landslides in Malaysia are mainly attributed to frequent and prolonged rainfalls, in many cases associated with monsoon rainfalls. Of the landslide prone areas in Malaysia, Hulu Kelang area has received the most publicity. Hulu Kelang is a residential area located at the toe of the Titiwangsa mountain range (Figure 1.1). The area has been constantly hit by fatal landslides since December 1993, when a block of residential apartment known as Highland Towers collapsed causing a tragedy involving 48 deaths (Gue and Cheah, 2008). Over the following two decades, a series of catastrophic and small to medium-sized landslides have been reported.

According to the data sources from the Ampang Jaya Municipal Council (MPAJ) and the Slope Engineering Branch of Public Works Department Malaysia (PWD), as well as data compilation from the previous reported studies by Farisham (2007), and Low and Ali (2012), a total of 28 historical landslide events have been reported in the Hulu Kelang area from 1990 to 2011.They were generally scattered all over the developed parts of the Hulu Kelang area implying hillside development has caused disturbance to the ecosystem, and hence the stability of the natural slopes.

Figure 1.1: Location of Hulu Kelang Area, Malaysia

The landslides in Hulu Kelang area have been studied by a number of local researchers and practicing engineers. Gue and Liong (2007) investigated the main causes of the landslides in Hulu Kelang area. They concluded that most of the landslides were caused by inadequate design of retaining structures and slopes. The finding was supported by Farisham (2007) who also investigated the hillside developments in Hulu Kelang. She found that most of the landslides were caused by improper design and construction method. Low et al. (2008), Mukhlisin et al. (2010), and Low and Ali (2012) used the Geographical Information System (GIS) application to perform area based slope hazard assessment and mapping at Hulu Kelang area. They concluded that the hazard map can be used as an effective tool for predicting the landslide occurrence. Ashaari et al. (2008) carried out a field survey work at Hulu Kelang area. A total of 152 landslide scars of both soil and rock slopes were identified as the potential slope failure sites. Akib and Aziz (2007) investigated the landslide motions at Kampung Pasir, Hulu Kelang using continuous monitoring approach. They found that the ground has moved from 2 mm to 17 mm during the monitoring period of 10 days. Low et al. (2012) performed a detailed investigation on one of the major landslides occurred in Hulu Kelang area, known as Bukit Antarabangsa 2008 landslide. They concluded that prolonged rainfall during the monsoon season is one of the main factors triggering the landslide.

Despite of the fact that abundance of relevant studies have been carried out, landslide is still a recurring hazard in Hulu Kelang area. It was either due to the proposed mitigation measures and slope design guidelines were not taken seriously by the engineers or the actual mechanism of the landslides have yet been revealed, is still unclear. Consequently, public protests have emerged against hillside development in the country. Abruptly halting all the hillside developments, however, is not the best solution in view of growing land scarcity issue in the urban areas like Kuala Lumpur.

1.2 Project Aims and Objectives

The aim of this project is to study the rainfall-induced landslides in Hulu Kelang area. The specific objectives are set forth:

i. To provide an overview of rainfall-induced landslides in Hulu Kelang area through five selected case studies
ii. To investigate the mechanism of rainfall-induced landslides through numerical simulation on a selected case study.
iii. To develop empirical rainfall thresholds for predicting the landslide event in Hulu Kelang area.

1.3 Scope of Study

The study area concerned was centralized in Hulu Kelang which located about 10km away from Kuala Lumpur city. The rainfall data is obtained from Jabatan Pengairan dan Saliran (JPS). While the rainfalls' record is based on the nearest rain gauge station for each landslide event. The historical landslide event is collected from local newspaper, Majlis Perbandaran Ampang Jaya (MPAJ), Public Work Department (JKR) and publication journal.

This project aims to provide an insight into the mechanism of rainfall-induced landslide, and develop empirical rainfall thresholds for anticipating the landslide occurrence in the Hulu Kelang area. Firstly, the rainfall patterns prior to the landslide occurrences at five selected case studies are analyzed. The analysis of the rainfall pattern is important for providing an overview of the rainfall conditions that had triggered the landslides in Hulu Kelang. Next, numerical simulation is carried out on a selected case study in Hulu Kelang to provide an insight into the mechanism of rainfall-induced landslide. Finally, three empirical rainfall threshold charts for the initiations of landslides in Hulu Kelang area are proposed based on the rainfall data that had resulted in the 21 historical landslide events. These charts could serve as the basis for developing an effective early warning system for the area concerned.

1.4 Problem Statement

On December 1993, a slope failure occurred in Hulu Kelang which consequently caused a block of the Highland Tower collapsed and claimed 49 lives. This tragedy was contained by small to medium size of landslide occurred in Hulu Kelang area which includes Bukit Antarabangsa landslide on May 1999, Jalan Bukit Antarabangsa landslide on October 2000, Taman Hillview landslide on November 2002, Kampung Pasir landslide on May 2006, Bukit Antarabangsa landslide on December 2008. A study found out that most of the landslides in Hulu Kelang area were due to the design and construction errors. However, prolonged and frequent rainfall could be a major triggering factor as most of the landslides occur during monsoon season.

Despite of the fact that abundance of relevant studies have been carried out, landslide is still a recurring hazard in Hulu Kelang area. It was either due to the proposed mitigation measures and slope design guidelines were not taken seriously by the engineers or the actual mechanism of the landslides have yet been revealed, is still unclear. Consequently, public protests have emerged against hillside development in the country. Abruptly halting all the hillside developments, however, is not the best solution in view of growing land scarcity issue in the urban areas like Kuala Lumpur.

1.5 Significance of Study

These studies provide the understanding of relationship between rainfall amount and duration that possesses the possibility to trigger a landslide. Since Hulu Kelang area is located in the high landslide prone area, thus, it is necessary to develop an empirical rainfall threshold to predict the landslide event.

1.6 Orientation of Thesis

This thesis was divided into five chapters. The first chapter briefly describes the background of study, project's aim and objective, scope of study, problem statement and significant of research. Second chapter reviewed the main factors and landslide problem that happened in Malaysia. It also reviewed the mechanisms of rainfall-induced landslide and empirical rainfall thresholds for landslide triggering. The background and previous research carried out at Hulu Kelang area are also discussed in chapter 2.

Furthermore, chapter 3 defined the methodology and research framework used to produce this report. This chapter will discuss the required information and data needed to develop an empirical rainfall threshold. It also explained the method to develop the threshold amount and duration. Next, chapter 4 discussed all the collected information and results. The occurrence of landslide, consequence, soil investigation and rainfall pattern for the five selected cases were also discussed in it. Lastly, the conclusion and recommendation will be presented in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 General

This chapter presents the general overview of landslides problem in Malaysia and factors causing landslides. It is important to show the mechanism of rainfall-induced landslide and empirical rainfall threshold for landslide triggering. The previous researches carry out at Hulu Kelang area are also included in this chapter.

2.2 Landslide Problem in Malaysia

Landslides are responsible for considerable losses in term of both money and lives. Figure 2.1 shows the annual economic costs due to landslide from 1973 to 2007. With particular reference to Malaysia, landslide problems are worsening as a result of rapid economic development (National Slope Master Plan , 2009).

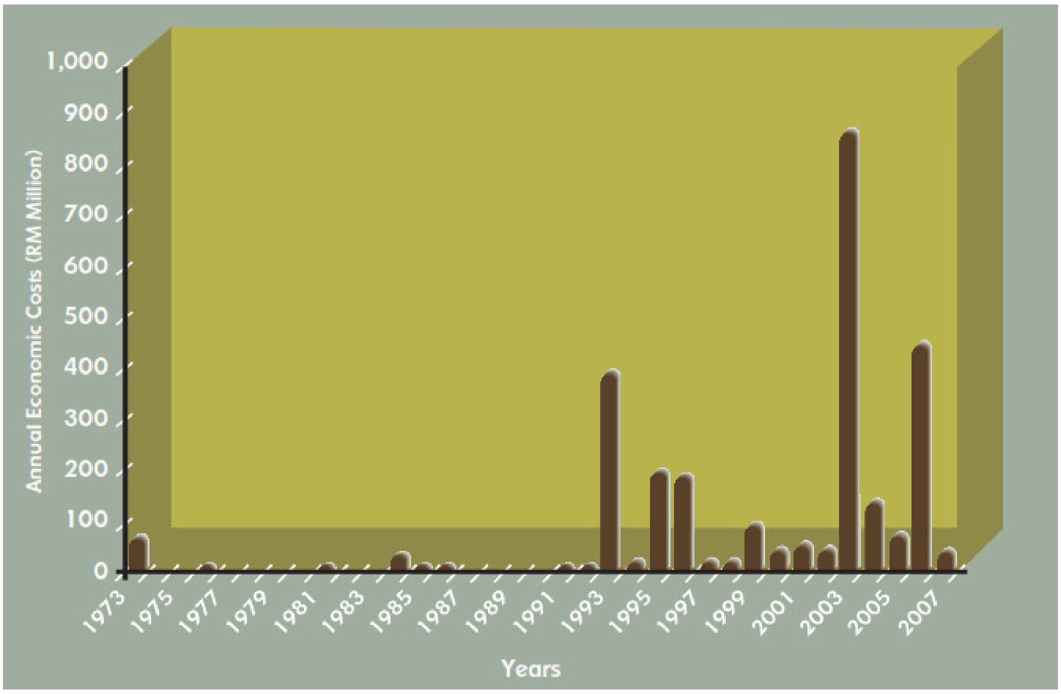


Figure 2.1: Annual Economic Costs due to Landslide from 1973 to 2007 (National Slope Master Plan 2009)

Landslides have posed serious threats to settlement and structures that support transportation, natural resource management and tourism. More than 100 hillslopes had been identified by Malaysian Public Works Department (PWD) as risky for possible landslides (Mukhlisin et al., 2010). Gue and Tan (2006) in the study of causes of slope failure found that eighty-eight percent of the 49 cases of slope failure in Malaysia are man-made slope failures. The failures are mainly due to the either design errors or construction errors. The finding was supported by Jamaluddin (2006) who studies on many cases of slope failures in Malaysia indicated that the slope failures are mostly attributed to human factors such as negligence, incompetence, lack or poor maintenance system, ignorance of geological inputs, unethical practice and various negative human attitudes.

Furthermore, the climate in malaysia are hot and humid all year around. The annual monsoons in Malaysia are from southwest and notheast which are started from April to October and from Octorber to February repectively. The average annual rainfall in Malaysia is around 2000 to 2500mm.With the larger amount in intensity, lanslides become one of the most critical natural disasters in Malaysia. Jamaludin (2011) in his study found that most of the landslides in Malaysia are shallow landslides. These shallow landslides mostly triggered by heavy rainfall in wet seasons due to loss of matrix suction or loss of negative pore-water pressure. In some other places, it was due to development of perched water table near to the soil surface.

The record of landslides in Malaysia was compiled by Abd Rasid (2006). He reviewed some of the landslides occurred in Malaysia from 1990 to 2004. The earliest written record of landslide in Malaysia is the rockfall that occurred on 7 December 1919 at Bukit Tunggal, Perak, which claimed 12 lives and damaged property. In this chapter, the landslides occurred in between 1990 and 2011 have been reviewed. Table 2.1 summaries some recorded landslides events in Malaysia from 1990 to 2004**.**

Table 2.1: Landslides Events in Malaysia from 1990 to 2011 (Rasid, 2006)

Date	Location	Fatalitis (No)	Injuries (No)	Consequences
11.12.1991	Km 47,KL,Karak Highway, Pahang	0	0	No record
17.10.1993	Km 32,Jalan Pahang to Cameron Highland, Pahang	0	0	No record
24.10.1993	Km 58, Kuala Lipis - Gua Musang road, Kelantan	1	15	No record
14.11.1993	Km 32, Jalan Bentong - Kuala Lumpur	0	0	No record
23.11.1993	Km 25.5, KL - Karak Highway, Pahang	0	0	Road closure for 2 days.
28.11.1993	Km 63, KL - Karak Highway, Pahang	2	0	No record
11.12.1993	Highland Towers, Selangor	48	2	Hundreds homeless and injured
15.12.1993	Kuala Lipis, Pahang	0	0	9 cars buried
21.12.1993	Km 11, Jalan Puchong, selangor	0	0	House/cars swept away
22.12.1993	Km 9, 20, 24, 25 and 26 of East- West Highway, Kelantan	0	0	No record
25.12.1993	Km 62 and 70, Kuala Krai - Gua Musang road, Kelantan	0	0	1 car damaged. Road closure for 1 day.
28.12.1993	Kg Lereng Bukit, Miri, Sarawak	0	0	300 persons evacuated.
31.12.1993	Km 59.5, East-West Highway, Kelantan	1	3	A car damaged
22.03.1993	Fraser Hill, Pahang	0	0	Part of a hotel damaged
14.02.1994	Jalan Ampang,Selangor	0	0	No record
02.05.1994	Puchong Perdana, Selangor	3	0	10 families evacuated.
11.11.1994	Km 32, East-West Highway,Kelantan	0	0	Road closure for days. Tens stranded
15.11.1994	Km 33, East-West Highway, Kelantan	0	0	Road closure for days.

03.05.1995	Tmn Keramat Permai, Selangor	0	0	No record
15.05.1995	Keramat Permai , Selangor	0	0	No record
30.06.1995	Genting Sempah, Selangor	20	22	Tens of vehicles damaged
05.07.1995	Rockfall, Batu Pahat, Johor	0	0	4 houses and 3 factories destroyed. 12 hoouses damaged
18.08.1995	Km 92 - 97, KL - Kuala Lipis road, Pahang	0	0	No record
20.08.1995	Ampang Jaya, Selangor	0	0	No record
18.09.1995	Hong Seng Estate	0	0	No record
19.09.1995	Penang Hill area, Penang	0	0	No record
24.09.1995	Taman Bukit Teratai, Ampang, Selangor	0	0	No record
16.10.1995	Bukit Tuanku, Kuala Lumpur	0	0	No record
24.10.1995	Tringkap, Cameron Highland, Pahang	1	0	A house damaged.
31.10.1995	Tapah - Cameron Highland road, Perak	0	0	Road closure for 2 days.
09.11.1995	Teluk Bahang, Penang	0	0	2 house damaged
20.11.1995	Km 27, Bahau - Tampin road, N. Sembilan	0	0	No record
21.12.1995	Km 61, Bailey Bridge, Kuantuan - Maran road ,Pahang	0	0	No record
23.12.1995	Km 19, Hulu Yam Baru - Sg Tua road, Selangor	0	0	A car damaged. 2 persons injured
25.12.1995	Jalan Belading, Tangkak, Johor	0	0	No record
Dec-95	Cameron Highlands, Pahang	7	0	Few houses damaged
06.01.1996	Km 303.8, North-South Expressway, Gunung Tempurung, Perak	1	1	2 weeks of expressway closure and 3 months of road diversion
28.01.1996	Bandar Ampang, Selangor	0	0	No record
10.06.1996	Ampang Jaya, Selangor	0	0	No record
02.09.1996	Pos Dipang, Perak	44	Tens	Whole village relocated
09.10.1996	Kuala Terla, Cameron Highlands, Pahang	3	2	Few houses damaged
26.12.1996	Keningan, Sabah(part of Gregg Typhoon)	300	Tens	Villagers relocated
Oct-96	Hye Keat Estate	0	0	Hundreds evacuated.
15.10.1996	Kg Chengkau Hilir, Rembau, N. Sembilan	0	0	No record
18.10.1996	Cameron Highlands, Pahang	0	0	16 families evacuated
18.10.1996	Gelang Patah, Johor	1	0	6 families evacuated
11.05.1997	Pantai Dalam, Kuala Limpur	1	4	19 families evacuated
28.11.1998	Paya Terubong, Pahang	0	0	17 vehicles buried
08.02.1999	Kg Gelam, Sandakan, Sabah	17	0	Squatters were relocated
14.05.1999	Bukit Antarabangsa,Selangor	0	0	No record

15.05.1999	Bukit Antarabangsa, Selangor	0	0	1,000 people evacuated and 15,000 people stranded. 1 day ofroad closure
10.07.1999	Kondominium Mutiara, Selangor	0	0	No record
28.11.1999	Bukit Aman, Pahang	0	0	15 cars/1 bus/ 1 motocycle damaged
03.12.1999	Km 449.6, North South Expressway, Sg Buloh, Selangor	0	0	Thousands of vehicles stranded. 1 day of road closure
13.12.1999	Km 52, Johor Bahru - Ayer Hitam road, Johor	0	0	No record
09.01.2000	Km 81.6,Tanah Rata - Brinchang road, Cameron Highland, Pahang	6	0	15,000 people stranded for hours
05.10.2000	Jln Bukit Antarabangsa, Selangor	0	0	No record
18.01.2001	Km 16.1, North South Expressway, Skudai, Johor	0	0	No record
22.09.2001	Sg. Chinchin, Gombak, Selangor	1	0	A house partly destroyed
29.10.2001	Taman Zooview, Selangor	0	0	No record
08.11.2001	Taman Zooview, Selangor	0	0	No record
Dec-01	Gunung Pulai debris flow, Johor	15	2	A house detroyed
28.01.2002	Ruan Changkul, Sarawak	16	0	Long houses relocated
20.11.2002	Taman Hillview, Selangor	8	5	A bungalow destroyed
03.03.2003	Bukit Indah Ampang, Selangor	0	0	No record
02.11.2003	Oakleaf Park Condo, Bukit.Antarabangsa, Selangor	0	0	No record
07.11.2003	Jalan Bukit Muliam Bukit Antarabangsa, Selangor	0	0	No record
26.11.2003	Km 21.8, North Klang Valley Expressway, Bukit Lanjan, Selangor	0	0	6 months of traffic diversions and massive jams in kl
24.02.2004	Km 52, Tapah-Ringlet road, Cameron Highland, Pahang	0	0	Main road cut off for hours
11.10.2004	Km 302, North South Expressway, Gunung Tempurung, Perak	0	0	Road closure for 2 days.
31.01.2005	Jln Tebrau, Dataran Ukay, Selangor	0	0	No record
01.02.2005	Jln Tebrau, Dataran Ukay, Selangor	0	0	No record
31.05.2006	Kampung Pasir	4	0	Damage 3 blocks of Long houses
24.04.2008	Condo Wangsa Height, Selangor	0	0	No record
06.12.2008	Tmn Bukit Mewah, Selangor	0	0	No record
19.09.2009	Wangsa Height, Selangor	0	0	No record
Jan-10	Pangsapuri Sri Wira, Selangor	0	0	No record
Apr-10	Ukay Club Villa , Selangor	0	0	No record
Ogos 2010	Bukit Antarabangsa, Selangor	0	0	No record
Feb-11	Ukay Perdana, Selangor	0	0	No record
21.06.2011	Taman Bukit Jaya, Selangor	0	0	No record

2.3 Factors Causing Landslide

A slope can be failed by many contributing factors, but there is always one main factor that triggers the landslides at the time of failure. It should be noted that landslides may occur without apparent triggering factors. This section discusses the contributing and triggering factors that cause the failure of the slope.

2.3.1 Worldwide Condition

According to the National Slope Master Plan (2009), the main contributing factors to trigger the landslides are found to be geological causes or ground conditions, hydrological causes, morphological causes, physical causes and human causes. These main contributing factors are based on the review of selected worldwide literatures. A total of 30 case studies excluding Malaysia case studies were carried out with reference from countries such as China, Italy, Thailand, Russia, Taiwan, Germany, Korea, Japan, and Australia**.** Figure 2.2 presents the contributing factors of landslides based on selective worldwide literatures. The statistics indicate that ground conditions and human causes are the major contributing factors of landslide failures on a worldwide basis. In addition, the occurrence of landslides also due to mismanagement of land use due to the increasing number of population and the needs of land for producing agricultural products that, that force people to stay in landslide hazard areas (Soralump, 2010).

