Jurnal Teknologi

Full paper

Analysis of Rainfall Effect to Slope Stability in Ulu Klang, Malaysia

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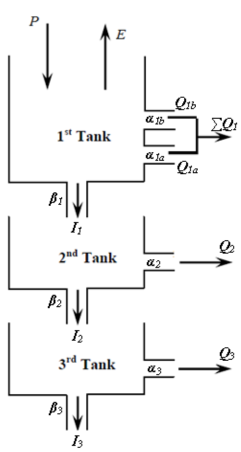
Article history

Received: 17 August 2014
Received in revised form:
17 November 2014
Accepted: 24 December 2014

Graphical abstract



Schematic of the tank model

Abstract

Malaysia is a country that is located near the equator line with tropical climates which receives high abundant rainfall, averaging 2,400mm annually. This makes Malaysia prone to the landslide events as rainfall is one of the main triggering factors that can cause landslide. Landslides in Malaysia are mainly attributed to frequent and prolonged rainfalls, in many cases associated with monsoon rainfalls. Of these, Ulu Klang area has received the most exposure. The area has constantly hit by fatal landslides since December 1993. This paper is aimed to investigate the correlation between the effective working rainfall and soil water index (SWI) methods with the landslide events in Ulu Klang, Malaysia. In this study 15 landslide events that occurred in Ulu Klang areas between years 1993 to 2012 were investigated and analyzed using rainfall threshold based on effective working rainfall and soil water index (SWI) methods. The analysis results showed that these methods are significant tools that can be used to identify the rainfall critical threshold of landslide event.

Keywords: Working rainfall, soil water index, landslide

Abstrak

Malaysia adalah sebuah negara yang terletak berhampiran garisan khatulistiwa dengan iklim tropika yang menerima hujan yang banyak dan tinggi , dengan purata 2,400 mm setahun . Ini menjadikan Malaysia terdedah kepada peristiwa-peristiwa tanah runtuh yang mana hujan adalah salah satu faktor utama yang boleh mencetuskan kejadian tanah runtuh. Tanah runtuh di Malaysia adalah disebabkan oleh hujan yang kerap dan berpanjangan, dalam banyak kes yang berkaitan dengan hujan monsun. Kesannya daripada keadaan ini, kawasan Ulu Klang telah menerima impak yang paling tinggi. Kawasan ini sering dilanda tanah runtuh dan meragut nyawa sebilangan penduduk sejak Disember 1993. Kajian ini bertujuan untuk menyiasat hubungan antara hujan berkesan dan kaedah indeks tanah air (SWI) dengan peristiwa-peristiwa tanah runtuh yang berlaku di Ulu Klang, Malaysia. Dalam kajian ini, 15 kes tanah runtuh yang berlaku di kawasan Ulu Klang di antara tahun 1993-2012 dikaji dan dianalisis dengan menggunakan kaedah hujan berkesan (WR) dan indeks air tanah (SWI) untuk menentukan hujan kritikal yang menyebabkan kejadian tanah runtuh tersebut. Keputusan analisis menunjukkan bahawa kaedah ini boleh digunakan untuk mengenal pasti hujan kritikal yang menyebabkan tanah runtuh berlaku.

Kata kunci: Hujan berkesan, indeks air tanah, tanah runtuh

1.0 INTRODUCTION

Rainfall has been considered as the cause of the majority of landslides in regions experiencing high seasonal rainfalls [1, 2], hence; rainfall characteristics should be considered in the analysis of such failure [3]. The effect of antecedent rainfall on slope instability has been well accepted; however, the critical duration of antecedent rainfall is still widely debated. Antecedent rainfall is defined as rain that falls in the days immediately preceding the landslide event [4]. Trigo et al. [5] suggested that slope failure could be triggered by high-intensity short-duration rainfall more than 130 mm daily rainfall, but other researchers [6-8] suggested that antecedent rainfall plays a more important role than the single rainstorm event for the initiation of slope failure. The durations of antecedent rainfall suggested by various researchers however differ considerably. Lumb [6] suggested that, in Hong Kong, antecedent rainfall up to 15 days prior to the failure event should be considered in addition to the intensity of the triggering rainstorm. Ng and Shi [7] proposed critical rainfall duration of antecedent rainfall between 3 to 7 days only. In Singapore, Rahardjo et al. [4] recommended 5 days of antecedent rainfall as the critical rainfall duration. Subsequent researches showed that the rainfall induced slope instability is affected by total rainfall and initial condition of the slope [9] as well as soil permeability and slope depth [10]. Case studies indicate that geographical location also has an effect on the occurrence of rainfall induced slope failure [11]. Experiences from different regions of the world have resulted in different conclusions in defining the duration of the cumulative rainfall. From the foregoing, it is clear that the local rainfall pattern plays an important role in the mechanism of rainfall-induced landslide in an area.