A study found that the most common landslides triggering factors are intense rainfall, rapid snowmelt, water level change, volcanic eruption, earthquake shaking and change of slope geometry. The landslides triggering factors based on selective worldwide literatures is presented in Figure 2.3. The statistic indicated that rainfall and water level change are the major triggering factors of a landslide (National Slope Master Plan , 2011). Rahardjo et al. (2001) in their studies also proposed that rainfall has been the triggering factor for slope failures. These failures can be hazardous, disruptive to the development of infrastructure and costly repair

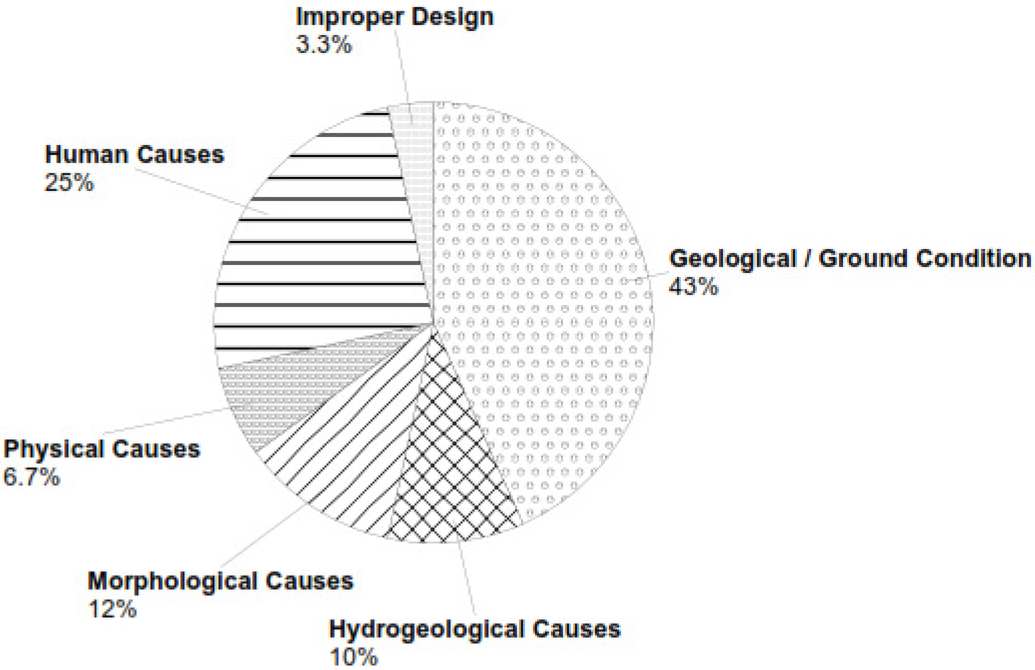


Figure 2.2: Contributing Factors of Landslides Based on Selective Worldwide Literature (National Slope Master Plan,2009)

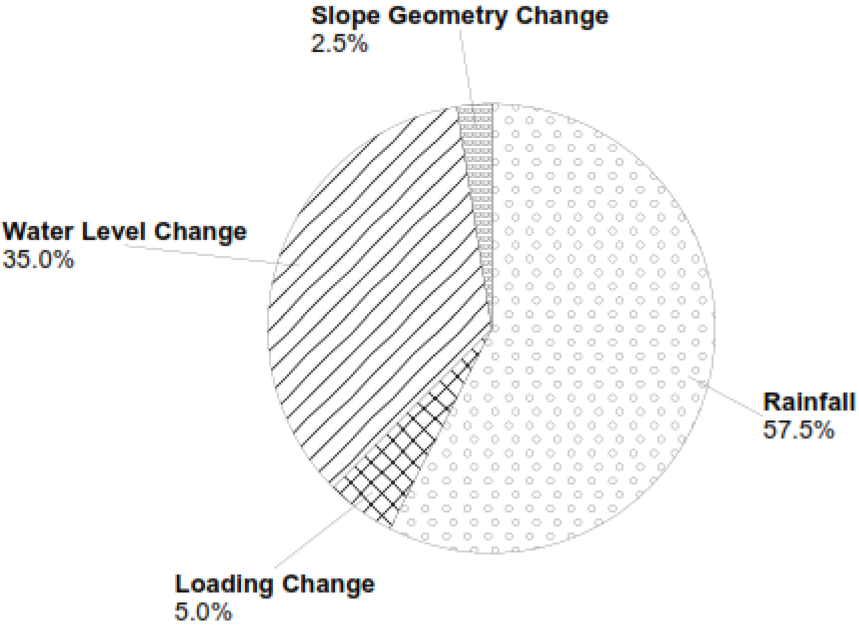


Figure 2.3: Landslides Triggering Factors Based on Selective Worldwide Literatures (National Slope Master Plan, 2009)

2.3.2 Relevance to Malaysia Condition

Based on the worldwide literature review, a summary of landslide contributory and triggering factors is presented. However, not all the factors are applicable to Malaysia condition. Gue and Tan (2006) found that most of the slope failures in Malaysia are due to design errors, construction errors, design and construction errors, geological features and maintenance. The study is based on 49 investigation cases of primarily large landslides on residual soils. Table 2.2 shows the causes of landslides. The results of the study indicate that 60% of the failures are due to inadequacy in design alone. The inadequacy in design is generally the result of a lack of understanding appreciation of the subsoil conditions and geotechnical issues. Failures due to construction errors alone either of workmanship, materials and/or lack of supervision contributed to 8% of the total cases of landslides. About 20% of the landslides investigated are caused by a combination of design and construction errors. For landslides in residual soil slopes, the landslides caused by geological features only account for 6% which is same as the percentage contributed by a lack of maintenance (Gue and Cheah, 2008).

Table 2.2: Causes of Landslides (After Gue & Tan, 2006)

Causes Of Landslides	*Number of Cases*	*Percentage (%)*
Design Errors	29	60
Construction Errors	4	8
Design and Construction Errors	10	20
Geological Features	3	6
Maintenance	3	6
Total	**49**	**100**

National Master Plan (2009) also has similar study after Gue and Cheah (2008). Figure 2.4 shows the statistic of contributing factors of landslides based on Malaysia case history. The causes of landslides can be due to the abuse prescriptive methods, inadequate study of past failures, design errors including insufficient site-specific ground investigation. However, lack of appreciation of water such as underestimating existing groundwater table and inadequate capacity of surface drainage is also one of the factors causing the landslides.

A guideline from government agencies like Minerals and Geosciences Department and Department of Town and Regional Planning stated that the degree of risky hilly area starts at 25 degree. Besides, the hilly area with intrusive acid rock gives higher probability to cause a slope failure (Mukhlisin et al., 2010).

Landslides in the Malaysia are often triggered by intense rainfall, change in water level and change of slope geometry. The main factor that caused slope failure at numbers site in hillside development in Malaysia is rainfall and storm water activity (Farisham, 2007). Figure 2.5 shows the landslides triggering factors based on selective Malaysia case history. The statistics indicated that rainfall is the major triggering factor to cause a slope failure. It is well known fact that in a tropical climate with a continuous heavy and prolonged rainfall during the two monsoons in a year, slope failures in Malaysia are not uncommon. As such, the effect of expected intense rainfall on the slope stability should have been taken into account in the slope design (National Slope Master Plan , 2009). Geometry change is also a significant factor to cause a slope failure. Liew et al. (2004) suggested that cut slope has a high frequency of failure. This is probably due to the many uncertainties in identifying and establishing the weak structure, subsoil variation and the adverse ground water level.

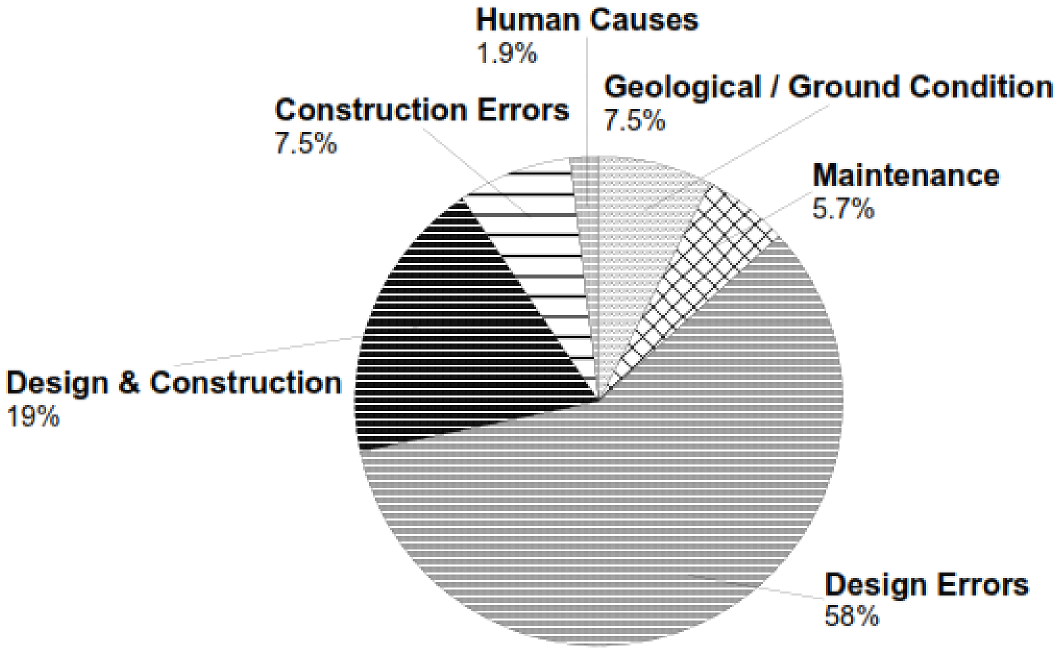


Figure 2.4: Contributing Factors of Landslides Based on Malaysia Case History (National Slope Master Plan, 2009)

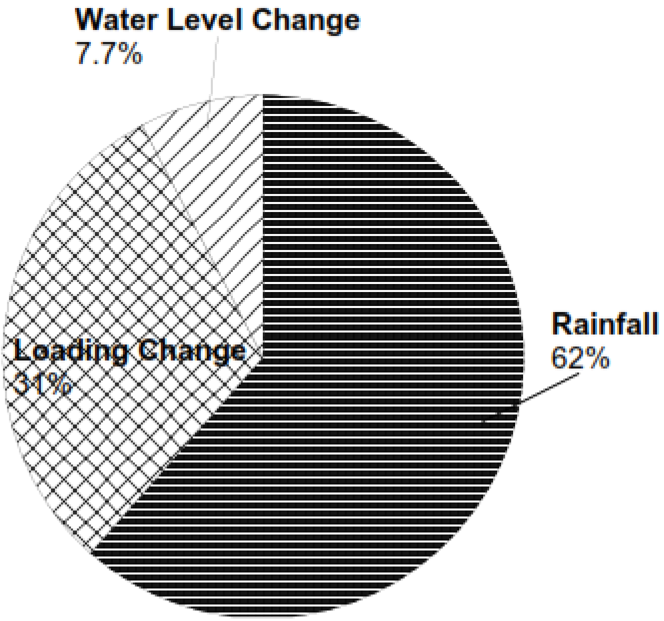


Figure 2.5: Landslide Triggering Factors Based on Selective Malaysia Case History (National Slope Master Plan, 2009)

2.4 Mechanism of Rainfall-Induced Landslides

Rainfall-induced landslide is a common geohazard in tropical regions like Malaysia in which the soil deposits are typically of residual soils (Brand, 1984; Liew, 2004; Huat et al., 2005; Rahimi, 2010). The tropical residual soils are commonly characterized by deep groundwater table with a significant thickness of unsaturated zone (Rahardjo et al., 2009). The understanding on the unsaturated soil mechanics is thus essential for the investigation of mechanism of rainfall-induced landslide in the tropical regions.

Figure 2.6 provides a thoughtful overview of the mechanism of rainfall-induced landslide in tropical residual soil slopes. The landslides are mainly initiated by a loss of matric suction in unsaturated zone during rainfall infiltration, and hence result in a reduction in shear strength. The shear strength reduction causes a decrease in factor of safety of the slope and sub sequently results in landslides (Fredlund and Rahardjo, 1993; Lu and Godt, 2008; Travis et al., 2010).

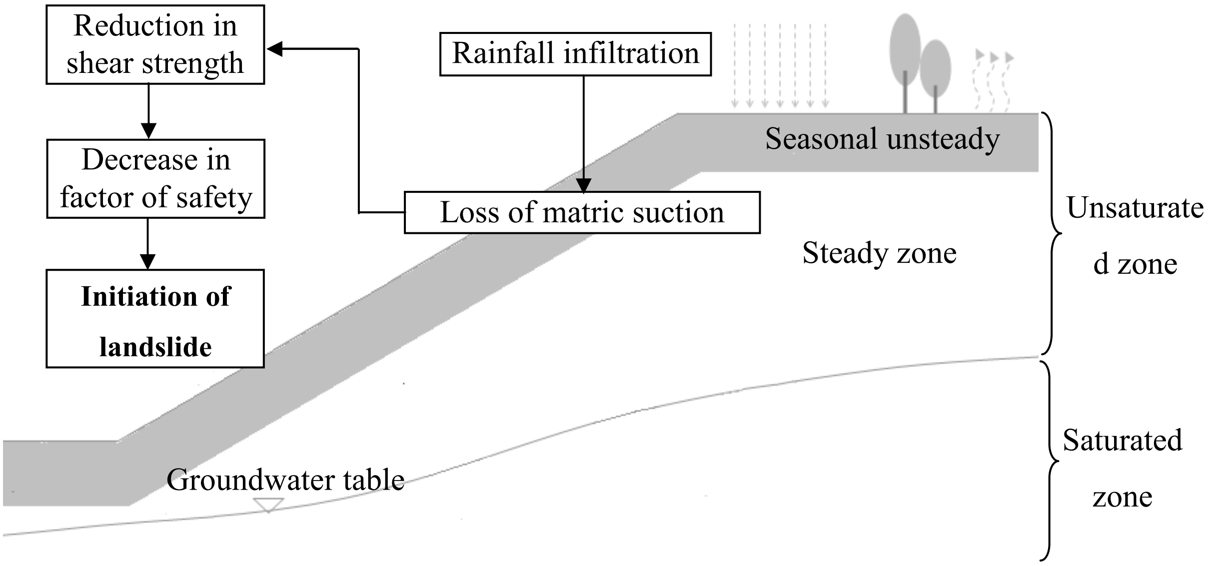


Figure 2.6: An Overview of Mechanism of Rainfall-Induced Landslide

In the unsaturated zone, the upper layer (1 to 3 m from ground surface) is known as *seasonal unsteady zone* because the matric suction in this zone is very sensitive to the surface boundary conditions. This zone is highly influential in the failure mechanism of many shallow geotechnical structures (Leong and Rahardjo, 1997; Totoev and Kleeman, 1998; Fredlund et al., 2001). The lower zone (from 3m to groundwater table) is known as *steady zone*. The name is given for the consistency in matric suction distribution within this zone.

The hydraulic properties of soil in the *seasonal unsteady zone* play an important role in determining the hydraulic responses of soil to the rainfall infiltration. The hydraulic properties of soil are mainly governed by the hydraulic conductivity function and soil water characteristic curve (SWCC). The former determine the seepage velocity while the latter determine the water holding or retention ability of the unsaturated soil. The procedures of obtaining these two parameters have been well established (Fredlund and Xing, 1994; Zapata et al., 2003; Simms and Yanful, 2004; Van Genuchten, 1980; Fredlund et al., 1994; Leong and Rahardjo, 1997).

Shear strength is an important parameter for any slope stability analysis. The factor of safety of a slope is defined by the ratio of the resistance force (quantified by the shear strength of the soil) to the mobilized force. The shear strength computed from the conventional Mohr-Coulomb failure criterion and effective stress concept (Terzaghi, 1936) is expressed as:

$$\tau_f = c' + \sigma' \tan \phi' \tag{2.1}$$

Where, τ_f = shear stress at failure

c' = effective cohesion

σ' = effective normal stress

ϕ' = effective friction angle

For unsaturated soil, the water phase occupies only parts of the pore volume, while the remainder is covered by air (Cai and Ugai, 2004). Therefore, the main difference between the shear strength of saturated and unsaturated soils is the functional relation between matric suction and effective stress in unsaturated soil. Several attempts for estimating this functional relation have been proposed by various researchers. Fredlund et al. (1978) developed a widely accepted equation that included a parameter known as angle of frictional resistance due to the contribution of matric suction (ϕ^b):

$$\tau_f = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \qquad (2.\ 2)$$

where $(\sigma_n - u_a)$ and $(u_a - u_w)$ are the net normal stress and the matric suction, respectively. The ϕ^b angle can be obtained by performing a series of triaxial compression tests with varying matric suctions. The practical range of ϕ^b is in between 15° and 20° (GeoSlope International Ltd., 2007a). Fredlund et al. (1996) found that ϕ^b remains constant and can be approximated to ϕ' up to the air entry value of the soil. Beyond the air entry value, ϕ^b decreases to 1/2 – 2/3 of ϕ'.

Lu and Likos (2006) and Lu and Godt (2008) have recently proposed a new equation for the effective stress under both saturated and unsaturated conditions:

$$\sigma' = (\sigma_n - u_a) - \sigma^s \qquad (2.3)$$

where σ^s is a newly introduced parameter defined as the suction stress with a general functional form of (Lu & Godt, 2008):

$$\sigma^s = -\frac{\theta - \theta_r}{\theta_s - \theta_r}(u_a - u_w) = -S_e(u_a - u_w) \qquad (2.4)$$

The advantage of using this functional relation between matric suction and effective stress is that it provides a quantitative means to describe effective stress regardless of the soil is in saturated or unsaturated states.

The applications of unsaturated soil mechanics in slope engineering have been well accepted. Regardless of which functional relations to be used, the shear strength of unsaturated soil is fundamentally related to the matric suction ($u_a - u_w$), which in turn is governed by the rainfall infiltration. These relationships reveal the importance of investigating the correlation between rainfall infiltration and initiation of landslide.

2.5 Empirical Rainfall Threshold for Predicting Landslide

Empirical thresholds for critical rainfall, either daily or hourly and antecedent rainfall which trigger the landslide, can be developed when the date, time and rainfall data prior to the occurrence are available (Jamaludin et al., 2011). The term "threshold" can be defined as the minimum or maximum level of some quantity needed for a process to take place (Reinchenbach et al., 1998). For rainfall-induced landslides, a rainfall threshold can be defined as the amount of rainfall that, when reached or exceeded, is likely to trigger landslides (Sengupta et al., 2010). The existing rainfall thresholds are normally formed by empirical correlations between rainfall intensity (I) and duration (D). The threshold is defined by drawing the lower-bound lines to the historical rainfall conditions that have triggered the landslides plotted in either Cartesian, semi-logarithmic, or logarithmic coordinates. This technique has been widely adopted in many parts of the world.

2.5.1 Antecedent Rainfall

Antecedent rainfall is defined as rainfall in the days immediately preceding a landslide event. Many researchers suggested that the antecedent rainfall could be significant in affecting slope stability (Tan et al., 1987; Chatterjea,1989; Wei et al., 1991; Rahardjo et al., 2001). In addition, the relative role of antecedent rainfall as a result of difference in soil properties from different regions of the world (Morgenstern,1992).

Many researchers have attempted to predict the time of rainfall induced landslides based on the amount of antecedent precipitation. When including the antecedent rainfall in predicting landslide occurrence, a key issue is to define the duration over which the accumulative precipitation needs to be considered (Sengupta et al., 2010). The duration of antecedent rainfall suggested by various researchers differs considerably: kim et al.(1991) considered 3 days; Crozier,(1999) and Glade et al.(2000) adopted 10 days; Rahardjo et al. (2001) suggested 5 days; Aleotti (2004) selected 7, 10, and 15 days; and Chelborad (2003) used 18 days (3-day event rainfall and 15-day antecedent rainfall); and Zêzere et al. (2005) suggested 1 – 15 days for shallow landslide and 1 – 3 months for deep-seated failure. Experiences from different regions of the world have resulted in different conclusions. It is important to determine duration of antecedent rainfall based on the local rainfall condition.

Guzzetti et al. (2007) pointed out that the large variation of the period can be attributed to several factors, including:

i. Diverse lithological, morphological, vegetation and soil condition
ii. Different climatic regimes and meteorological circumstances leading to slope instability; and
iii. Heterogeneity and incompleteness in the rainfall and landslide data used to determine the thresholds.

In addition, Chleborad's (2000) suggested that to incorporate the two ideas of antecedent wetness and unusual recent rainfall, two variables were defined: P_3 the 3-day precipitation immediately prior to the landslide event and P_{15} the antecedent precipitation that occurred prior to the 3 days of P_3. Furthermore, the cumulative 3-day/15-day precipitation threshold (CT) is based on an analysis of historical rainfall data associated with wet-season landslides (Figure 2.7).From this scatter plot, an approximate lower-bound precipitation threshold was defined by the equation $P_3=3.50-0.67P_{15}$. The precipitation threshold thus defined is interpreted as an approximate lower-bound threshold which below the specified level of rainfall-induced landslide activity does not occur, or occurs only rarely, and above which it may occur under certain condition (Chleborad et al., 2006).

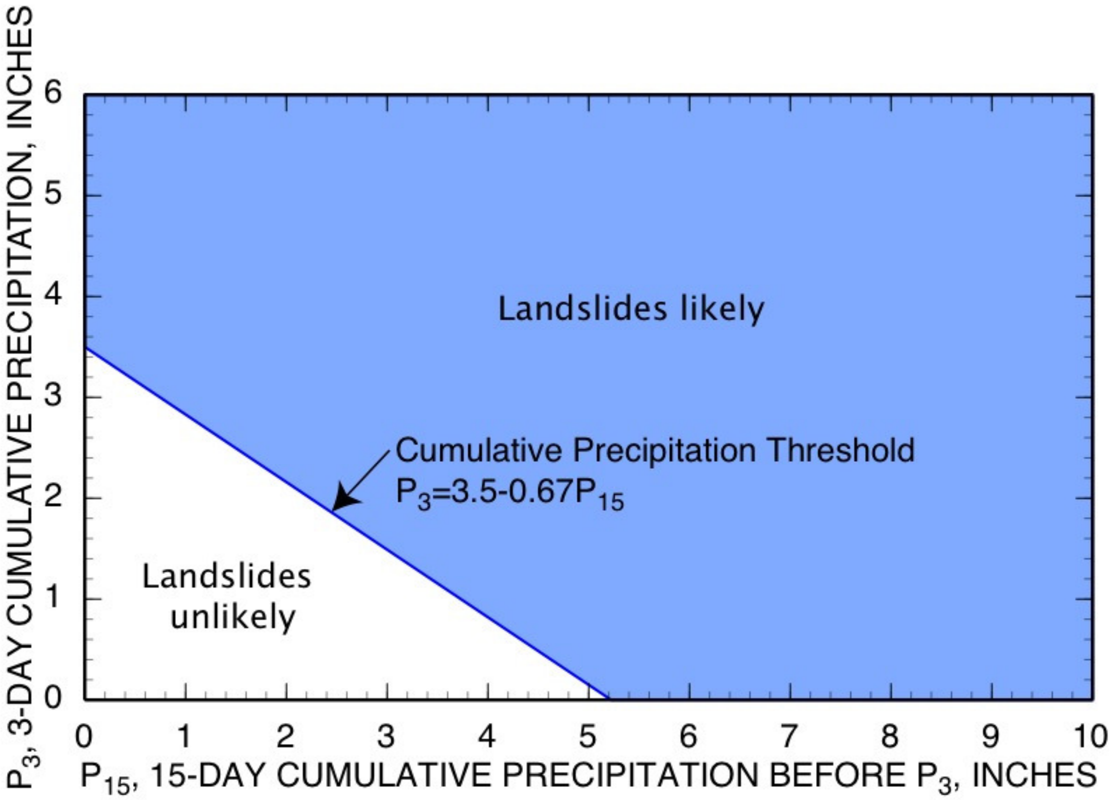


Figure 2.7: Cumulative 3-day and previous 15-day Rainfall Threshold (CT) (Chleborad, 2000, 2003)

2.5.2 Intensity-Duration Thresholds

Caine (1980) in his noteworthy study on prediction of shallow landslide and debris flow suggested a limiting rainfall threshold line of $I = 14.82\ D^{-0.39}$ to be applied to all slopes across the world. After Caine (1980) works, there are many researchers follow the same method and among them are Cancelli and Nova (1985), Crosta ,Frattini (2001), Aleotti (2004), Dahl and Hasegawa (2008), and Guzzeti et al (2008) and the most recent works are reported by R.Giannecchini (2012). Figure 2.7 shows global ID thresholds developed by various researchers as reported by Guzzeti et al (2008)

Crosta and Frattini (2001), and Guzzetti et al. (2008) have developed similar thresholds with some improvements. Recent studies suggested that the threshold should be limited to a localized area to improve the accuracy of the landslide prediction (Sengupta et al. (2010) in India; Godt et al. (2006) in Seatle, USA; Ahmad

(2003) in Jamaica; Annunziati et al. (2000) in Italy; Brand (1984) in Hong Kong; Kim et al. (1991) in Korea; and Corominas and Moya (1999) in Spain etc). Figure 2.8 shows the global intensity-duration (ID) thresholds developed by various researchers as reported by Guzzeti et.al (2008)

Jamaludin and Ali (2011) modified the rainfall intensity (*I*) and duration (*D*) threshold developed by Caine (1980) to anticipate the landslide occurrences in three landslide prone areas in Malaysia, namely Hulu Kelang, Penang Island, and Cameron Highland. However, their verification results showed that numerous non-occurrence rainfall events had yielded above the limiting threshold line which impaired the reliability of the model.

Giannecchini et al. (2012) has subdivided the intensity-duration field into three parts, including the rainfall conditions of rainstorms which induce different stability condition **(**Figure 2.9**).** The rainfall events falling between the two curves should trigger only a few landslides, while those falling above the upper curve should trigger more than ten landslides.

In addition to rainfall intensity and duration, prestorm soil wetness is a significant factor in rainfall inducement of landslides. The observation that landslides occur primarily during the rainy season at times when the soil is relatively wet indicates that an antecedent soil moisture threshold must be exceeded before the ID can be used.

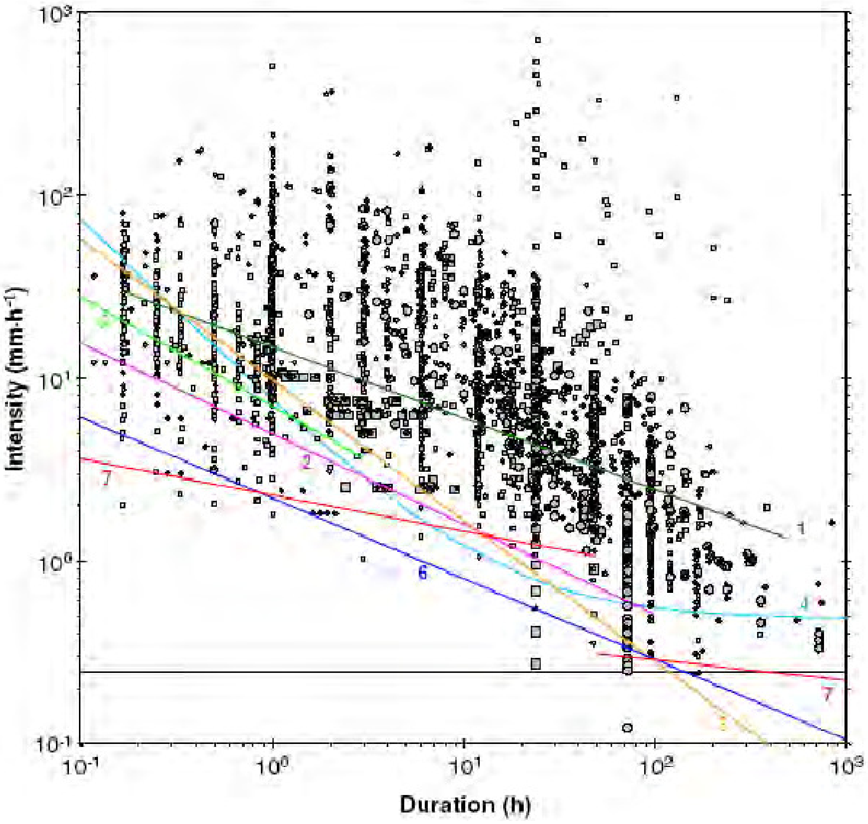


Figure 2.8: Global ID Thresholds Developed by Various Researchers as Reported by Guzzeti et.al (2008) : 1 Caine (1980), 2 Innes (1983), 3 Clarizia et al (1996), 4 Crosta and Frattini (2001), 5 Cannon and Gartner (2005), 6 Guzzeti et. al (2008) and 7 Guzzeti et al (2008)

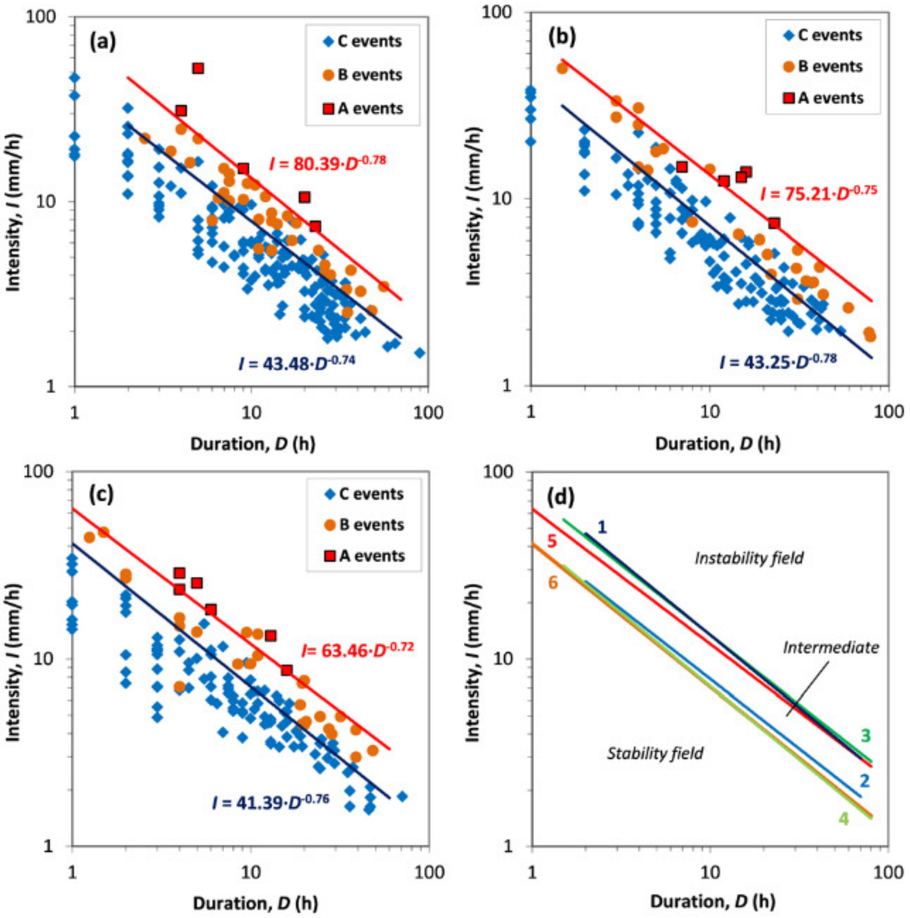


Figure 2.9: Intensity-Duration Correlation for the Borgo a Mozzano (a), Mutigliano (b) and Vinchiana (c) rain gauges. The lower (blue) and upper (red) threshold curves are shown. (d) Comparison between the ID thresholds obtained for the study area. The three stability fields are highlighted; (1) Borgo a Mozzano upper curve; (2) Borgo a Mozzano lower curve; (3) Mutigliano upper curve; (4) Mutigliano lower curve; (5) Vinchiana upper curve; (6) Vinchiana lower curve.

2.5.3 Intensity versus Working Rainfall Thresholds

Effects of a particular rainy event decrease in time owing to drainage processes. Therefore in order to account for this dampening effect in the rainfall-landslide analysis, the antecedent rainfall was calibrated applying the formula proposed by Crozier (1986) as shown by equation 2**:**

$$CARx_n = KP1 + K^2P2 + \ldots + K^nPn \tag{2.5}$$

Where CARx is the calibration antecedent rainfall for day x; P1 is the daily rainfall for the day before x; Pn is the daily rainfall for the nth day before day x. The constant K is an empirical parameter (typical value range between 0.8 and 0.9) depending on the draining capacity and the hydrological characteristics of the area (Hasnaw Ir et al., 2008).

Calibrated Antecedent Rainfall (CAR) named by Crozier (1986) was also called the Antecedent Working Rainfall (RWA) in the MILT (2004). The working rainfall is a cumulative rainfall that takes into account the effect of an antecedent rainfall. In general, shallow landslides occur under the influence of not only a landslide-causing rain events but also antecedent rainfall. The degree of influence of an antecedent rainfall normally reduces as time becomes distant from a landslide-causing rain (Jamaludin et al., 2011). To derive the effect of an antecedent rainfall, similar method proposed by Crozier (1986) was used by MILT (2004) with value of K of 0.5.

Working Rainfall (WR) was derived as the sum of the Absolute Cumulative Rainfall (RAC) produced by a series of rain prior to the occurrence of landslide and the Antecedent Working Rainfall (normally RWA of 14 days). A series of rain was defined as a continuous rain prior to the occurrence and it was terminated when there is presence of 24 hours non-rain (Jamaludin et al., 2011)**.** Figure 2.10 shows an example of critical line (CL) produced from Working Rainfall vs Hourly Rainfall graph (MLIT, 2004).

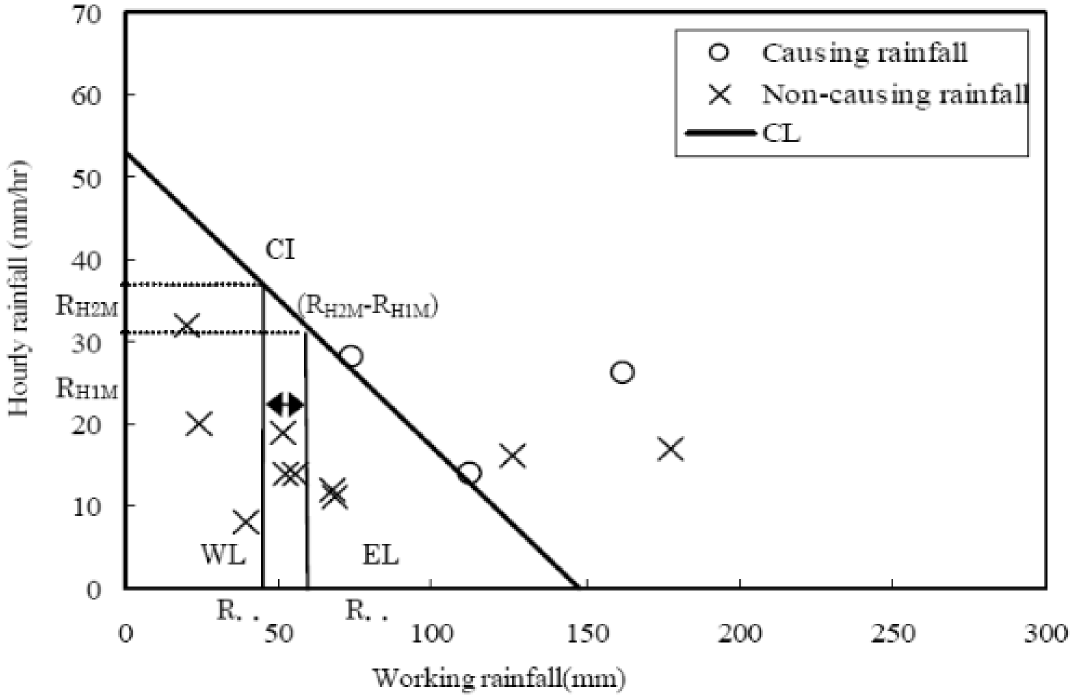


Figure 2.10: Example of Warning Based on Intensity – Working Rainfall (MLIT 2004)

2.5.4 Normalization

Various authors assert that each area is in equilibrium with its rainfall conditions. Therefore, in order to normalize the rainfall data, they are commonly compared to the mean annual precipitation (MAP) (Giannecchini et al, 2012). Guidicini and Iwasa (1977) introduced the normalized event rainfall (E_{MAP}), i.e. the cumulative event rainfall divided by MPA.

The $E_{MAP}I$ and the $E_{MAP}D$ thresholds are expressed by the equation (2.6) and Equation (2.7), respectively:

$$E_{MAP} = \alpha \; x \; I^{\beta} \tag{2.6}$$

$$E_{MAP} = \alpha \; x \; D^{\beta} \tag{2.7}$$

Where E_{MAP} is the normalized event rainfall, I is the rainfall intensity (mm/h) , D is the duration of the rainfall event (in h), α is the intercept and β defines the slope of the power low curve.

2.6 Previous Researches Carried Out at Hulu Kelang Area

Farisham (2007) has carried out the study on rapid landslide occurrence at the hillside development areas, in the Hulu Kelang. The study was focused on the architectural approach, the theory and the practice in the hillside development, aspects to be considered by the architect, in proposing the site layout. The study found that the occurrences of landslides in Hulu Kelang are due to the design and construction failure of the retaining wall, lack of maintenance and triggering by rainfall.

In addition, Farisham (2007) concluded that understanding on original terrain is very important; site layout proposal must be done through detail site investigations. The selected design approaches and method of construction for hillside development have given major impact on the safety of the development. Therefore, the hillside area must be designed and constructed, with proper understanding and should be responsive to the natural terrain, in order to protect the stability of the land due to the fact that when the land stability is low or bad the chances of landslide occurrence is very high.

Gue & Liong (2007) examined the landslide investigation results and the main causes of the landsides in Hulu Kelang area. Four landslides that happened in Hulu Kelang area were investigated: Highland Tower (December 1993); Bukit Antarabangsa (May 1999); Taman Hillview (November 2002); and Kampung Pasir (May 2006). The study found that three landslides were attributed to inadequate design of walls and slopes, in which the Factor of Safety (FOS) of the un-engineered walls and slopes was less than 1.0 even without considering any presence of geological features such as relic joints etc and water table. The FOS for all three landslides are grossly inadequate. Akib and Aziz (2007) investigated the landslide motions at Kampung Pasir, Hulu Kelang using continuous monitoring approach. They found that the ground has moved from 2 mm to 17 mm during the monitoring period of 10 days.

Ashaari et al. (2008) in their paper addressed the itinerary and methodologies required to conduct geomorphological mapping to extract out impediments which could lead to a potential soil or rock slope failure. Based on the field survey works at Hulu Kelang area, they have made the following conclusion:

i. Major failures are related to rock falls of which the places involved are mainly in ex quarry area, developed without proper scaling and protection of loose rocks. The rocks falls are mainly due to discontinuity, day lighting effect and many other factors. Hence it is recommended that the rock slope areas need to be monitored carefully and perform stabilization works.
ii. As observed in Hulu Kelang area, a total of 152 landslide scars of both soil and rock slopes were identified. Most of it have not been remedied and left unattended. These sites could beome the potential slope failure site which could be fatal.
iii. Some of the slopes in Hulu Klang area have been stabilized using ground anchors, which are not maintained based on field observations. It is highly recommended for the respective local authorities to take actions, as some of the slopes are very steep and high next to roads and residential areas.
iv. Another main factor causing slope failures are due to poorly maintained drainage system for slopes, this study has also identified the areas which requires improvement in the drainage system. The need to conduct regular maintenance and repair works is critical in Ampang area. There are areas with no drainage system to prevent surface runoff, water ponding and infiltration.

Hence, based on the list of defects or matters related to geotechnical, geological and structural in Table 2.3 which could cause potential landslide or slope failure, the local authorities need to address the defects systematically.

Table 2.3: Cases Identified to Prevent Landslides (Ashaari et al., 2008)

a) Geotechnical related matters:	b) Geological related matters
i. Areas of blocked drains ii. Areas of broken drains iii. Areas of undersized drains or no drainage system iv. Areas of surface runoff v. Areas of over grown bushes vi. Areas of steep slopes condition at developed area vii. Areas of steep slope condition with inadequate design (assumed) viii. Areas of steep slope condition due to ignorance of resident's cutting ix. Areas of heavy seepage x. Areas of saturated ground xi. Areas of inadequate buffer zone (< 6m) for old development (assumed older than 1995) xii. Areas of inadequate buffer zone (< 6m) for new development xiii. Areas with valley and stream facing development xiv. Areas of potential debris flow xv. Areas of serious erosion xvi. Areas of tension crack on pavement and gunite surface xvii. Areas of soil creep on slope xviii. Areas of ground anchors	i. Areas of potential rock fall ii. Areas of daylighting rock and soil slope iii. Areas of rock overhang iv. Areas of inadequate buffer zone (<6m) near rock slope v. Areas with rock surface runoff over joint vi. Areas with weak interface between soil and rock vii. Areas with seepage on rock slope viii. Areas with deep tree rooting in cracks or joints in rock c) Structure related matters i. Areas of structural defects on walls ii. Areas of weep holes requires services iii. Areas of seepage from wall iv. Areas of cracks on wall v. Areas of cracks on buildings vi. Areas with structural defects (on buildings)

Mukhlisin et al. (2010) proposed the Geographical Information System (GIS) as based machine for the production of landslide hazard map in Hulu Kelang area. Four main parameters were used to analysis probability location of landslide in Hulu Kelang area include slope gradient, geology, surface/cover land used and precipitation distribution. Table 2.4 shows the parameter analysis for the risky area. The result showed that the model was very suitable in predicting landslide hazard and generating hazard maps (Figure 2.11). These data can be used as basic data to assist slope management and land-use planning. The finding was supported by Low and Ali (2012) who also used Geographical Information System (GIS) application to perform area based slope hazard assessment and mapping at Hulu Kelang area. They concluded that the hazard map can be used as an effective tool for predicting the landslide occurrence.

Table 2.4: Parameter Analysis for the Risky Area (Mukhlisin et al., 2010)

Location	Coordinate	Parameter		Parameter (Dominant)
		Parameter	Detailes	
Bukit Antarabangsa	101°45'33.392" E, 3°9'58.94"N	Gradient Surface Cover Geology Precipitation (mm) Height(m)	35°-60° Paved Intrusive acid 0-100 100-150	Gradient
Ukay Height	101°45'45.481" E, 3°10'23.436"N	Gradient Surface Cover Geology Precipitation (mm) Height(m)	35°-60° Agriculture Intrusive acid 0-100 100-150	Gradient
Taman Sri Ukay	101°46'0.497"E, 3°10'41.484"N	Gradient Surface Cover Geology	35°-60° Forest Intrusive acid	Gradient

		Precipitation (mm)	0-100	
		Height(m)	100-150	
Kampung Pasir	101°46'21.305" E, 3°12'10.748"N	Gradient	35°-60°	Gradient
		Surface Cover	Paved	
		Geology	Non-Intrusive acid	
		Precipitation (mm)	100-118	
		Height(m)	150-200	
Taman Zoo view	101°46'0.694"E, 3°12'28.28"N	Gradient	35°-60°	Gradient
		Surface Cover	Forest	
		Geology	Non-Intrusive acid	
		Precipitation (mm)	100-118	
		Height(m)	100-150	
Kemensah Height	101°46'3.323"E, 3°12'53.492"N	Gradient	35°-60°	Gradient
		Surface Cover	Forest	
		Geology	Intrusive acid	
		Precipitation (mm)	100-118	
		Height(m)	56-100	

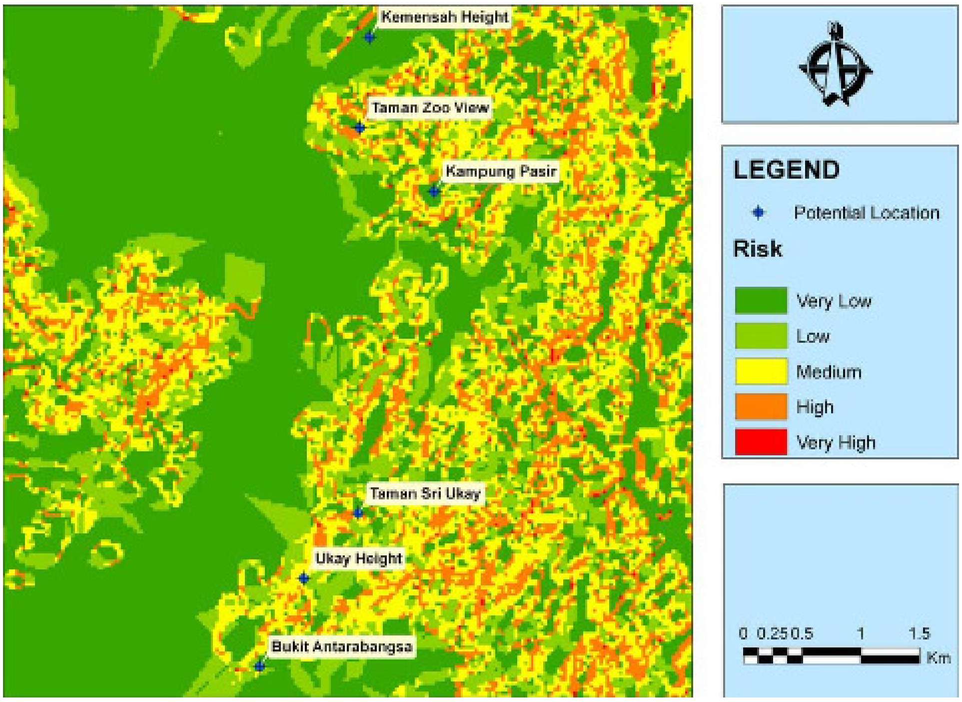


Figure 2.11: End Result of Landslide Risky Analysis (Mukhlisin et al., 2010)

In addition, a detailed investigation of the failure and site investigation for Bukit Antarabangsa 2008 case were carried out by Messrs Mohd Asbi and Associates and Kumpulan Ikram Sdn Bdh, respectively. The investigation found that the primary cause of slope failure is attributed to rise in ground water level due to prolong rainfall continuous creep of slope over a long period of time, sustained saturation of the slope at pockets of voids within the slope mass, as the slop were constructed by means of end tipping (Mariappan et a.l, 2010).