Rainfall-induced landslide is a typical geohazard in tropical territories like Malaysia in which soil commonly of residual soils. For assessing rainfall-induced landslides, it is important to understand the relation between historical landslide events and rainfall conditions [12, 13]. Regional-scale analysis includes empirical methods based on statistical correlations between landslides and rainfall variables [14-17]. Among these absolute rainfall variables, the cumulative event rainfall and hourly rainfall intensity are the basic rainfall variables [18]. In Japan, hourly rainfall intensity (60 min cumulative rainfall) and Soil Water Index (SWI) [19] are used for early warning system of landslide disasters [20]. These previous studies have shown that landslides are more likely to occur with increasing cumulative antecedent rainfall, hourly rainfall intensity, and SWI.

With this in view, this paper aims to demonstrate the effect of cumulative antecedent rainfall (i.e., 72-hour), hourly rainfall intensity (i.e., 1.5-hour), and soil water index (SWI) to analyze the susceptibility of slope to rainfall induced landslide by using fifteen cases of landslide in Ulu Klang, Malaysia. Initially, a daily rainfall records was collected for this study from Ampang and Empangan Genting Klang stations through Department of Irrigation and Drainage (DID). The rainfall patterns prior to the landslide occurrence were analyzed and the effective working rainfalls were calculated for the following periods: 1.5-hour and 72-hour. The working rainfalls are used to determine the critical duration of antecedent rainfall or rainfall threshold for each landslide case. The soil water index (SWI) are then calculated using the tank model where the soil water index equals to the total storage volume of three tanks laid vertically in series. The SWI is used to determine the total of water contain in the ground at the day of the landslide occurred. A high level of SWI means that the rainfall has a significant role in destabilizing the slope. Finally, the calculated 72-hour cumulative antecedent rainfall, 1.5-hour rainfall intensity, and SWI are correlated with the mechanism of rainfall-induced landslides in Ulu Klang area. The findings from this study will demonstrate the significant of this method to identify the critical rainfall threshold of the landslide event.

■2.0 MATERIALS AND METHODS

2.1 Study Area

Ulu Klang is geographically located at the latitude of 3° 10’ 00’’ North and 101° 45’0’’ East which is under the jurisdiction of Ampang Jaya Municipality and Kajang Public Work Department [21]. This area covering about 100 km^2 is a highly landslide prone area within the country due to the hilly terrain as well as intense rainfall pattern (Figure 1). Situated near to Kuala Lumpur and consists of hilly area, it is one of the popular residential area for people who live in Kuala Lumpur. High demand for residential have increased the development around the area. Rapid development of hillside in ulu klang thus has caused disturbances to the characteristics of the natural slopes and consequently contributed to the landslide occurrences. Ulu Klang area has continually hit by fatal landslides since December 1993, which causing a tragedy involving 48 deaths, when a block of Highland Towers collapsed, [22]. Table 1 summarizes some of the catastrophic landslide incidents reported in Ulu Klang area and their impacts on the socio-economic. Figure 2 illustrates the catastrophic landslide incidents reported in Ulu Klang area from 1993 - 2012.

Figure 1 Location of Ulu Klang, Malaysia (Lee et al., [26])

Figure 2 Catastrophic landslide incidents in Ulu Klang (Lee et al., [26])

The landslides in Ulu Klang area have been studied by several researchers and practicing engineers [21- 26]. Despite of the fact that extensive studies have been carried out, landslide is still a recurring hazard at the study area concerned. It was either due to the proposed mitigation measures were not taken seriously by the authorities or the actual mechanism of the landslides have yet be revealed, is still unclear. As a result, public protests have emerged against hillside development in the country. Abruptly halting all the hillside developments, however, is not the best solution as the demand of land use is increasing rapidly, particularly in the urban area of Kuala Lumpur [26].

Table 1 Impacts of the landslide incidents in Ulu Klang area (Lee et al., [26])

Date	Location	Casualties	Loss of Properties
11-Dec-1993	Highland Towers	48 killed	Collapse of one block of 12-storey high apartment
15-May-1999	Bukit Antarabangsa	-	Closure of the main and only access road to the residential area
05-Oct-2000	Jalan Bukit Antarabangsa	-	Damage of road
20-Nov-2002	Taman Hillview	8 killed	Damage of 1 unit of bungalow
31-May-2006	Kampung Pasir	4 killed	Damage of 3 blocks of longhouses
24-Apr-2008	Condo Wangsa Height, Bukit Antarabangsa	-	Damage of 4 vehicles
6-Dec-2008	Tmn Bukit Mewah, Bukit Antarabangsa	5 killed, 7 injured	Damage of 14 units of bungalows

2.2 Landslide Data

In this study, 15 landslides that occurred in the Ulu Klang areas were investigated and analyzed. The landslides data are obtained from the data source of IKRAM Sdn Bhd. and also through literature surveys. Table 2 summarizes the landslide events that happen in Ulu Klang areas from 1993 to 2012.