Jamaludin et al. (2011) developed a landslide early warning system based on empirical correlation of rainfall data and landslide cases. There were 40 landslides recorded in Hulu Kelang area since 1984. However, only 16 landslides were identified as rainfall-induced landslides. A landslide threshold relation was derived by fitting the lower boundary of the landslide triggered rainfall events (Figure 2.12), and express as :

$$I = 11D - 0.5317 \quad (2.8)$$

Where I is the rainfall intensity (mm/h) and D is duration (h)

Author found that the Ampang/Hulu Kelang landslide-rainfall correlation has its limitations that may affect the accuracy of the derive curve. The following is the factors:

i. Report landslide: Only limited cases of landslides have been investigated and reported in the developed areas that had damaged the properties or poses a greater risk to life. Therefore, the total number of landslides over a given years, percentages and probabilities were only referred on those reported cases.
ii. Rainfall data: Only limited numbers of rain gauges were installed in specific locations. Therefore, the exact total amount of rainfall at the Ampang landslides site can only be estimated using the nearest rain gauge data which is in Klang Gates area and Department of Irrigation and Drainage (DID) Ampang office.

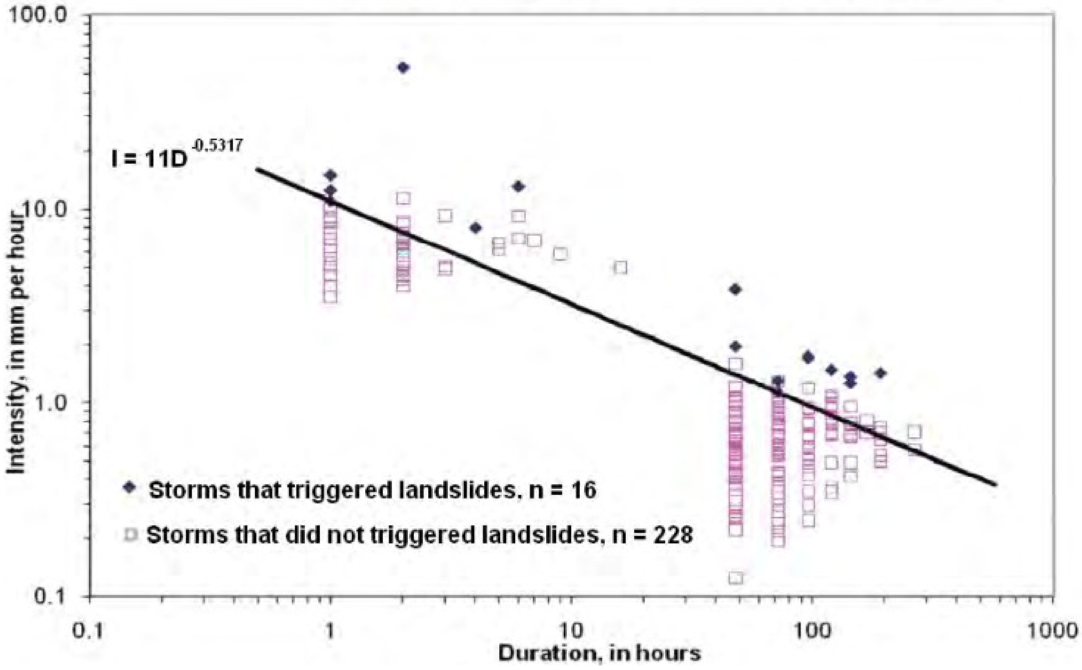


Figure 2.12: Rainfall-landslide Thresholds for Ampang/Hulu Kelang Area (Jamaludin et al., 2011)

Low et al. (2012) performed a detailed investigation on one of the major landslides occurred in Hulu Kelang area, known as Bukit Antarabangsa 2008 landslide. They concluded that prolonged rainfall during the monsoon season is one of the main factors triggering the landslide.

2.7 Concluding Remark

Landslide can be triggered by many factors: changes of slope geometry, changes of water level, rainfall intensity, and changes in loading. However, the major factor that triggers landslides in Malaysia is due to precipitation. In addition, average annual precipitation in Malaysia is around 2000mm to 2500mm. With this amount of average rainfall, the rainfall-induced landslides become a significant study area.

The mechanisms for rainfall-induced landslides include the dynamic and hydrostatic pressure due to infiltration is unfavourable for slopes stability, the water content increase, and the matric suction decrease which resulted in the decreases of soil shear strength and subsequently leads to slope failure. To monitor landslide events, it is necessary to develop a landslide warning system. However, it is sometimes difficult and costly to install a landslide warning system based on rainfall monitoring. Therefore, empirical correlation between rainfall and landslide can be developed and used in the development of landslide early warning system for either localises or regional level.

Empirical rainfall threshold for landslide triggering was carried out by many researcher (Guidicini & Iwasa,1977;Caine,1980; Cancelli & Nova,1985;Kim et al.,1991; crozier,1999; Glade et al., 2000; Frattini, 2001; Chelborad,2000,2003,2006; Aleotti,2004; Guzzetti,2007, Guzzeti et al.,2008; Dahl & Hasegawa,2008;Jamaludin et al., 2011; R.Giannecchini et al., 2012). The threshold can be developed when the date, time and precipitation data prior to the occurrence are available. A literature review shown various works and methods to define rainfall thresholds such as Cumulative Antecedent Rainfall, Intensity vs Duration Thresholds, Intensity versus Working Rainfall Thresholds, and Normalization.

Hulu Klang have increased the demand of its land resulted in rapid increased of development and housing project in this area. Because of the rapid hillside development, Hulu Klang area is prone to natural disaster such as landslides. A number of fatal landslides have been recorded in newspaper. The Highland Tower tragedy, the Taman Hill view tragedy, and a slope failure near the Athenaeum Tower are some of the example of the development of failure causes by landslide. This fatal landslide has brought awareness to society, researcher, and geology expert. Therefore, a lot of researcher and geology expert have carry out the investigation and study of the landslide in Hulu Klang area.

The study of landslide in Hulu Klang area was carried out by many researcher and expert. (Farisham ,2007; Gue & Liong ,2007 ;Ashaari et al. ,2008; Mukhlisin et al.,2010; Jamaludin et al., 2011) Among them only Jamaludin et al., 2011 carried out the study on rainfall-induced landslide. He has developed an early warning system based on the Intensity vs Duration curve to predict the landslide in Hulu Klang area.

Since rainfall is the major factor that triggers landslide, therefore it is necessary to study the rainfall induced landslide in Hulu Klang area. Jamaludin et al. (2011) has developed a rainfall-landslide threshold for Hulu Kelang area. However the first attempt produced only a crude correlation. The rainfall-landslide correlation developed by Jamaludin et al. (2011) has its limitation due to limited landslide cases to be investigated and limited number of rain gauges being installed in the specific locations in that particular region. This project aims to provide an insight into the mechanism of rainfall-induced landslide, and develop empirical rainfall thresholds for anticipating the landslide occurrence in the Hulu Kelang area.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Rainfall is a major triggering factor that causes slope failure in Malaysia. The infiltration of rain water will cause the loss of matrix suction or loss of negative pore-water pressure. Landslide warning system can be developed by using a rainfall monitoring system. However, it is usually costly and difficult to measure the field metric suction and ground water level. Therefore, empirical rainfall threshold is developed to predict the landslide activity. This chapter will discuss on the necessary information and data needed to develop an empirical rainfall threshold. It explains the method of developing the threshold amount and duration.

3.2 Research Framework

Figure 3.1 shows the research framework for this project. The research started with collecting the rainfall data and landslide information from various sources. Firstly, the rainfall patterns prior to the landslide occurrences at five selected case studies are analyzed. The analysis of the rainfall pattern is important for providing an overview of the rainfall conditions that had triggered the landslides in Hulu Kelang. Next, numerical simulation is carried out on a selected case study in Hulu Kelang to provide an insight into the mechanism of rainfall-induced landslide. Finally, three empirical rainfall threshold charts for the initiations of landslides in Hulu Kelang area are proposed based on the rainfall data that had resulted in the 21 historical landslide events. Non-occurrence rainfall data were plotted into the threshold chart to verify the reliability of the proposed chart for anticipating landslides in the area.

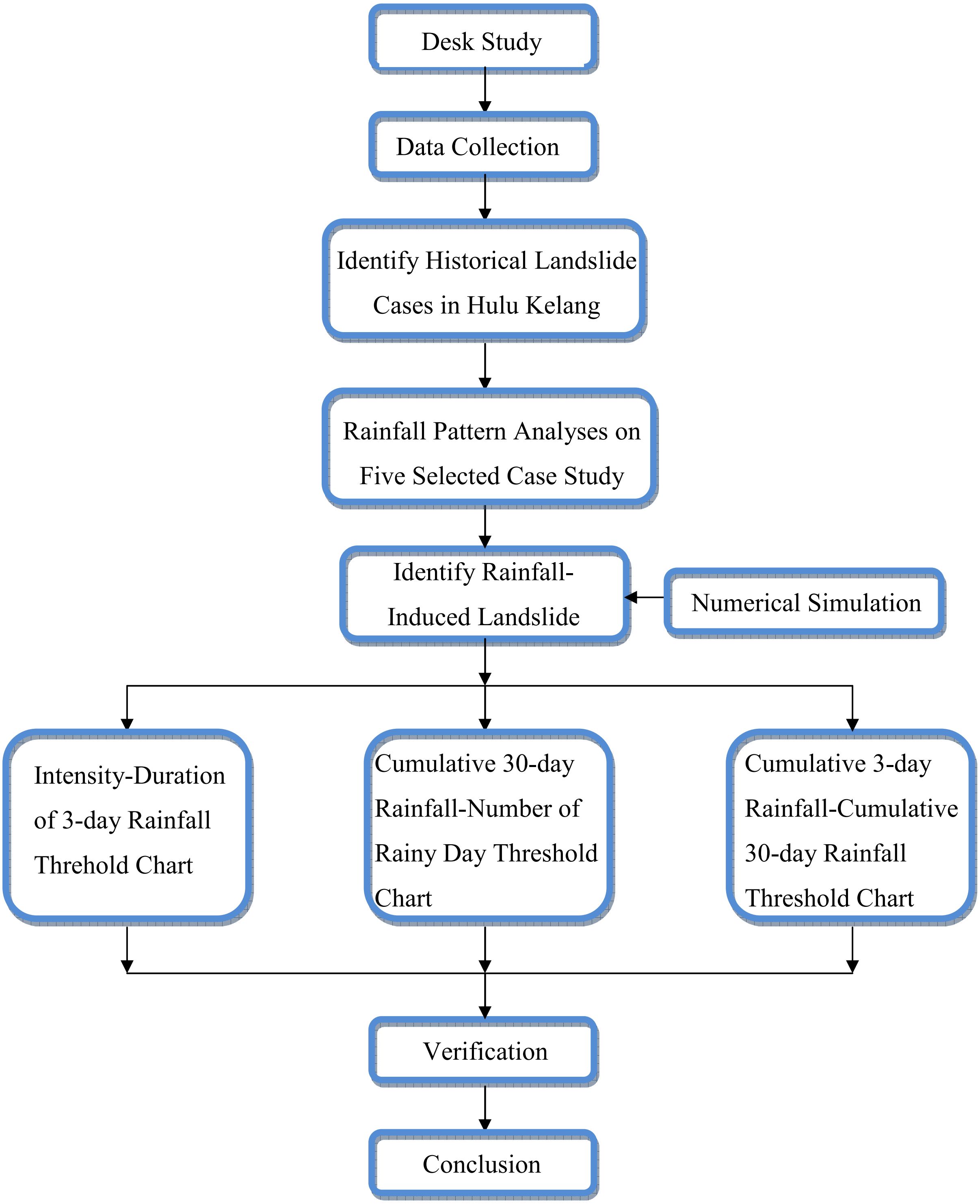


Figure 3.1: Research Framework

3.3 Data Collection

The threshold analysis was carried out by analyzing the historical rainfall data associated with the landslide incidents that happened in Hulu Kelang. It was found that the rainfall data and landslide information in Hulu kelang were important in this project.

3.3.1 Rainfall Data

The rainfall data of Hulu Kelang area was obtained from the Department of Irrigation and Drainage, Malaysia (DID). Ideally, the rainfall record should be derived from the particular landslide site. But, the rain gauge station in Hulu Kelang area comes with limited amount; therefore, the rainfall records of the nearest rain gauge stations were used. Rainfall record of JPS Amang station, Bukit Antarabangsa station and Empangan Klang Gate station were used in this analysis. Generally, the selected stations were located about 2km to 7km away from the studied area. Hence, it was assumed that the particular rainfall data is suitable in representing the regional rainfall data at the particular landslide locations. Figure 3.2 shows the location of nearest rain gauge station for studied area. The rainfall record in the periods of 1990-2011 for Emapangan Klang Gate station and JPS Ampang station were obtained from DID. However, the rainfall record of Bukit Antarabangsa covered the period from 2003 to 2011. The completed analysis used 15-minute interval rainfall records that were obtained from the DID.

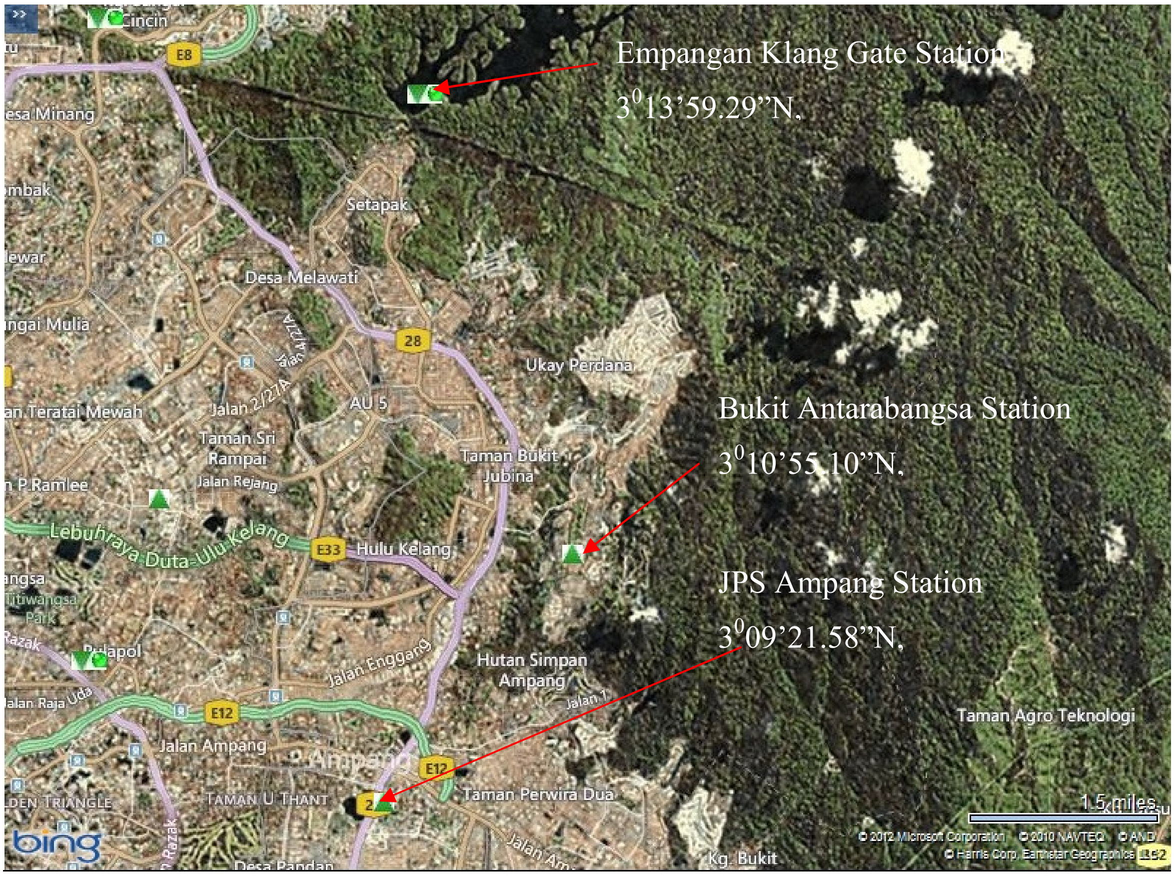


Figure 3.2: Location of nearest Rain Gauge Station for Studied Area.

3.3.2 Landslide Information

Table 3.1 shows the landslide location and time of occurrence in Hulu Kelang area. There were 28 landslide incidents occurred in Hulu Kelang area between 1993 and 2011. The information was collected from various sources: Newspapers, publication journal, PWD and MPAJ. The landslide information was used to

Table 3.1: Landslide Location and Time of Occurrence in Hulu Kelang Area since 1993-2011.

No	Location	Date	Time
1	Highland Tower	11/12/1993	1.30Pm
2	Jalan Ampang	14/02/1994	-
3	Tmn Keramat Permai	03/05/1995	-
4	Keramat Permai	15/05/1995	-
5	Ampang Jaya	20/08/1995	-
6	Bandar Ampang	28/01/1996	-
7	Ampang Jaya	10/06/1996	-
8	Bukit Antarabangsa 1999	14/05/1999	4.30pm
9	Bukit Antarabangsa 1999	15/05/1999	5am
10	Kondominium Mutiara	10/07/1999	-
11	Jln Bukit Antarabangsa	05/10/2000	4.45Pm
12	Taman Zooview 2001	29/10/2001	-
13	Taman Zooview 2001	08/11/2001	-
14	Taman Hillview	20/11/2002	4.30am
15	Bukit Indah Ampang	03/03/2003	-
16	Oakleaf Park Condo, B.Antarabangsa	02/11/2003	-
17	Jalan Bukit Muliam B.Antarabangsa	07/11/2003	-
18	Jln Tebrau, Dataran Ukay	31/01/2005	-
19	Jln Tebrau, Dataran Ukay	01/02/2005	-
20	Kampung Pasir	31/05/2006	4.45Pm
21	Condo Wangsa Height, B.A	24/04/2008	2.20am
22	Tmn Bukit Mewah, B.A	06/12/2008	4am
23	Wangsa Height, B.A	19/09/2009	5.30pm
24	Pangsapuri Sri Wira	Jan-10	-
25	Ukay Club Villa	Apr-10	-
26	Bukit Antarabangsa	Ogos 2010	-
27	Ukay Perdana	Feb-11	-
28	Taman Bukit Jaya	21/06/2011	-

3.4 Rainfall Pattern Analysis

To provide an overview of the correlation between rainfall infiltration and landslide initiation, the rainfall patterns prior to the occurrences of five landslide events in Hulu Kelang were investigated. The five selected case studies include Highland Tower landslide (11-Dec-93), Bukit Antarabangsa landslide (15-May-99), Taman Zooview landslide (29-Oct-01), Taman Hillview landslide (20-Nov-02), and Bukit Antarabangsa landslide (06-Dec-08). These landslides represent the major events that had occurred in Hulu Kelang area from 1990 to 2011.

In this project, the cumulative 3-day, 5-day 7-day, 14-day and 30-day rainfalls for each case study were computed as attempts to determine the critical duration of antecedent rainfall for each case study. The critical duration is defined as the duration that yields the highest amount on the day of landslide occurrence.

3.5 Numerical Simulation

Numerical simulation was carried out on a selected case study to provide an insight into the mechanism of rainfall-induced landslide in this area. The selected case study was known as Bukit Antarabangsa 2008 landslide, which was regarded as one of the largest in Hulu Kelang area over the past decade.