Table 2 Dates and Location of Landslide Event in Ulu Klang

No	Date	Location
1	11.12.1993	Highland Tower
2	14.05.1999	Bukit Antarabangsa, Ulu Klang-Ampang
3	15.05.1999	Menara Athaneum, Ulu Klang
4	05.10.2000	Bukit Antarabangsa, Ulu Klang-Ampang
5	29.10.2001	Taman Zoo View, Ulu Klang
6	08.11.2001	Taman Zoo View, Ulu Klang
7	20.11.2002	Taman Hillview
8	02.11.2003	Kondominium Taman Oakleaf, Bukit Antarabangsa
9	07.11.2003	Jalan Bukit Mulia, Bukit Antarabangsa, Ulu Klang
10	31.01.2005	Jalan Tebrau, Dataran Ukay, Ulu Klang
11	01.02.2005	Jalan Tebrau, Dataran Ukay, Ulu Klang
12	31.05.2006	Taman Zoo View, Kampung Pasir, Ulu Klang
13	06.12.2008	Bukit Antarabangsa, Ulu Klang
14	19.09.2009	Wangsa Height, Selangor
15	21.06.2011	Taman Bukit Jaya, Selangor

2.3 Rainfall Data And Analysis

There are two locations of rainfall data stations used in this study which are JPS Ampang and Empangan Genting Klang. The rainfall data record in the periods of 1993-2012 was taken from the Department of Irrigation and Drainage, Malaysia (DID). The selection these two sites are because of their location that is near to the Ulu Klang landslides area. Figure 3 shows the location of the rainfall data station used in this study.

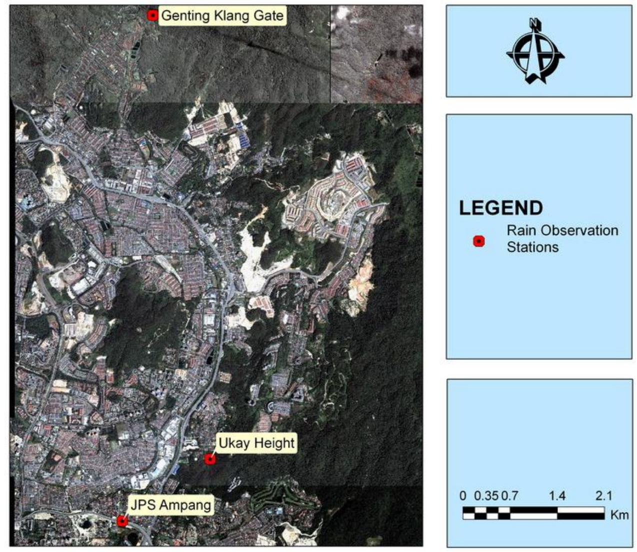


Figure 3 Location of the rain observation stations (Mukhlisin et al. [21])

To provide an overview of the correlation between rainfall infiltration and landslide initiation, the rainfall patterns prior to the occurrences of 15 landslide events in Ulu Klang were investigated. In this study, the effective working rainfall of 1.5-hour and 72-hour were computed to determine the critical duration of antecedent rainfall for each landslide case. The critical duration is defined as the duration that yields the highest rainfall amount on the day of landslide occurrence which is made based on the assumption that the highest rainfall should be indicative of a landslide event. Initially, the snake curve (SC) is drawn in x-y plane where the horizontal axis indicates the impact of the cumulative antecedent rainfall (i.e., 72-hour) while the vertical indicate the impact of hourly rainfall intensity (i.e., 1.5-hour). Then, the critical line (CL) is drawn based on the maximum working rainfall of 1.5-hour and 72-in the year when each landslide happened. The critical line is a line separating the areas where landslide likely to occur (i.e., on or above the CL) and unlikely to occur (i.e., below the CL). When the snake line reaches to the critical line, these mean the accumulated rainfall and the current intensity is very high, and thus can cause landslide occurrence.

The effective working rainfall can be calculated as follow:

$$1.5\ hours\ working\ rainfall = (WR_0(t)\times 0.5^{\frac{1}{1.5}})+R(t) \qquad (1)$$

$$72\ hours\ working\ rainfall = \left(WR_0(t)\times 0.5^{\frac{1}{72}}\right)+R(t) \qquad (2)$$

where WR_0 is previous hour working rainfall (mm/hr) and R is rainfall intensity at time t (mm).

In order to prevent landslide disasters during heavy rainfall, it is important to clear the relationship between rainfall and soil quality. Here, the function of soil water index (SWI) is used to give an indication on the level of soil moisture in the area of landslide. The soil water index is calculated using the tank model developed by Sugawara [27] where the soil water index equals to the total storage volume of three tanks laid vertically in series. This tank model is a simple concept that uses three tanks which are illustrated as reservoirs in a watershed that considering rainfall as the input and generate the output as the surface runoff, subsurface flow, intermediate flow, sub-base flow, as well as the phenomenon of infiltration, percolation, and water storages in the tank can be explained by the model. Figure 4 shows assumed flow patterns in tank model while Table 3 show the parameters of three series tank model used in this study.

Table 3 Parameters of three series tank model used in this study

Three series tank model	Height of tank holes (mm)		Coefficient of tank holes (mm)			
			Lateral		Vertical	
First Tank	H1b	60	α_{1b}	0.15	I_1	0.12
	H1a	15	α_{1a}	0.10		
Second Tank	H2	15	α_2	0.05	I_2	0.05
Third Tank	H3	15	α_3	0.01	I_3	0.01

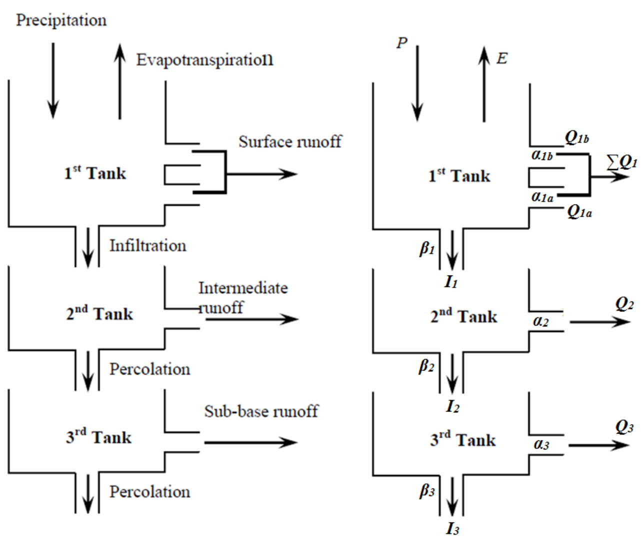


Figure 4 Schematic of the tank model in this study

Then the lateral flow discharge, $Q_i(t)$ and the vertical seepage volume $I_i(t)$ at one specific time can be calculated by the following equations:

$$Q_i(t)=\alpha(i)[WL_i(t)-H_i] \quad (3)$$

$$I_i(t)=\beta(i)[WL_i(t)-H_i] \quad (4)$$

where $WL_i(t)$ is the water table of corresponding tank, H_i is height of the lateral outlet, i is a number of lateral and vertical outlet for the respective tanks (i= *1a, 1b, 1, 2, 3*), $\alpha(i)$ and $\beta(i)$ are the lateral and vertical discharge coefficients respectively.

The SWI equals to the total storage volume of three tanks laid vertically in series. The storage volume on each tank can be calculated using the following equations:

$$\Delta S_1=R(t)-Q_1(t)-I_1(t)$$

$$\Delta S_2=I_1(t)-Q_2(t)-I_2(t)$$

$$\Delta S_3=I_2(t)-Q_3(t)-I_3(t) \quad (5)$$

where $\Delta S_{1,2,3}$ is the fluctuation of water storage in tank (i.e. tank 1, 2 and 3 respectively), and $R(t)$ is the rainfall intensity at specific time.

3.0 RESULTS AND DISCUSSION

Based on the analysis, we concluded that the critical duration of rainfall to be the threshold for massive landslide in Ulu Klang area can be categories into three; (1) the landslide is triggered by the cumulative antecedent rainfall, (2) the landslide is triggered by the highest rainfall intensity during the event and (3) the landslide events is not associated with the rainfall.

3.1 Landslide Caused By Cumulative Antecedent Rainfall

Based on the rainfall data from Empangan Genting Klang station, Figure 5 presents the critical line of Bukit Mulia Road event, Bukit Antarabangsa (i.e., event no. 9) and precipitation on 7 November 2003 during the landslide incident. The result indicates that the event occurred under the critical line which implies that the accumulated 72-hour rainfall before the event is very high while the current rainfall during the event is lower. This situation shows that a prolonged and continuous low intensity rainfall is occurred during these periods. As shown in Figure 5, the observation also reveals that the cumulative 72-hour antecedent rainfall was ten times higher than the 1.5-hour major rainfall during the event (i.e., 7 November 2003). Hence shows that the cumulative antecedent rainfall play a significant role on triggering the landslide occurrence.