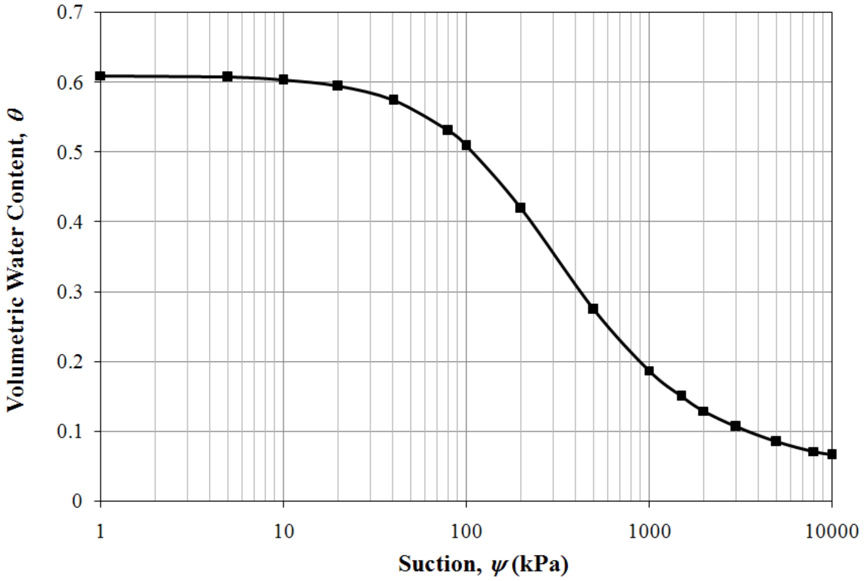
3.5.1 Slope Geometry and Soil Properties

The original slope stood at approximately 65 m in height and 145 m in length, forming an inclination of approximately 25^{o}. Site investigation data retrieved from Low et al. (2012), and Mariapan et al. (2010) revealed that the slope was underlain by three soil layers, namely silt, sandy gravel, and granite. The properties of the soils are tabulated in Table 3.2. The angle of frictional resistance due to the contribution of matric suction (ϕ^b) was not tested in laboratory, but assumed to be equal to 2/3 of ϕ'. Groundwater table was detected at about 15 m from ground level at the crest, and 1.5 m at the toe during dry condition.

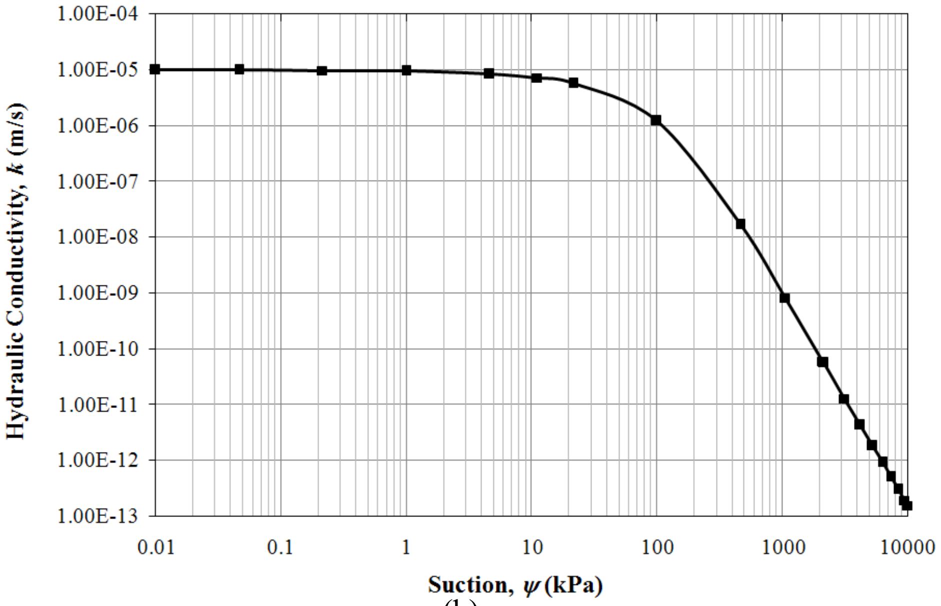
Table 3.2: Soil Properties Data of Bukit Antarabangsa Slope

Soi layer	**Soil type**	**Depth**	**Effective cohesion, *c'* (kPa)**	**Effective friction angle, ϕ' (°)**	**Soil unit weight, γ' (kPa)**
Layer 1	SILT	0 – 13.5 m	3	26	17.5
Layer 2	Sandy GRAVEL	13.5 – 17 m	8	32	18
Layer 3	GRANITE	17 m onwards	10	38	18.5

Site observations suggested that the actual failure plane developed within the soil layer 1 only. Thus, the hydraulic properties of this soil layer were focused in this section. The saturated coefficient of permeability of the soil was in the range of 1 – 5 × 10^{-5} m/s (Low et al., 2012). A typical SWCC for silty residual soil in Malaysia was used in this simulation (Lee et al., 2009). The hydraulic conductivity function was estimated from the SWCC and the saturated coefficient of permeability of 1 × 10^{-5} m/s using Van Genuchten's method (1980). Figure 3.3(a) and 3.3(b) show the SWCC and hydraulic conductivity function used in the simulation, respectively.



(a)



(b)

Figure 3.3: (a) Soil-water Characteristic Curve (SWCC), (b) Hydraulic Conductivity Function

3.5.2 Numerical Model

Transient seepage analysis was performed using Seep/W (GeoSlope International Ltd., 2007b), and the pore-water pressure distributions obtained from the seepage analysis was incorporated into Slope/W (GeoSlope International Ltd., 2007a) for slope stability analysis.

Figure 3.4 shows the slope model simulated in the Seep/W. The seepage model comprised 7,206 nodes and 9,755 mesh elements. Fine unstructured elements (side length in the range of 0.5 – 1m) were adopted for the soil layer 1. Fine quadrilateral elements (1 × 1 m) were used for the underlying soil layer 2. Large quadrilateral elements (5 × 1 m) were used for the entire granite layer. The left and right edges above the water table were specified as a no flow boundaries (Q = 0), while the edges below the water table were assigned as head boundaries with pressure head equal to the elevation of the water table. On the exposed sloping surface, infiltration due to rainfall was simulated by applying a unit flux (q) equaled to the actual rainfall intensity. The simulation was carried out for a period of more than 3 months (from 15 August to 6 December 2008) prior to the landslide occurrence. The starting date of the simulation was set on 15 August 2008 because the slope had experienced a prolonged dry period during that time. A limiting negative pore-water pressure of 70 kPa was imposed as the initial condition for the dry period.

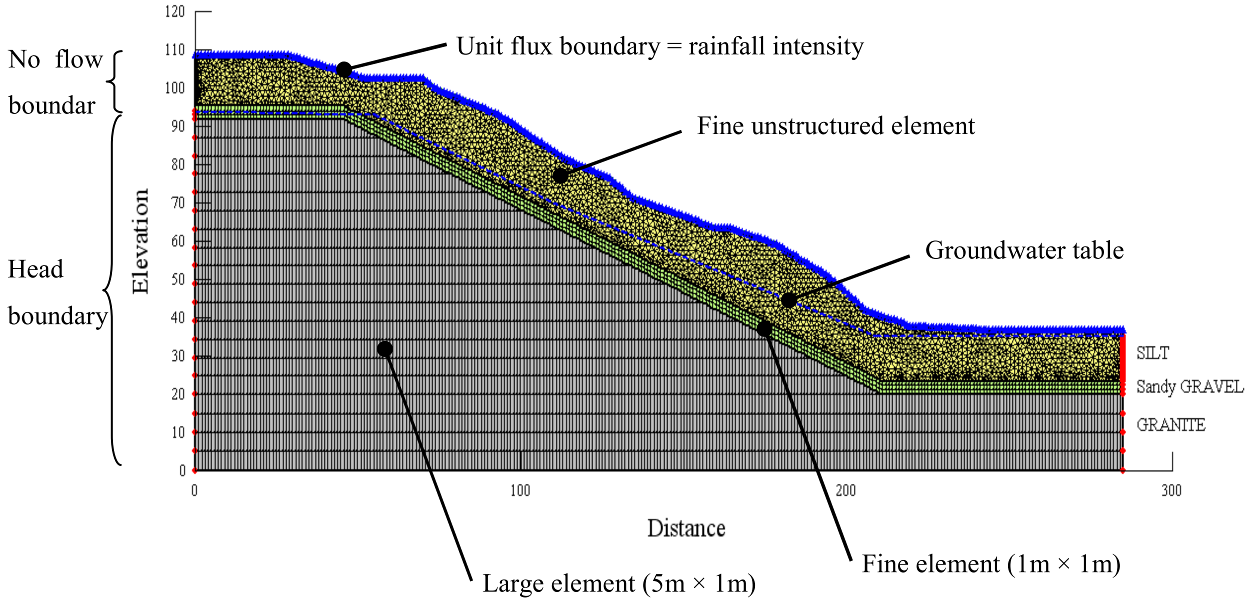


Figure 3.4: Seep/W Model of Bukit Antarabangsa Slope

3.6 Development of Rainfall Threshold Chart

Most of the existing rainfall thresholds were formed by empirical correlations between rainfall intensity (I) and duration (D). 21 cases of rainfall-induced landslides in Hulu Kelang area were plotted in either Cartesian, semi-logarithmic, or logarithmic coordinates to develop the empirical rainfall threshold charts. The threshold is defined by drawing the lower-bound lines to the historical rainfall conditions that have triggered the landslides.

3.7 Verification

Non-occurrence rainfalls were plotted in the empirical rainfall threshold charts to verify the reliability of the charts. The rainfall data between 1990 and 2011 from Genting Klang Gate station were selected for this verification purpose. The threshold chart that resulted in too many non-occurrence rainfalls plotted above the limiting threshold was deemed as unreliable.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

Hulu Kelang is the landslide prone area with most of the landslides occurred in the Monsoon season. This chapter gives an overview of the landslide cases in Hulu Kelang area. The important of correlating landslide occurrences in Hulu Kelang with rainfalls and geological profile and soil properties were presented. Besides, to provide an overview of the correlation between rainfall infiltration and landslide initiation, the rainfall patterns prior to the occurrences of five landslide events in Hulu Kelang were investigated. In addition, numerical simulation was carried out on a selected case study to provide an insight into the mechanism of rainfall-induced landslide in this area. The results of pore-water pressure and slope stability were presented in this chapter. Lastly, three empirical rainfall threshold charts were proposed.

4.2 Overview of the Landslide Cases in Hulu Kelang

Hulu Kelang which is, geographically located at the latitude of 3° 10’ 00’’ North and 101° 45’0’’ East is under the jurisdiction of Ampang Jaya Municipality and Kajang Public Work Department (Mukhlisin et al., 2010). This area, covering about 100km^2 is a highly landslide prone area within the country due to the hilly terrain as well as intense rainfall pattern. In term of elevation, this area cannot be considered as mountainous area where it is only at 50m to 250m above mean sea level (MSL) (Jamaludin et al., 2011).

The location of Hulu Kelang in the Klang valley has increased the demand for its land. Hulu Kelang is on a fast track of urbanization. As a close area form the Kuala Lumpur city, Hulu Kelang have increased the demand of its land resulted in rapid increased of development and housing project in this area (Mukhlisin et al., 2010). Rapid development of urban area has made the local government unable to establish adequate landslide or slope failure preventive measures (Ashaari et al., 2008).

According to the data sources from the Ampang Jaya Municipal Council (MPAJ) and the Slope Engineering Branch of Public Works Department Malaysia (PWD), as well as data compilation from the previous reported studies by Farisham (2007), and Low and Ali (2012), a total of 28 historical landslide events have been reported in the Hulu Kelang area from 1990 to 2011; of which, 21 cases have been identified as potentially triggered by rainfall **(**Table 4.1**)**. Figure 4.1 shows the specific locations of these rainfall-induced landslides. They were generally scattered all over the developed parts of the Hulu Kelang area implying hillside development has caused disturbance to the ecosystem, and hence the stability of the natural slopes.

Table 4.1: Historical Rainfall-induced Landslides in Hulu Kelang Area from 1993 to 2011

No	Location	Date	Casualties	Loss of Properties	Estimated Economic Loss
1	Highland Tower	11-Dec-93	48 killed	Collapsed of one block of 12-storey high apartment	RM 184M
2	Keramat Permai	03-May-95	-	-	RM1.3M
3	Keramat Permai	15-May-95	-	-	< RM 1M
4	Ampang Jaya	20-Aug-95	-	-	RM1.3M
5	Ampang Jaya	10-Jun-96	-	-	RM1.3M
6	Bukit Antarabangsa	14-May-99	-	-	-
7	Bukit Antarabangsa	15-May-99	-	Closure of the main and only access road to the residential area	RM 5.4M
8	Jln Bukit Antarabangsa	05-Oct-00	-	Damage of road	-
9	Taman Zooview	29-Oct-01	-	-	-
10	Taman Zooview	08-Nov-01	-	-	RM 1.3M
11	Taman Hillview	20-Nov-02	8 killed	Damage of 1 unit of bunglow	RM 17.4M
12	Oakleaf Park Condo, Bukit Antarabangsa	02-Nov-03	-	-	-
13	Jalan Bukit Mulia Bukit Antarabangsa	07-Nov-03	-	-	-
14	Jln Tebrau, Dataran Ukay	01-Feb-05	-	-	-
15	Kampung Pasir	31-May-06	4 killed	Damage of 3 blocks of longhouses	RM 20.7M
16	Condo Wangsa Height, Bukit Antarabangsa	24-Apr-08	-	Damage of 4 vehicles	-
17	Tmn Bukit Mewah, Bukit Antarabangsa	06-Dec-08	5 killed, 7 injured	Damage of 14 units of bungalows	RM 7.6M
18	Wangsa Height, Bukit Antarabangsa	19-Sep-09	-	-	-
19	Ukay Club Villa	Apr-10	-	-	RM 1.3M
20	Bukit Antarabangsa	Aug-10	-	-	RM 1.3M
21	Ukay Perdana	Feb-11	-	-	RM 1.3M

Figure 4.1: Specific Locations of the 21 Historical Rainfall-induced Landslides in Hulu Kelang Area from 1990 to 2011

4.3 Importance of Correlating Landslide Occurrences in Hulu Kelang with Rainfalls

Based on the rainfall data of the past 22 years (from 1990 to 2011), Hulu Kelang area received an average annual rainfall of about 2440 mm. Figure 4.2 shows the correlation between the number of landslide occurrence and the annual rainfall amount. The results showed that there was only a weak correlation between the two entities implying that the spatial and temporal rainfall variability played a more dominant role in triggering the landslide.

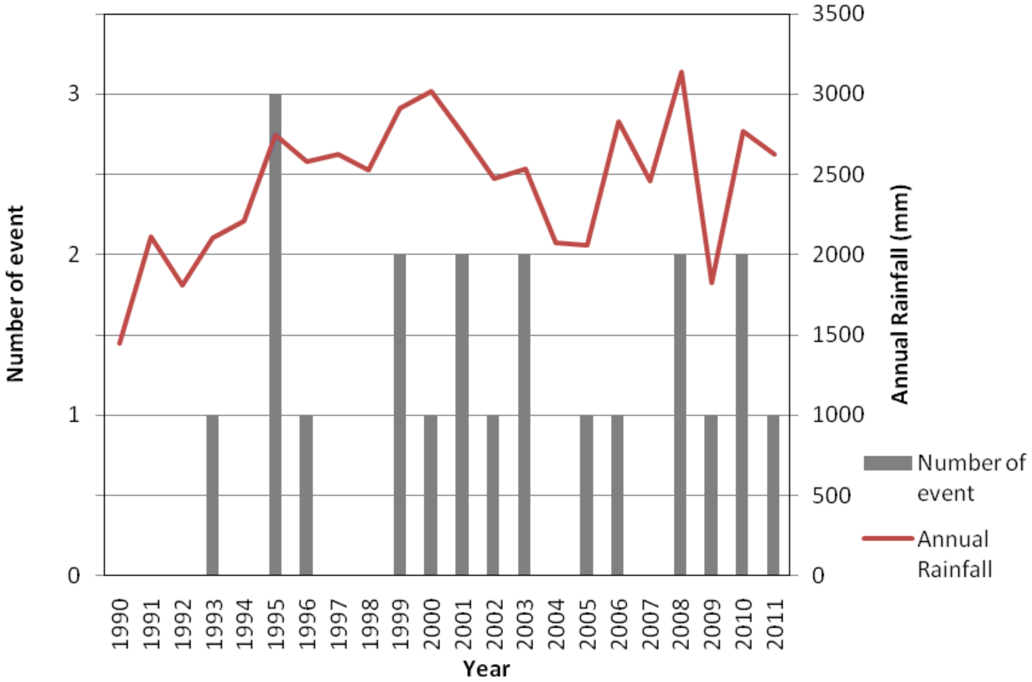


Figure 4.2: Correlations between Number of Landslide Occurrence and Annual Rainfall Amount in Hulu Kelang Area from 1990 to 2011

The rainfall distributions in Malaysia are characterized by two monsoon seasons, namely the Southwest Monsoon from late May to September and the Northeast Monsoon from November to March. However, the highest rainfall normally occurs during the transition period between the Monsoon seasons, or known as inter-Monsoon season. Department of Irrigation and Drainage (Department of Drainage and Irrigation, 2000) reported that April and May normally receive the highest rainfall amount, and followed by October and November. January is normally the driest month throughout a year (Desa and Niemczynowicz, 1996). Figure 4.3 summarizes the month of occurrences of the 21 landslide events in Hulu Kelang area from 1990 to 2011. Apparently, the landslide occurrences showed good agreements with the rainfall characteristics as discussed earlier. Over 60% of the landslides occurred within the months of April, May, October, and November, while no landslide has been reported in the month of January. These observations signified the importance of correlating the initiations of landslide occurrences in Hulu Kelang area with rainfall infiltrations.

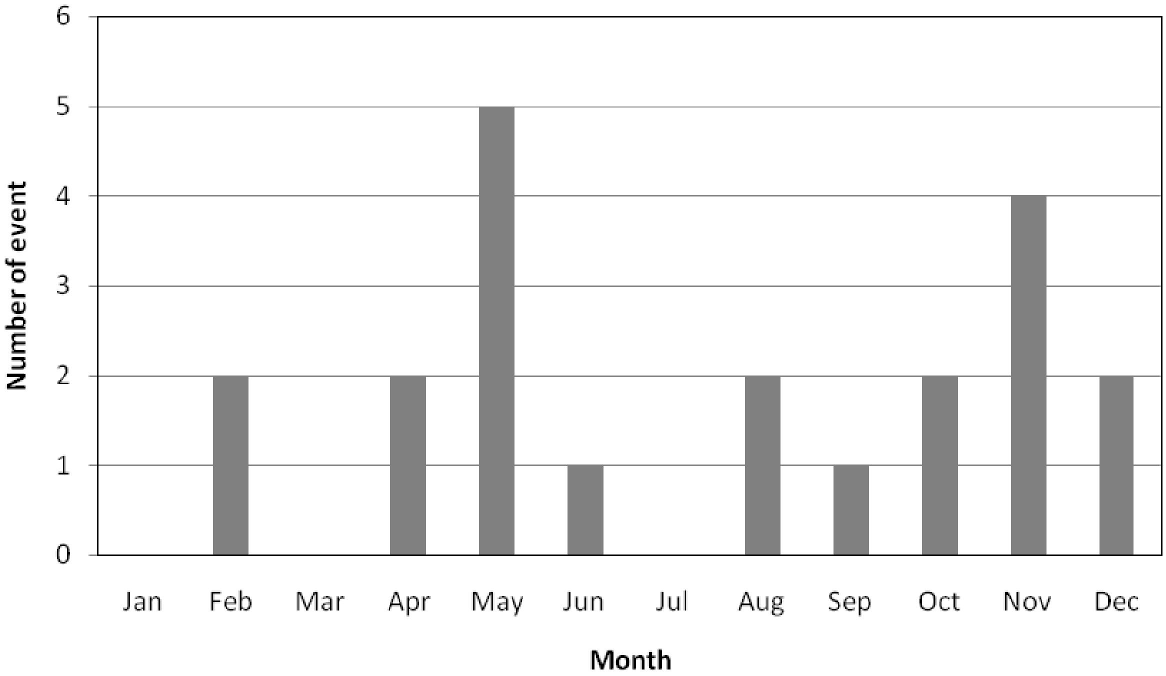


Figure 4.3: Statistic on the Month of Landslide Occurrence in Hulu Kelang Area from 1990 to 2011

4.4 Geological Profile and Soil Properties

Figure 4.4 shows the geological profile of the Hulu Kelang area reproduced from the Geological map of Selangor (Geological Survey Department of Malaysia). The area is generally underlain by granitic rocks, phyllite and schist, and Limestone with minor intercalations of phyllite. However, most of the historical landslides only occurred on the granitic rocks formation. Weathering of the granitic rocks produced

Grade V and Grade VI sandy silt residual soils with a thickness of approximately 15 m to 30 m (Ali, 2000). This deep deposit of granitic residual soil layer is prone to landslides. To further complicate the problem, this layer of residual soil is normally characterized by large variability of engineering properties due to different degrees of weathering process. For instances, the saturated coefficient of hydraulic conductivity within a residual soil layer may vary up to two orders of magnitude (Agus et al., 2005; Kassim et al., 2012). The hydraulic responses of the soil slope to rainfall infiltration are thus exposed to numerous uncertainties due to this variability. Table 4.2 shows the typical soil properties for Bukit Antrabangsa and Table 4.3 shows typical infiltration rate for different type of soil in Bukit Antarabangsa.

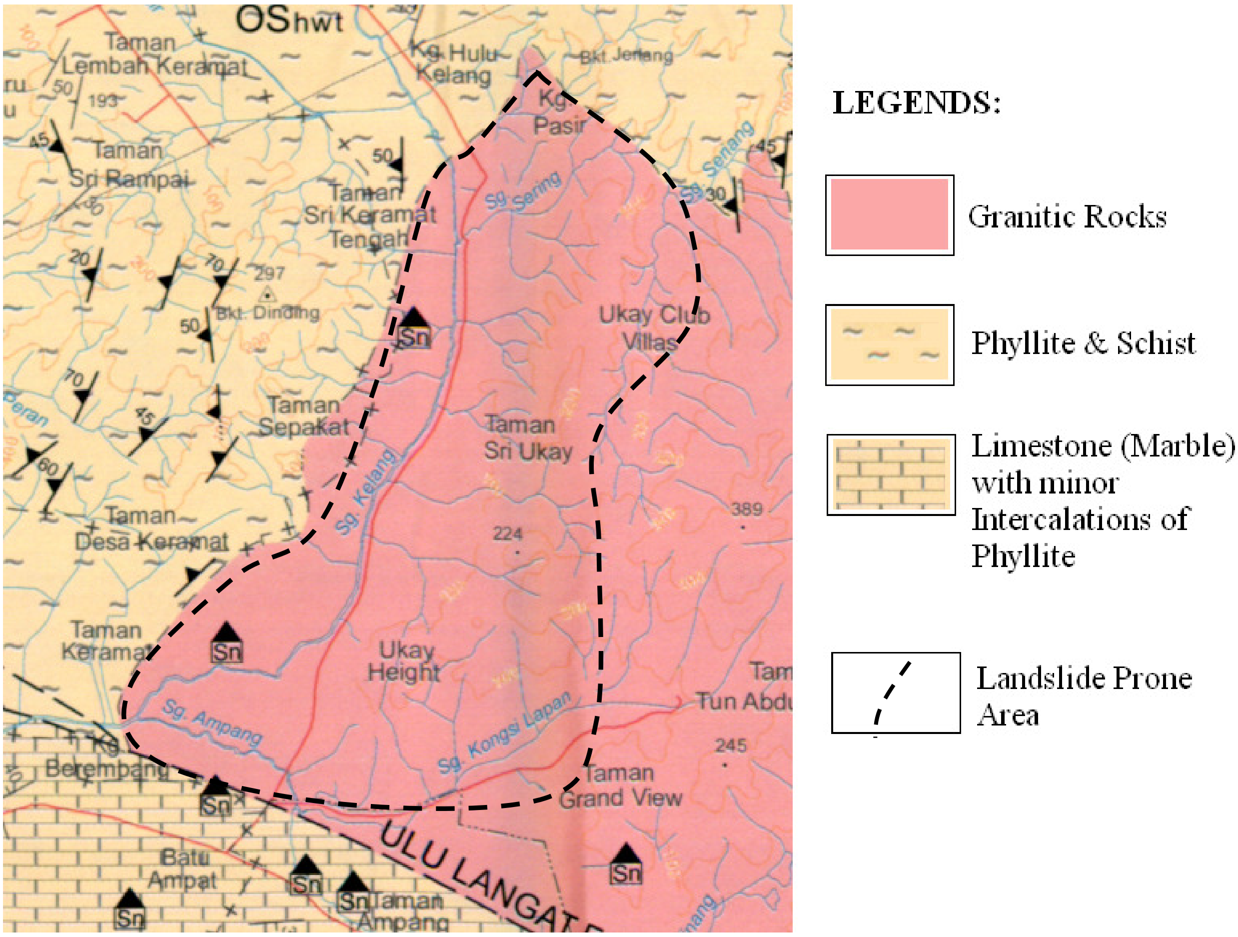


Figure 4.4: Geological Map of Hulu Kelang Area

Table 4.2: Typical soil properties at Bukit Antarabangsa (Mukhlisin et.al, 2011)

Soil Characteristic	
Unit weight (kN/m^3)	18.5
Specific gravity	2.65
Dry unit weight (kN/m^3)	1.42
Shear Strength Parameter	
Friction Angle (ϕ)	23
Cohession (kPa)	8.7
Permeability (m/s)	2.4048×10^{-3}
Porosity	43

Table 4.3: Typical infiltration rate of different type of soil at Bukit Antarabangsa

Type of Soil	Infiltration Rate (m/s)
Very Clayey Sand with trace of gravel	1.0×10^{-5}
Sandy Silt with trace of gravels	5.0×10^{-5}
Very Silty Sand with trace of gravels	3.0×10^{-5}
Sandy Silt with trace of gravels	1.0×10^{-5}
Very Silty Sand	4.0×10^{-5}
Well-graded Sand with trace of gravels	4.0×10^{-6}

4.5 Rainfall Pattern Analyses for Five Selected Case Studies

To provide an overview of the correlation between rainfall infiltration and landslide initiation, the rainfall patterns prior to the occurrences of five landslide events in Hulu Kelang were investigated. The five selected case studies include Highland Tower landslide (11-Dec-93), Bukit Antarabangsa landslide (15-May-99), Taman Zooview landslide (29-Oct-01), Taman Hillview landslide (20-Nov-02), and Bukit Antarabangsa landslide (06-Dec-08). These landslides represent the major events that had occurred in Hulu Kelang area from 1990 to 2011.

Figure 4.5 to Figure 4.9 shows the daily rainfall distributions for 3 months period prior to the occurrences of the five selected case studies. Except the Taman Zooview landslide (Figure 4.7), all the landslide events did not occur during the highest daily rainfall. These observations suggested that the amount of the daily rainfall may not be the only factor affecting the slope stability. The prolonged antecedent rainfall could also play a role in building up the mechanism of landslide.

When including the antecedent rainfall in predicting landslide occurrence, a key issue is to define the duration over which the accumulative rainfall needs to be considered (Sengupta, et al., 2010). Experiences from different regions of the world have resulted in different conclusions. It is important to determine duration of antecedent rainfall based on the local rainfall condition.

Figure 4.10 to Figure 4.14 shows the critical rainfall durations for the five selected case studies. The Taman Zooiew landslide can be best predicted by the daily rainfall distribution. The Bukit Antarabagsa 1999 landslide is best predicted by 3-day cumulative rainfall. The Highland Tower landslide is best predicted by 14-day cumulative rainfall, while the 30-day cumulative antecedent rainfall gives the best predictions for the landslides at Taman Hillview and Bukit Antarabangsa 2008.

The rainfall pattern analyses showed that both the short and long duration rainfalls may trigger for the landslides in Hulu Kelang area. Previous studies (Lee et al., 2009) suggested that the duration of rainfall to be considered for the analysis of a rainfall-induced landslide is governed by the hydraulic properties of soil. For instances, the slope with low permeability soil is susceptible to failure under long duration rainfall, and vice versa. The residual soil in Hulu Kelang has an intermediate value of permeability with large variability (ranging from 10^{-4} to 10^{-6} m/s). The large variability in hydraulic properties can be attributed to different degree of weathering of the residual soils, as explained earlier. Therefore, the critical duration for predicting the landslides in Hulu kelang should cover both the short and long duration rainfalls. For this reason, it was suggested that the cumulative 3-day and 30-day rainfalls were used for the prediction of landslide in this area.

The rainfall threshold amount / intensity is another important parameter for predicting the rainfall-induced landslide. From the rainfall pattern analyses, it was found that the rainfall threshold amounts for 3-day and 30-day cumulative rainfalls were about 140 mm and 500 – 600 mm, respectively.

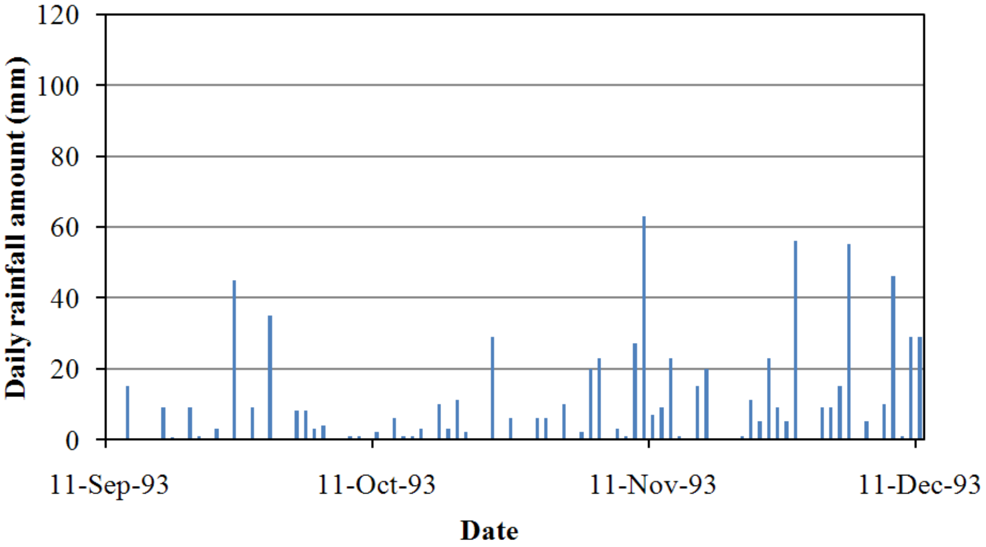


Figure 4.5: Daily Rainfalls for Highland Tower Landslide (11-Dec-93)

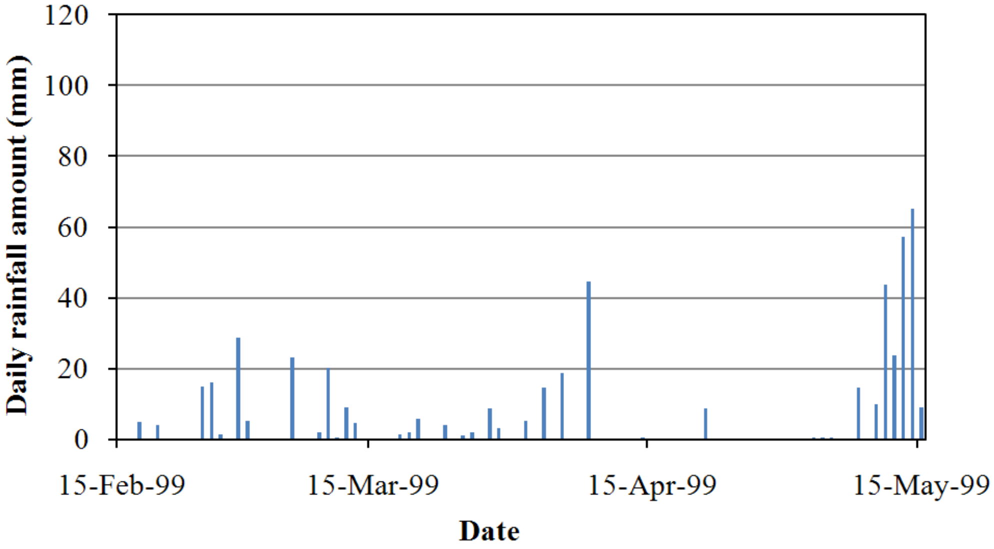


Figure 4.6: Daily Rainfalls for Bukit Antarabangsa Landslide (15-May-99)

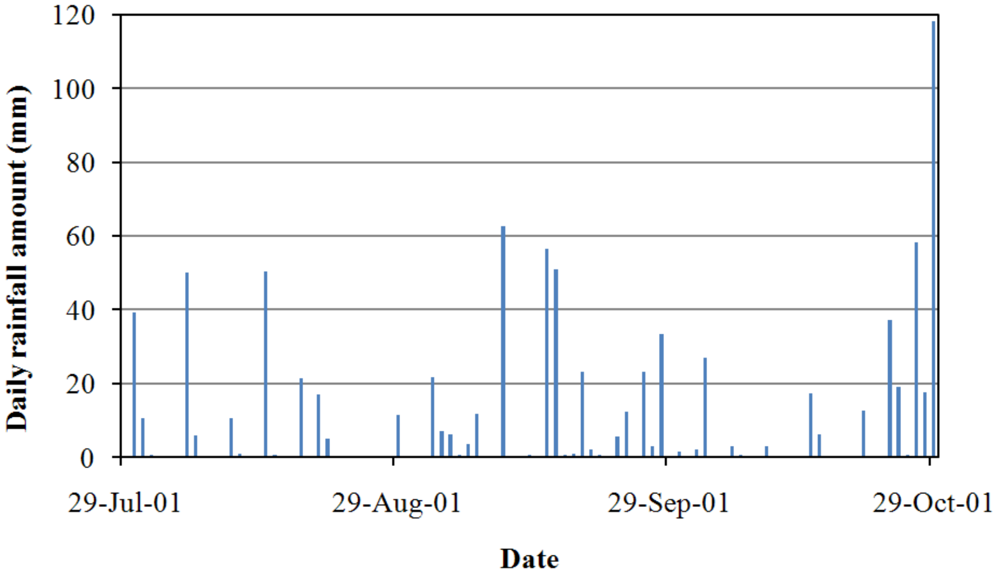


Figure 4.7: Daily Rainfalls for Taman Zooview Landslide (29-Oct-01)

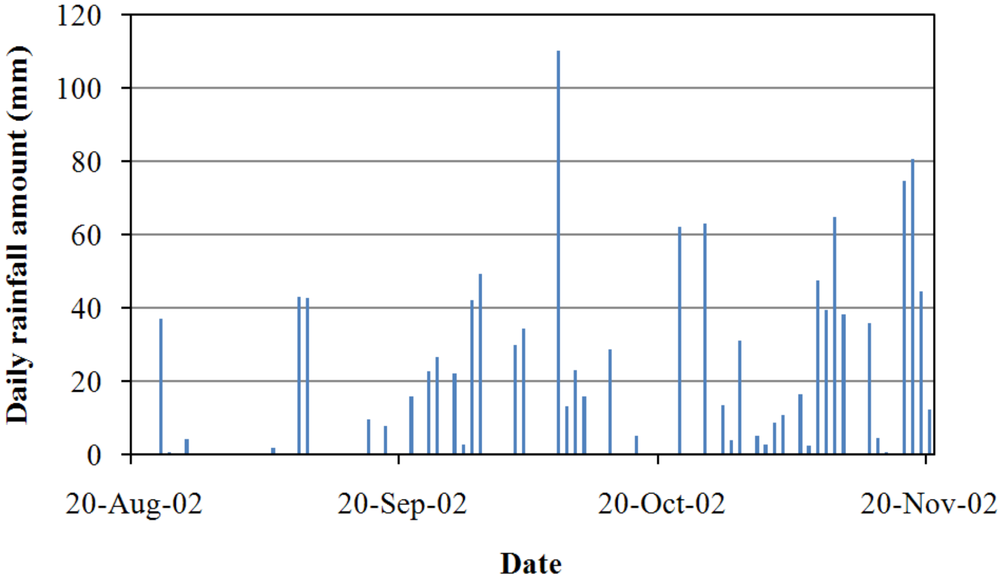


Figure 4.8: Daily Rainfalls for Taman Hillview Landslide (20-Nov-02)

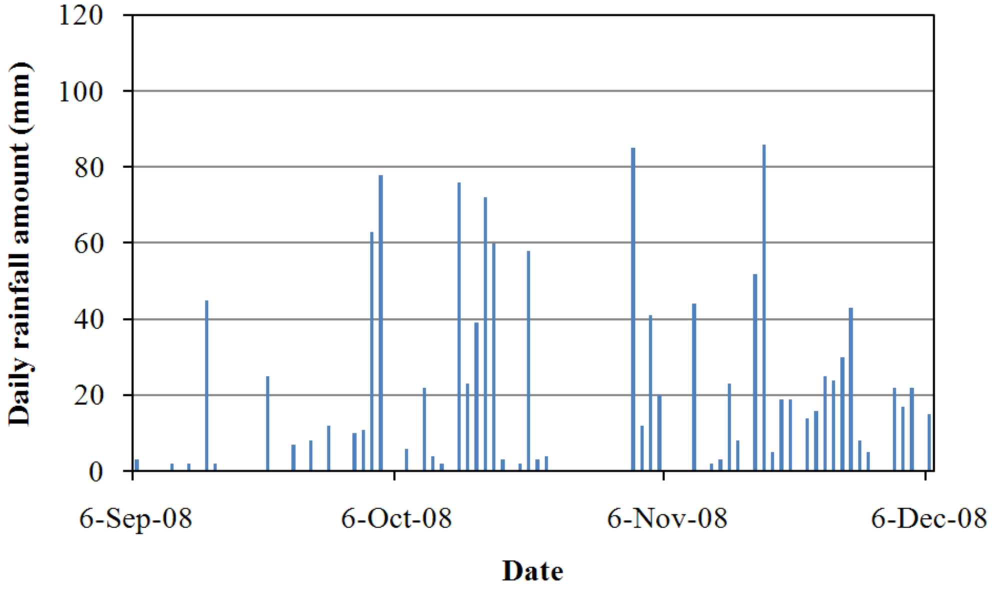


Figure 4.9: Daily Rainfalls for Bukit Antarabangsa Landslide (06-Dec-08)

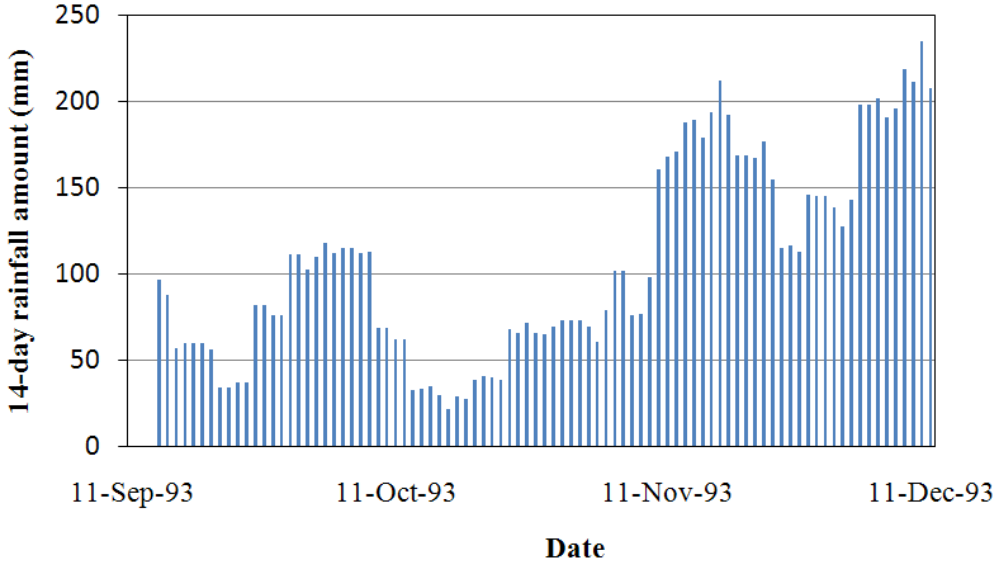


Figure 4.10: Critical Duration Cumulative Rainfalls for Highland Tower Landslide (11-Dec-93)

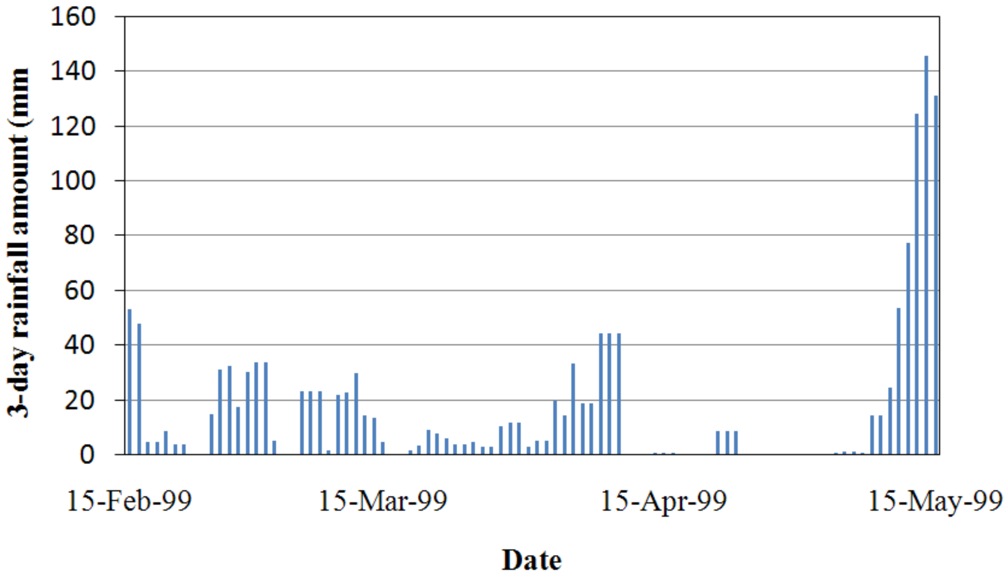


Figure 4.11: Critical Duration Cumulative Rainfalls for Bukit Antarabangsa Landslide (15-May-99)