With regard to the SWI in Figure 6, the result shows that the level of SWI during the day of event is low. However, the SWI of 3 days prior to the landslide incident is the highest SWI value recorded in the year 2003. This is due to the highest rainfall intensity that occurs 3 days before the landslide event occurred (i.e., 47mm/hr). The observation implies that the cumulative antecedent rainfall plays a significant role in destabilizing the slope and thus is the dominant triggering factor for the landslide occurrence at Bukit Mulia Road, Bukit Antarabangsa on 7 November 2003. This result illustrates that both the matric suction and factor of safety decreased steadily overtime until they reached the lowest values on the day of landslide occurrence as demonstrated by Lee [26] in their study. The SWI result also demonstrated the redistribution of infiltrated rainwater in the ground which is a reason for the slow response of failure mechanism to rainfall.

In the present study, observation on the rainfall pattern in event no. 1 - 4, 7, 9, 12 and 14 shows that all these landslide events did not occurred during the highest daily rainfall. These observations thus revealed that the amount of the daily rainfall is not the factor affecting the slope instability. In the other words, the cumulative antecedent rainfall could play a role in building up the mechanism of landslide. This mechanism is explained by Lee et al. [26] as a prolonged and low-intensity rainfall could result in a relatively greater amount of infiltration and eventually cause the slope more susceptible to failure.

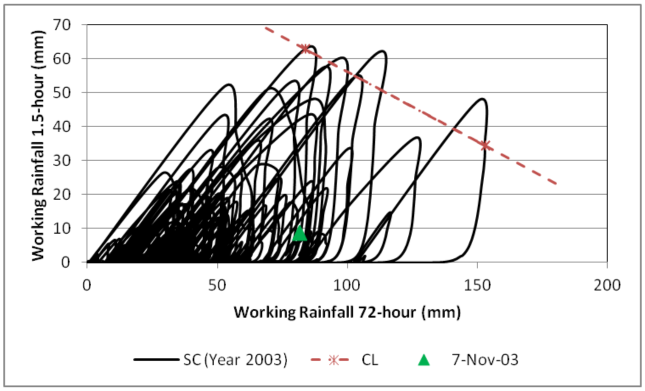


Figure 5 Critical line of Bukit Mulia Road event, Bukit Antarabangsa and precipitation on 7 Nov. 2003 during the landslide event – Rainfall data is based on rain gauge of Empangan Genting Klang station

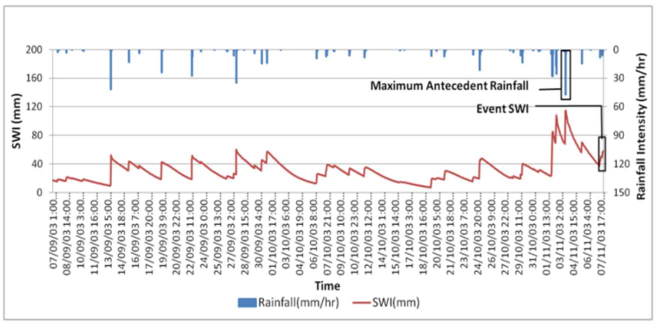


Figure 6 SWI of Bukit Mulia Road Event, Bukit Antarabangsa (07 Nov. 2003) – Rainfall data is based on rain gauge of Empangan Genting Klang station

3.2 Landslide Caused By Highest Rainfall Intensity During The Event

Based on the rainfall data from Empangan Genting Klang station, Figure 7 shows the critical line of Taman Zoo View event, Ulu Klang (i.e., event no. 5) and the precipitation on 29 October 2001 during the landslide event. The result indicates that the event occurred on the critical line which implies that the accumulated 72-hour rainfall before the event and current rainfall during the event is very high and thus has caused the landslide occurrence. As shown in Figure 7, the observation also reveals that the 1.5-hour major rainfall during the event (i.e., 29 October 2001) was more than half of the cumulative 72-hour antecedent rainfall. Hence shows that the 1.5-hour major rainfall play a significant role to cause the landslide occurrence.

With regard to the SWI, Figure 8 shows that there is a sharp rise in the value of SWI during the event. This is due to the highest rainfall intensity during the landslide incident (i.e., 88.1 mm/hr). This result reveals that the sharp rise of SWI has caused destabilization of the slope consequently triggering the landslide event. This is therefore concluded that the major contributor inducing the landslide event at Taman Zoo View, Ulu Klang on 29 October 2001 is the highest rainfall intensity during the event.

Previous research made by Lee et al. [26] has concluded that the critical rainfall duration for Taman Zoo View, Ulu Klang landslide event on October 2001 can be best predicted by daily rainfall distribution. Brand [1] also recommended that the most catastrophic landslides are triggered by major rainfall of more than 70mm/day. These critical rainfall duration and intensity showed good agreement with the result of working rainfall analysis and the SWI of the present study.

Observation on the rainfall pattern in event no. 5, 6, 8, 10, 11 and 13 also shows that all these landslide events was occurred during the short and intense daily rainfall. These observations thus suggested that the amount of the daily rainfall is the factor affecting the slope instability.

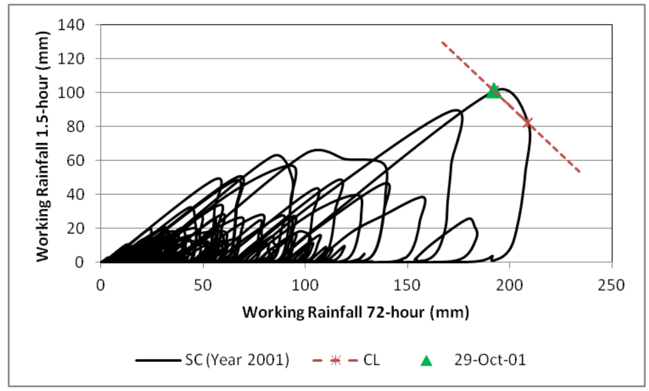


Figure 7 Critical line of Taman Zoo View event, Ulu Klang and precipitation on 29 Oct. 2001 during the landslide event – Rainfall data is based on rain gauge of Empangan Genting Klang station

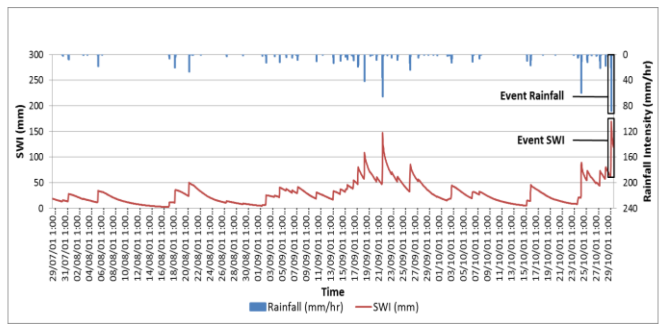


Figure 8 SWI of Taman Zoo View Event (29 Oct. 2001) – Rainfall data is based on rain gauge of Empangan Genting Klang station

3.3 Landslide Not Associated With Rainfall

Based on the rainfall data from JPS Ampang station, Figure 9 shows the critical line of Taman Bukit Jaya event, Ulu Klang (i.e., event no. 15) and precipitation on 21 June 2011 during the landslide event. The result indicates that the event occurred far below the critical line which implies that the accumulated 72-hour rainfall before the event and current rainfall during the event is very low. Hence show that the 1.5-hour rainfall and cumulative 72-hour antecedent rainfall did not play a significant role on triggering the landslide occurrence.

As shown in Figure 10, it was found that no rainfall was actually recorded on the day of landslide occurrence. Besides, the SWI level is also at the lowest level recorded for the whole year of 2011. The observation therefore suggested that the rainfall does not affect the occurrence of landslides in Taman Bukit Jaya event, Ulu Klang on 21 June 2011. The result support the fact that landslides could be caused by other contributing factors such as inadequate slope design [23], improper design and construction method [24], poor maintenance of the internal drainage system of slope and retaining structures [26], soil type, land cover, and slope gradient [29]. In this case, proper mitigation measures and slope design guideline must be taken seriously by the engineers especially in hillside development of Ulu Klang which could cause disturbances to the characteristics of the natural slopes and their surrounding area.

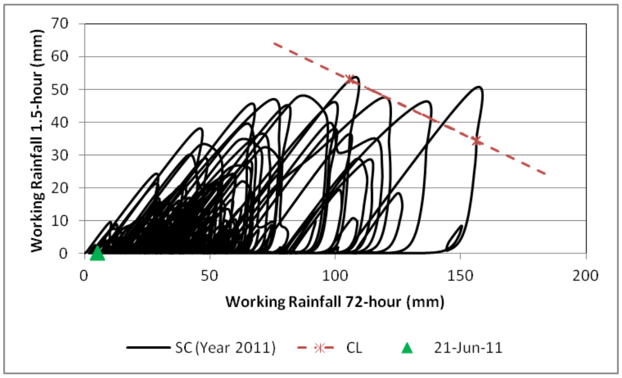


Figure 9 Critical line of Taman Bukit Jaya event, Ulu Klang and precipitation on 21 June 2011 during the landslide event – Rainfall data is based on rain gauge of JPS Ampang station.