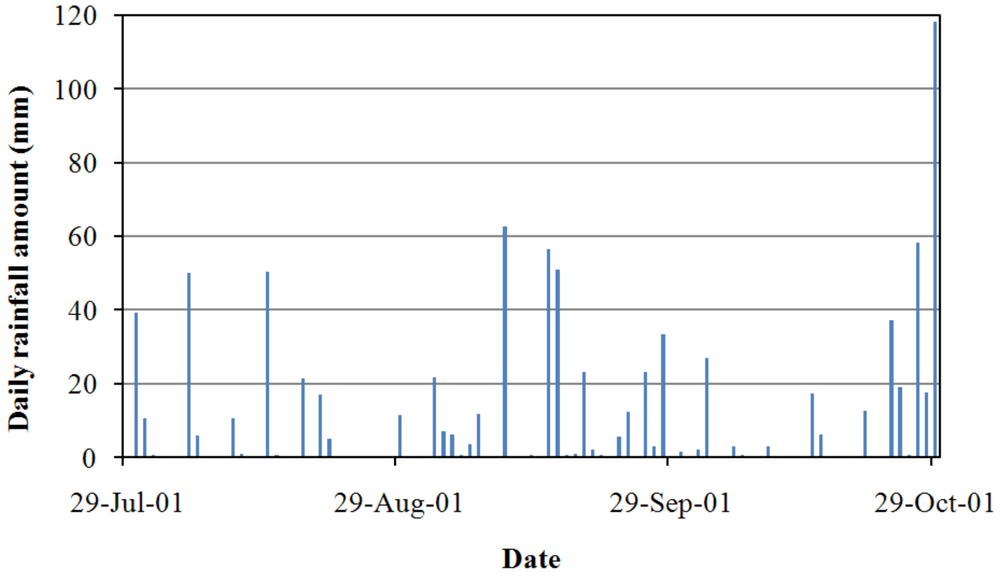


Figure 4.12: Critical Duration Cumulative Rainfalls for Taman Zooview Landslide (29-Oct-01)

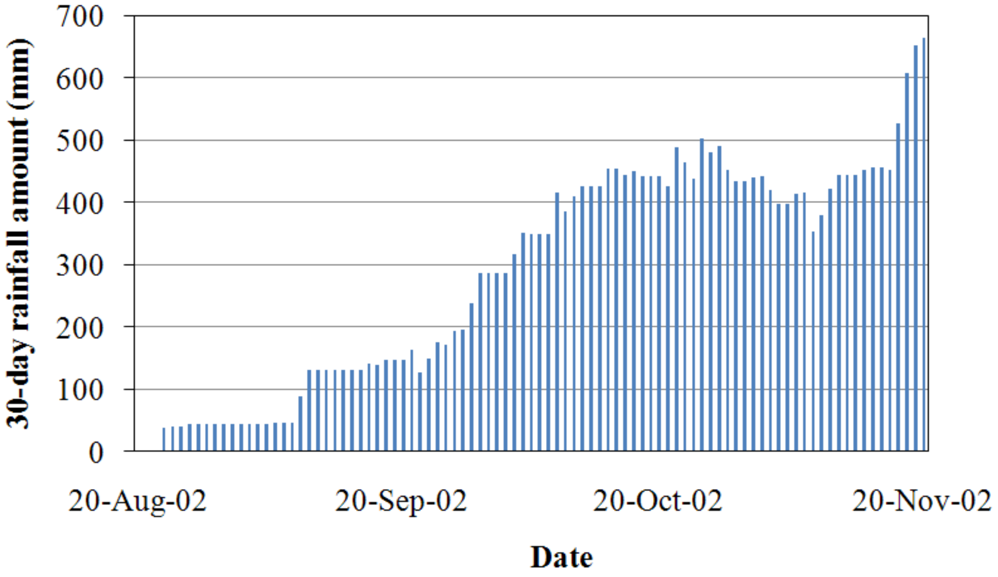


Figure 4.13: Critical Duration Cumulative Rainfalls for Taman Zooview Landslide (29-Oct-01)

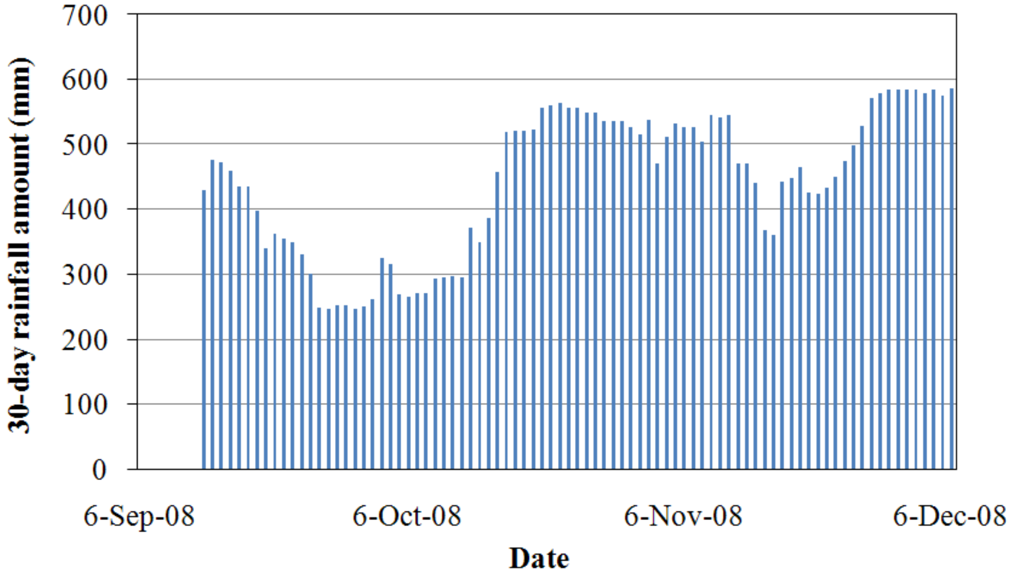


Figure 4.14: Critical Duration Cumulative Rainfalls for Bukit Antarabangsa Landslide (06-Dec-08)

4.6 Numerical Simulation of a Selected Case Study

Numerical simulation was carried out on a selected case study to provide an insight into the mechanism of rainfall-induced landslide in this area. The selected case study was known as Bukit Antarabangsa 2008 landslide, which was regarded as one of the largest in Hulu Kelang area over the past decade. The landslide struck at about 3.30 a.m. on 6th December 2008, when residents were mostly fast asleep. Figure 4.15 shows the aerial view of the endangered area of the landslide. The landslide had translated a total soil volume of about 101,500 m^3 generating a maximum run out distance of approximately 210 m (Low et al., 2012). Fourteen bungalow houses located at the toe of the slope were destroyed resulting in five fatalities and another fourteen injured.

Figure 4.15: Aerial View of the Bukit Antarabangsa Landslide on 6 December 2008

4.6.1 Pore-water pressure Results

Figure 4.16 shows the transient pore-water pressure variations at the middle of the slope. The pore-water pressures increased gradually over time. The pore-water pressures in the upper 2 m layer were subjected to large variations. The hydraulic response of the soil beyond 2 m was relatively slow. It should also be noted that positive pore water pressure was not detected throughout the simulation period. The landslide was mainly triggered by the loss of matric suction or negative pore-water pressure in the soil.

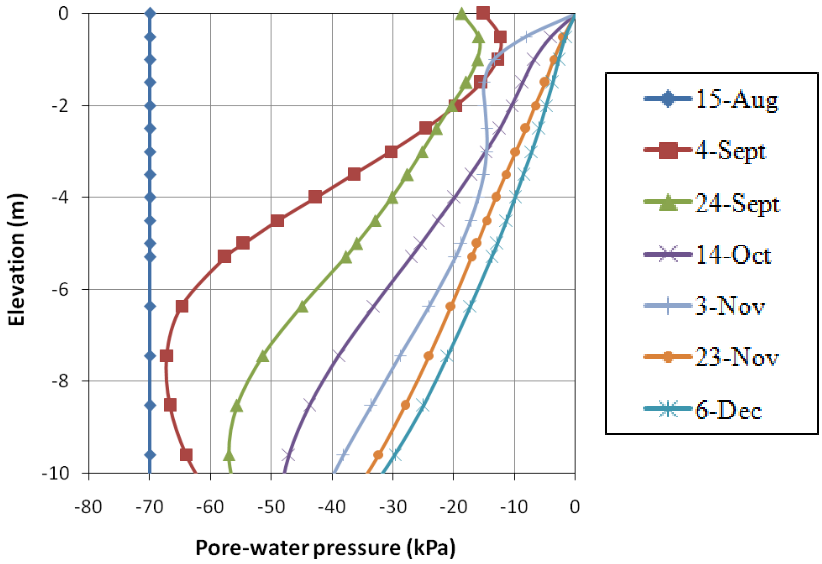


Figure 4.16: Transient Pore-water Pressure Distributions

4.6.2 Slope Stability Analysis Results

The result of slope stability analysis exhibited a similar trend as that of pore-water pressure whereby the factor of safety (FOS) decreased steadily over time (Figure 4.17). The FOS of the slope decreased from 1.269 (15th August 2008) to the lowest value of 0.986 on the day of landslide occurrence (6th December 2008). There was no drastic drop of FOS in the buildup to the landslide. This can be explained by the daily rainfall data as shown in Figure 4.9. The rainfalls for few days prior to the landslide were of low intensity / negligible (< 30 mm / day). However, there were two intense rainfall events (> 80 mm / day) occurred on 2nd and 17th November 2008 coupled with a long wet period. It was believed that the gradual reduction in FOS was caused by these prolonged antecedent rainfalls and the redistribution of infiltrated rainwater. This simulation result concluded that the landslide may not necessary to be triggered by a major rainfall event. The prolonged antecedent rainfall could play a dominant role in triggering the landslide.

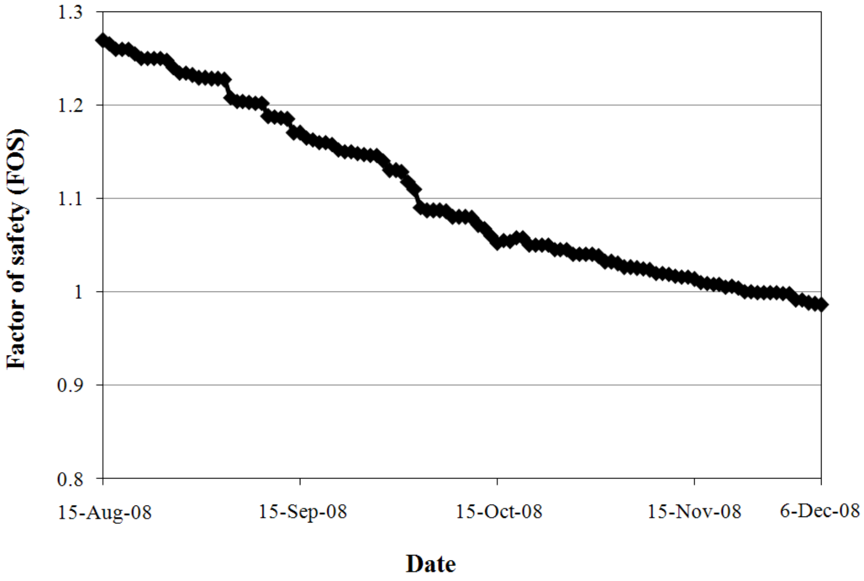


Figure 4.17: Changes of Factor of Safety (FOS) Over Time

4.7 Empirical Rainfall Threshold Charts

In this project, three empirical rainfall threshold charts were proposed, namely Intensity – Duration of 3-day rainfall threshold chart $(I - D)_3$, Cumulative 30-day rainfall – Number of rainy day threshold chart ($E_{30} - N$), and Cumulative 3-day rainfall – Cumulative 30-day rainfall threshold chart ($E_3 - E_{30}$). These threshold charts were proposed to account for both short and long duration rainfalls that may trigger the landslides in Hulu Kelang area.

4.7.1 Intensity-Duration of 3-day Rainfall Threshold Chart *(I-D)₃*

This proposed rainfall threshold chart took into account the short duration rainfall (3-day rainfall) in predicting the landslide. For the slopes triggered by short duration rainfall, the soil is normally of high permeability. When the ratio of rainfall intensity to saturated permeability (I / k_{sat}) is smaller than 1, which is very common for soil of high permeability, the intensity of rainfall plays a more dominant role in altering the pore-water pressure, and hence slope stability. The use of intensity (I) – duration (D) threshold as that suggested by Caine (1980) is thus justified. Figure 4.18 shows the plotting of Intensity – Duration of 3-day rainfall $(I - D)_3$ for the historical rainfalls that have resulted in landslides. Apparently, the limiting threshold proposed by Caine (1980) could not provide a good prediction to the landslide occurrence in Hulu Kelang. Numerous landslide occurrence rainfalls were plotted below the limiting threshold. A new limiting threshold was proposed empirically:

$$I = 55.23\, D^{-1.09}\,; \qquad \text{but } I > 1 \tag{4.1}$$

Figure 4.19 shows the $(I - D)_3$ rainfall threshold chart developed based on the newly proposed threshold line (4.1). The chart was tested for its reliability using non-occurrence rainfall data from 1990 to 2011, as tabulated in Table 4.4. Over the past 22 years, there were 978 occasions where the non-occurrence rainfalls were plotted above the limiting threshold. The verification results yielded a reliability of 87.8% implying the landslides in Hulu Kelang can be predicted reasonably well by taking into considerations the intensity of the 3-day rainfall only.

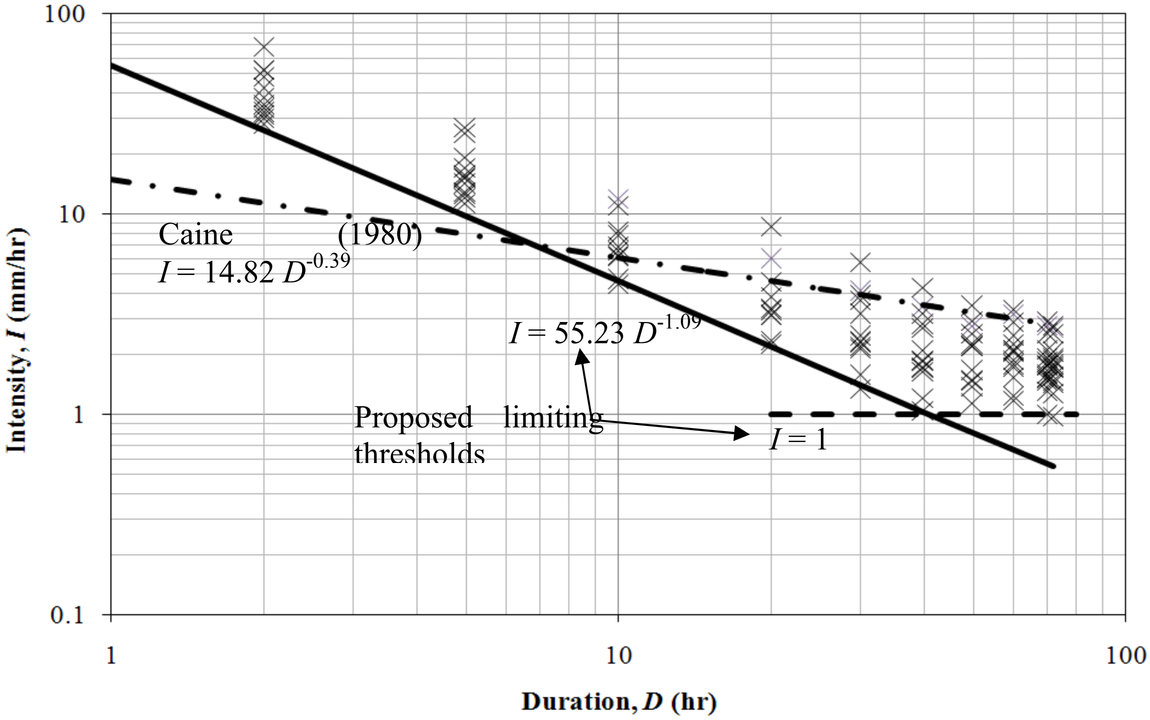


Figure 4.18: Plotting of Intensity – Duration of 3-day Rainfall $(I – D)_3$ for Historical Rainfalls that have Resulted in Landslides

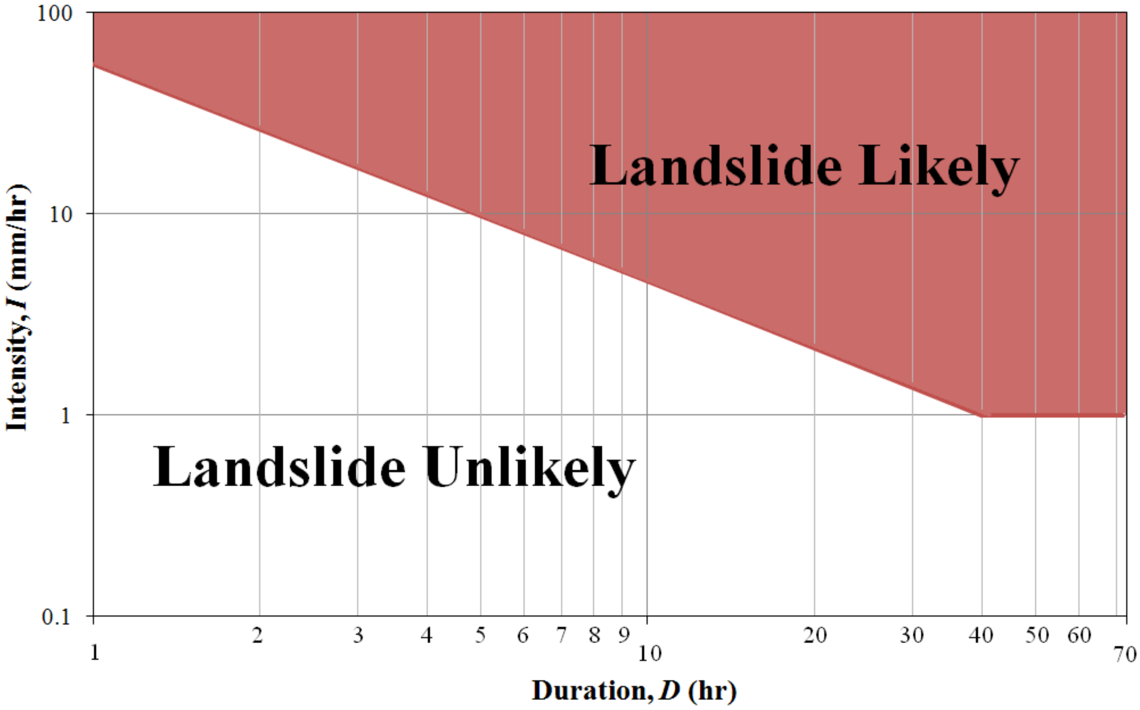


Figure 4.19: Proposed Intensity – Duration of 3-day Rainfall $(I – D)_3$ Threshold Chart

Year	**Total no. of day**	**No. of non-occurrence rainfall plotted above limiting threshold**	**Reliability (%)**
1990	365	25	93.1
1991	365	43	88.2
1992	366	26	92.9
1993	365	30	91.8
1994	365	34	90.7
1995	365	57	84.4
1996	366	47	87.2
1997	365	47	87.1
1998	365	35	90.4
1999	365	62	83.0
2000	366	60	83.6
2001	365	49	86.6
2002	365	46	87.4
2003	365	46	87.4
2004	366	41	88.8
2005	365	35	90.4
2006	365	57	84.4
2007	365	43	88.2
2008	366	66	82.0
2009	365	32	91.2
2010	365	56	84.7
2011	365	41	88.8
Overall	**8035**	**978**	**87.8**

Table 4.4: Verification Results of the proposed Intensity – Duration of 3-day Rainfall $(I - D)_3$ Threshold Chart

4.7.2 Cumulative 30-day Rainfall-Number of Rainy Day Threshold Chart (E_{30}-N)

The second proposed rainfall threshold chart incorporated the long duration rainfall (30-day rainfall) in predicting the landslide. The long duration rainfall normally governs the stability of less permeable soil. The infiltration of the intense rainfall is limited by the low permeability of soil. Therefore, the cumulative amount and frequency of rainfall appear to be the more dominant triggering factors than the rainfall intensity. For this reason, the number of rainy day and the cumulative 30-day rainfall amount were taken into considerations in developing this rainfall threshold chart. Figure 4.20 shows the plotting of Cumulative 30-day rainfall – Number of rainy day ($E_{30} - N$) for the historical rainfalls that have resulted in landslides in Hulu Kelang area. A limiting threshold line was proposed:

$$E_{30} = 163.6 + 1.27 \times 10^{-7} N^{7} \qquad (4.2)$$

Where E_{30} is the cumulative amount of 30-day rainfall, and N is the number of rainy day within the 30 days concerned. Figure 4.21 shows the ($E_{30} - N$) rainfall threshold chart developed from the proposed equation (4.2). The verification results for the chart, as tabulated in Table 4.5, shows that there were 1521 occasions where the non-occurrence rainfalls were plotted above the limiting threshold. The reliability of the chart was only about 81.1% implying that the prediction of landslide in Hulu Kelang could not be relied on the long duration rainfall only.