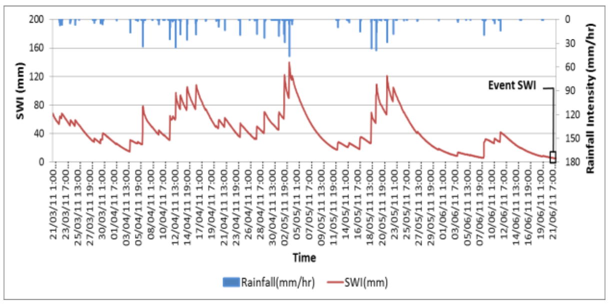


Figure 10 SWI of Taman Bukit Jaya Event (21 June 2011) – Rainfall data is based on rain gauge of JPS Ampang station.

From the summary results of Table 4, the rainfall pattern analyses showed that both the short (i.e, hourly rainfall) and long duration rainfalls (i.e., within 7 days) may trigger the landslides occurrence in Ulu Klang area. It was concluded that 8 landslide events (i.e., event no. 1 - 4 , 7, 9, 12, 14) are related to the cumulative antecedent rainfall while 6 events (i.e., event no. 5, 6, 8, 10, 11, 13) are related to the highest rainfall intensity during the event. These conclusions are supported by previous research by Lee et al. [26] and Jemec and Komac [28] which they found that both short-intense rainfall and prolonged antecedent rainfall were responsible for the landslide initiations. Under most circumstances, a sharp increase in the SWI during the event indicated that the soil loss its strength dramatically due to infiltration of rainwater into the soil before it failed. The result also shows that attention and cautious need to be done in relation to prolonged and continuous rainfall occurs within 7 days, in which it can cause the SWI value to increase while weakening the slope slowly, and consequently trigger landslides to occur at any time within that's.

For other instances, the destabilization of the slope that failed with a low level of SWI is suggested cannot be associated with rainfall (i.e., event no. 15). Due to this reason, other factors that can contribute to the landslide occurrence such as the stability of slope retaining structure, the surcharge that comes from superstructure, and damaged of facilities such as water reticulation pipe nearby need to be taken into account in the stability analysis of the slope in that area. Such factor also can lead to the destabilization of the slope and thus triggering the landslide occurrences [22-26].

Table 4 Summary values of highest rainfall intensity, highest antecedent rainfall and soil water index (SWI) according to two rainfall stations.

No	Event	$\left[\frac{\text{Highest rainfall intensity}}{\text{total daily rainfall}}\right]$ during the landslide event $\left(\frac{\text{mm/hr}}{\text{mm/day}}\right)$		$\left[\frac{\text{Highest antecedent rainfall}}{\text{total cumulative antecedent rainfall}}\right]$ within 7 days prior to landslide event $\left(\frac{\text{mm/hr}}{\text{mm}}\right)$		Soil Water Index (SWI) during the landslide event (mm)	
		JPS Ampang	Empangan Genting Klang	JPS Ampang	Empangan Genting Klang	JPS Ampang	Empangan Genting Klang
1	11/12/1993	0.5/2	12/24	12.7/17.5	20.5/78	9.4	50
2	14/05/1999	25.5/65	36/36.5	31.8/149.1	42/116.1	113	68
3	15/05/1999	8.8/9	16.2/17	31.8/214.1	42/152.6	92	67
4	05/10/2000	31.8/37.2	18.9/22	87.8/301.2	15.7/140.7	110	76
5	29/10/2001*	88.9/119.4	88.1/128.5	45/137	59.7/174.5	162	169
6	08/11/2001	4.4/9.1	37.6/46.5	5.2/22.1	25.2/66.5	28	82
7	20/11/2002	9.6/13.9	13.5/19.5	48.9/246.7	22/127	106	75
8	02/11/2003	27.5/64.5	28/114.5	1.5/2	13.5/32.5	69	108
9	07/11/2003*	9/17.5	8.5/26	27.5/99	47/189.5	59	58
10	31/01/2005	14/14	20/25	12.8/14.3	1.5/1.5	27	25
11	01/02/2005	41.7/43.7	24.5/27.5	14/28.3	20/26.5	67	49
12	31/05/2006	0/0	0.5/0.5	32/82.6	35.5/63.7	32	21
13	06/12/2008	29.3/30.3	23/23.5	34.7/60.7	17/49.5	72	53
14	19/09/2009	5.5/15.7	0.5/0.5	52.7/98	0.5/3.5	62	8
15	21/06/2011*	0/0	0.5/0.5	0.6/1.7	9.5/12.5	6	13