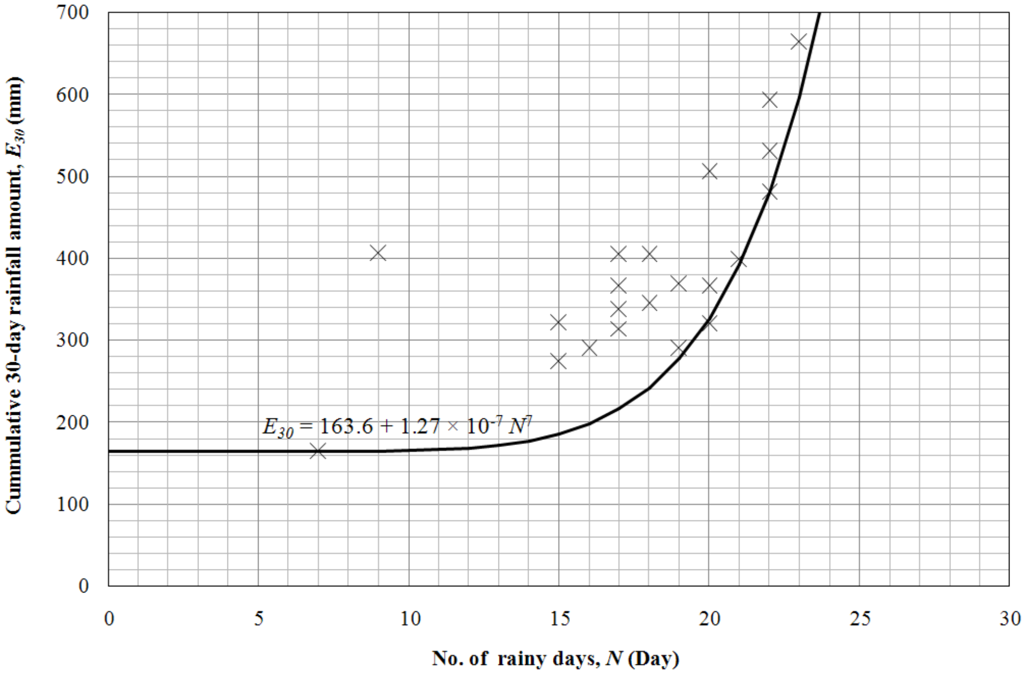


Figure 4.20: Plotting of Cumulative 30-day rainfall – Number of Rainy Day (E_{30} – N) for Historical Rainfalls that have Resulted in Landslides

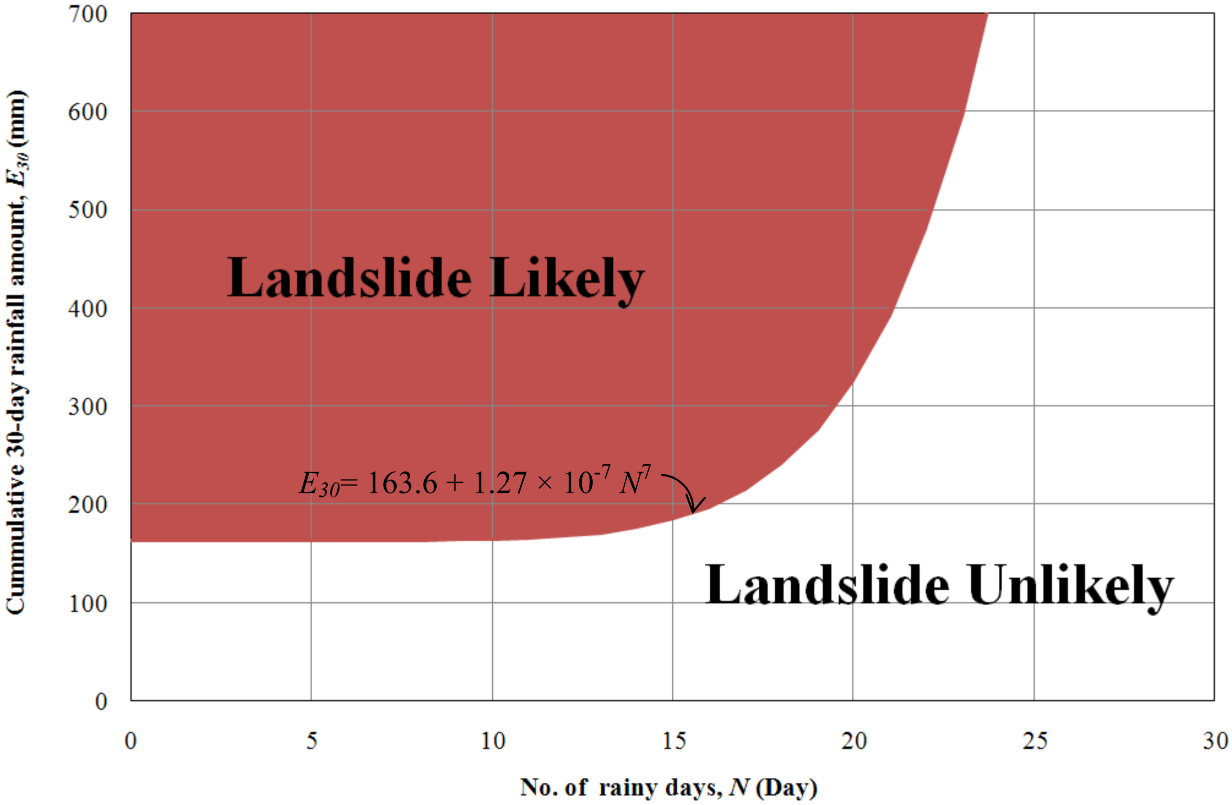


Figure 4.21: Proposed Cumulative 30-day rainfall – Number of Rainy Day (E_{30} – N) Threshold Chart

Year	Total no. of day	No. of non-occurrence rainfall plotted above limiting threshold	Reliability (%)
1990	365	15	95.9
1991	365	97	73.4
1992	366	4	98.9
1993	365	5	98.6
1994	365	51	86.0
1995	365	82	77.5
1996	366	84	77.0
1997	365	63	82.7
1998	365	53	85.5
1999	365	86	76.4
2000	366	119	67.5
2001	365	75	79.5
2002	365	62	83.0
2003	365	82	77.5
2004	366	87	76.2
2005	365	43	88.2
2006	365	43	88.2
2007	365	75	79.5
2008	366	130	64.5
2009	365	53	85.5
2010	365	98	73.2
2011	365	114	68.8
Overall	**8035**	**1521**	**81.1**

Table 4.5: Verification Results of the proposed Cumulative 30-day Rainfall – Number of Rainy day (E_{30} – N) Threshold Chart

4.7.3 Cumulative 3-day Rainfall – Cumulative 30-day Rainfall Threshold Chart ($E_3 - E_{30}$)

As both the short and long duration rainfalls may trigger the landslides in Hulu Kelang, it is thus necessary to develop a threshold model that incorporates both the 3-day and 30-day cumulative rainfalls. Figure 4.22 shows the limiting threshold lines generated from the correlation between the 3-day and 30-day cumulative rainfalls. Two limiting threshold lines were formed based on the occurrences of minor and major landslide events:

$$E_3 = -0.607\,E_{30} + 307.5 \qquad \text{for major landslide} \qquad (4.3)$$

$$E_3 = -0.607\,E_{30} + 202.2 \qquad \text{for minor landslide} \qquad (4.4)$$

The major landslides were defined based on the total volume of soil movement and casualties resulted from the landslide. Figure 4.23 presents the rainfall threshold chart formed by the Eq 4.3 and Eq 4.4. The reliability of the chart was examined, as summarized in Table 4.6. By taking reference to the limiting threshold for minor landslide, there were 1211 occasions where the non-occurrence rainfalls were plotted above the limiting threshold line for the past 22 years. This resulted in a reliability of 84.9%. The reliability of the prediction (i.e. 97.5%) was significantly improved by taking reference to the limiting threshold for major landslide. There were only 201 non-occurrence rainfalls plotted above the limiting threshold.

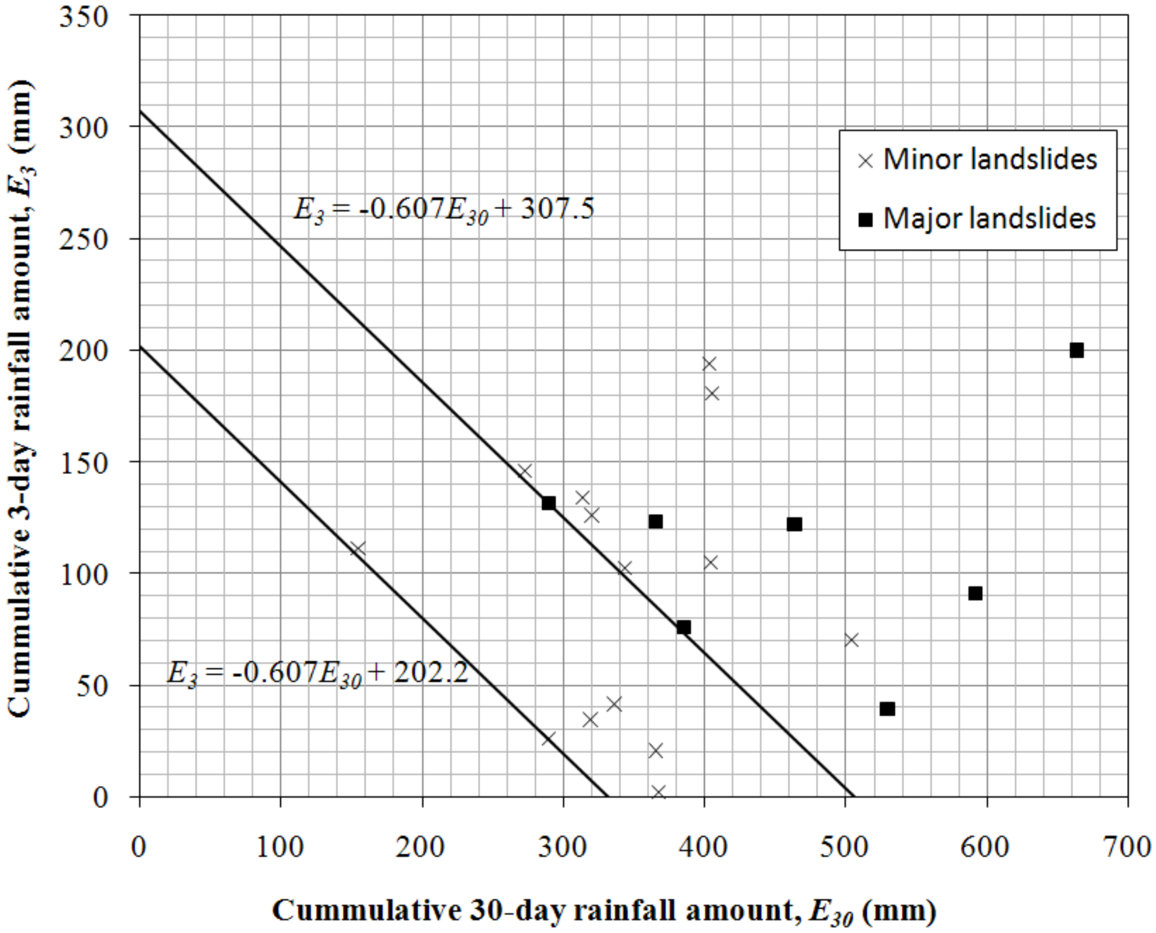


Figure 4.22: Plotting of Cumulative 3-day Rainfall – Cumulative 30-day Rainfall ($E_3 – E_{30}$) for Historical Rainfalls that have Resulted in Landslides

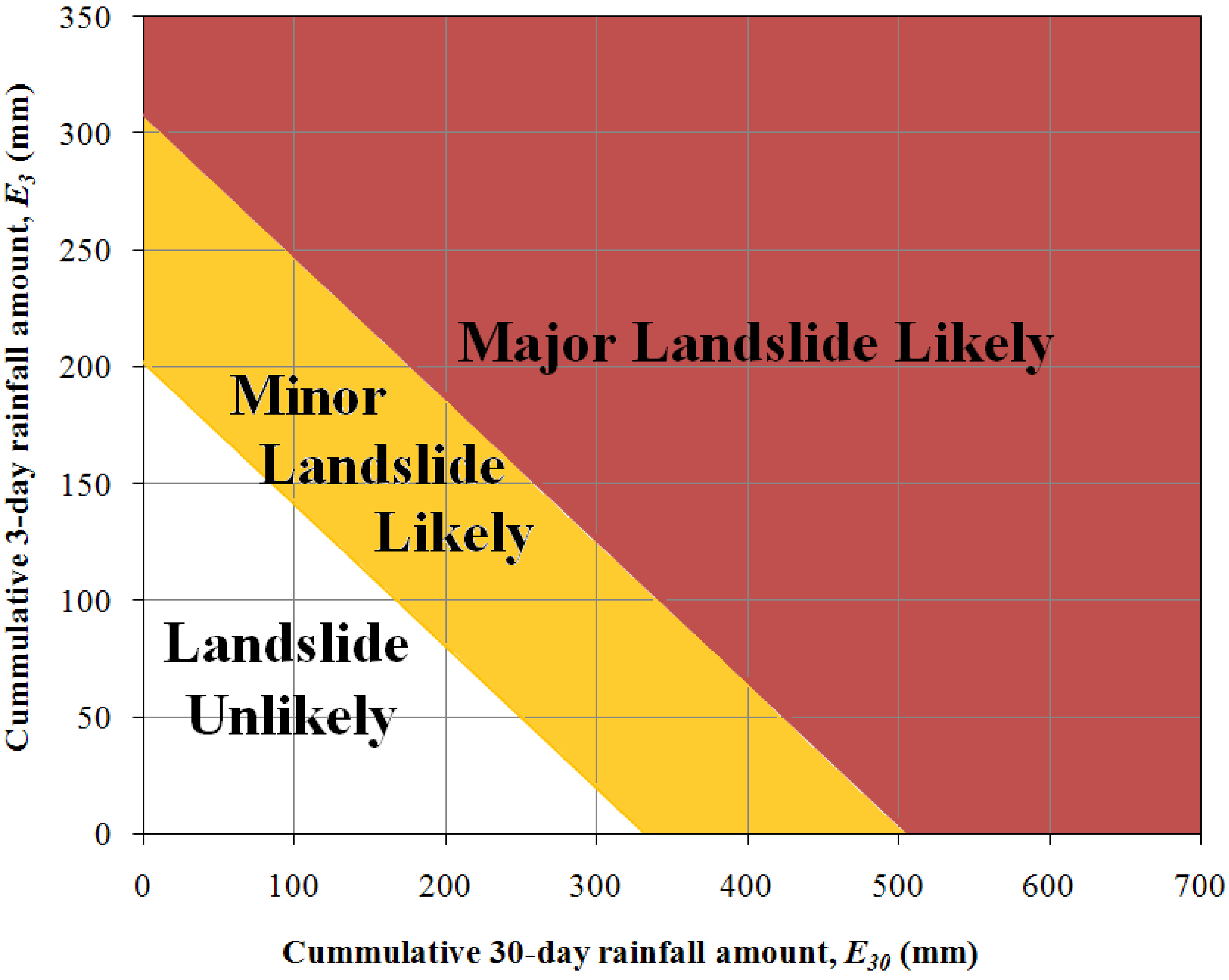


Figure 4.23: Proposed Cumulative 3-day Rainfall – Cumulative 30-day Rainfall (E_3 – E_{30}) Threshold Chart

Year	**Total no. of day**	**No. of non-occurrence rainfall plotted above limiting threshold for minor landslide**	**No. of non-occurrence rainfall plotted above limiting threshold for major landslide**	**Reliability based on limiting threshold for minor landslide (%)**	**Reliability based on limiting threshold for minor landslide (%)**
1990	365	3	0	99.2	100.0
1991	365	28	3	92.3	99.2
1992	366	12	0	96.7	100.0
1993	365	13	0	96.4	100.0
1994	365	28	3	92.3	99.2
1995	365	78	9	78.6	97.5
1996	366	47	3	87.2	99.2
1997	365	59	25	83.8	93.2
1998	365	64	26	82.5	92.9
1999	365	89	12	75.6	96.7
2000	366	91	11	75.1	97.0
2001	365	100	26	72.6	92.9
2002	365	59	14	83.8	96.2
2003	365	61	0	83.3	100.0
2004	366	52	17	85.8	95.4
2005	365	17	0	95.3	100.0
2006	365	72	2	80.3	99.5
2007	365	46	13	87.4	96.4
2008	366	135	14	63.1	96.2
2009	365	16	0	95.6	100.0
2010	365	86	10	76.4	97.3
2011	365	55	13	84.9	96.4
Overall	**8035**	**1211**	**201**	**84.9**	**97.5**

Table 4.6: Verification Results of the proposed Cumulative 3-day Rainfall – Cumulative 30-day Rainfall (E_3 – E_{30}) Threshold Chart

4.8 Discussions

The slope failures in the tropical regions, particularly Malaysia are commonly triggered by frequent rainfalls. In addition to the typical short and intense tropical rainfall, the rainfall characteristics in Malaysia are also influenced by two monsoon seasons and inter-monsoon seasons. Prolonged and low intensity rainfall is a norm during these periods. Under such circumstances, the rainfall threshold for the possible initiation of landslide in Malaysia should account for both the short and long duration rainfalls.

From the rainfall pattern analyses on the five selected case studies, it was found that most of the landslides were unlikely to occur if antecedent rainfall is not taken into consideration. This was because the rainfall on the day of landslide occurrence were of low intensity or negligible. Rainfalls of longer durations (i.e. 3-30 days) were required for better prediction of these landslides. The results from the numerical simulation confirmed this finding. The factor of safety and matric suction of the slope were reduced steadily over a long period. The redistribution of infiltrated rainwater in soil mass could be the factor causing the slow response of the failure mechanism to rainfall.

The landslide prediction based on the long duration rainfall alone was relatively unreliable, as demonstrated in the ($E_{30} - N$) rainfall threshold chart. This was because the granitic residual soil in Hulu Kelang area was mainly characterized by intermediate permeability (ranging from 10^{-4} to 10^{-6} m/s). The rainfall threshold based on intensity and duration ($I - D$) such as that proposed by Caine (1980) could give a reasonably good prediction. However, the threshold line should be modified by adapting to the local rainfall conditions. Comparatively, the 3-day versus 30-day cumulative rainfall threshold chart ($E_3 - E_{30}$) could give a better prediction to the landslide.

Uncertainties always prevail in any hazard prediction system. Two important criteria in assessing the quality of a rainfall threshold are its reliability and accuracy. A threshold chart that results in too many non-occurrence rainfalls plotted above the threshold line is deemed as unreliable. It could lead to too many false alarms which can substantially compromise the credibility of the early warning system (Larsen 2008). An accurate rainfall threshold means the system will not miss the prediction of any landslide event. In reality, a high accuracy prediction system would normally yield a low reliability. It is a challenge to strike a balance between the two criteria. One of the alternatives is by incorporating the inherent hazard level of the landslide event into the rainfall threshold model. When developing the (E_3 – E_{30}) rainfall threshold chart, the landslides were categorized into major and minor events based on their severity, cost and casualties incurred. The limiting threshold line for the major event could yield a reliability of up to 97.5%.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This project investigated the mechanisms of rainfall-induced landslide in Hulu Kelang area, Malaysia through rainfall pattern analysis and numerical simulation on selected case studies. Several rainfall thresholds were developed as attempts to predict the occurrence of rainfall-induced landslide in the area. The following conclusions can be drawn from the study:

(i) The slopes in Hulu Kelang area are underlain by deep deposit of granitic residual soil with intermediate permeability and large variability. The landslides could be triggered by both the short and intense rainfall, and the prolonged antecedent rainfall.

(ii) The daily rainfall could not be used for predicting the landslides in Hulu Kelang as most of the historical landslides did not occurred during the highest daily rainfall.

(iii) The numerical simulation results demonstrated that both the matric suction and factor of safety decreased gradually over time until the lowest values were obtained on the day of landslide occurrence. The redistribution of infiltrated rainwater in soil mass could be the reason for the slow response of failure mechanism to rainfall. Further investigations are required to confirm this finding.

(iv) The rainfall intensity – duration threshold as proposed by Caine (1980) could provide a reasonably good prediction to the landslides in Hulu Kelang. However, the limiting threshold line needs to be modified to adapt to the local rainfall conditions.

(v) The cumulative 3-day versus 30-day rainfall threshold chart could give the most reliable prediction to the landslide in Hulu Kelang. The reliability based on the limiting threshold line for major landslide yielded a reliability of 97.5%.

5.2 Recommendations of Research

This project can be improved by considering the following recommendations:

(i) The information of landslides was only collected from the PWD, MPAJ, local newspaper and publication journal. The information may not be sufficient to develop a reliable rainfall-landslide correlation for Hulu Kelang. The information can be collected from other government agencies such as Majlis Perbandaran Kajang (MPKj). In addition, the reliability of the rainfall threshold charts can be improved by considering a longer time frame, i.e. from 1980 – 2011.

(ii) Rainfall data is an important criterion to develop an empirical rainfall threshold. In this project, the rainfall amount of each landslide sites is based on the nearest rain gauge station. Ideally, the rainfall amount should be estimated from the rainfall device at the landslide site. Therefore, regionalization method can be used to calculate the rainfall amount of each landslide site.

(iii)The reliability of the empirical rainfall threshold is examined based on the Empangan Klang Gate station. As mentioned, Empang Klang Gate station represents all the other stations in Ulu Kelang area. However, if subsequent stations could be examined as well, the reliability of the empirical rainfall threshold would be further improved.

(iv) Most of the landslides occurred during the rainy days when the soil is relatively wet. An Antecedent Water Index is necessary to predict the soil moisture of a ground. The soil moisture must exceed the antecedent soil moisture threshold before the Intensity-Duration Threshold can be used.

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