* Landslide events those were analyzed and demonstrated in 3.2, 3.1 and 3.3 respectively.
Event no. 1 - 4 , 7, 9, 12 and 14 are related to the cumulative antecedent rainfall
Event no. 5, 6, 8, 10, 11 and 13 are related to the maximum rainfall intensity during the event
Event no. 15 is not associated with rainfall

■4.0 CONCLUSION

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 about 2400 mm. With this amount of average rainfall, the rainfall-induced landslides become a significant study area. This paper investigated the correlation between the effective working rainfall and soil water index (SWI) methods with the landslide events in Ulu Klang, Malaysia. In this study 15 landslide events that occurred in Ulu

Klang areas between years 1993 to 2012 were investigated and analyzed using rainfall threshold based on effective working rainfall and soil water index (SWI) methods. The result showed that these methods are significant tools that can be used and considered to identify the rainfall critical threshold and also as a warning alert system of landslide event.

References

[1] Brand, E. 1984. Landslide in Southeast Asia. *Proceedings of 4th Intl. Conf. on Landslides* Toronto. 1:17–59

[2] Shaw-Shong, L. 2004. Slope failures in tropical residual soil. *In Tropical Residual Soil Engineering* Balkema: Leiden. 71–102.

[3] Matlan, S.J, Lee M.L and Gofar, N. 2010. Backanalysis of rainfall induced landsides by PERISI model. *International Conference on Geotechnical and Transportation Engineering* (GEOTROPIKA 2010), Kota Kinabalu, Sabah 1–3 December 2010.

[4] Rahardjo, H., Li X. W., Toll D. G. and Leong E. C. 2001. The Effect of Antecedent Rainfall on Slope Stability. *J. Geotech and Geological Eng. Netherlands*.19:371-399.

[5] Trigo R. M., Zeˆzere J.L., Rodriguez M.L., Trigo I.F. 2005. The influence of the north Atlantic oscillation on rainfall triggering of landslides near Lisbon. *Nat Hazards* 36: 331–353.

[6] Lumb, P. 1975. Slope Failures in Hong Kong. *Q.J.Eng. Geol*. 8: 31–65.

[7] Ng, C.W.W. and Shi,Q. 1998. A numerical investigation of the stability of unsaturated soil slopes subjected to transient seepage. *Comput.Geotech*. 22(1): 1–28.

[8] Tsaparas, I., Rahardjo, H., Toll, D.G., and Leong, E.C. 2002. Controlling parameters for rainfall –induced landslides. *Comput. Geotech*. 29: 1–27.

[9] Tsaparas, I.,Rahardjo, H.,Toll, D.G.and Leong E.C. 2003. Infiltration Characteristics of Two Instrumented Residual Soil Slopes. *Can. Geotech J*. 40: 1012–1032.

[10] Pradel, D. & Raad, G. 1993. Effect of Permeability on Surficial Stability of Homogeneous Slopes. *Journal of Geotechnical Engineering, ASCE*. 119(2): 315–332.

[11] Gofar, N., Lee, M.L. and Kassim, A. 2007. Stability of Unsaturated Slopes Subjected to Rainfall Infiltration. *Proceecings 4th International Conference on Disaster Prevention and Rehabilitation*, Semarang. 158–167.

[12] Keefer, D., R. Wilson, R. Mark, E. Brabb, W. Brown, S. Ellen, E. Harp, G. Wieczorek, C. Alger, and R. Zatkin. 1987. Real-time landslide warning during heavy rainfall. *Science*. 238: 921−925. doi:10.1126/science.238.4829.921.

[13] Wieczorek, G., and T. Glade. 2005. Climatic factors influencing occurrence of debris flows. Jakob, M. and Hunger, O., Eds. *Debris-flow Hazards and Related Phenomena*. 325–362.

[14] Caine, N., 1980. The rainfall intensity−duration control of shallow landslides and debris flows. *Geogr. Ann*. 62A: 23–27. doi:10.2307/520449.

[15] Chang, K., S. Chiang, and F. Lei, 2008. Analyzing the relationship between typhoon-triggered landslides and critical rainfall conditions. *Earth Surf. Process.* Landforms. 33: 1261–1271. doi:10.1002/esp.1611.

[16] Guzzetti, F., S. Peruccacci, M. Rossi, and C. Stark, 2008. The rainfall intensity−duration control of shallow landslides and debris flows: An update. *Landslides.* 5: 3−17. doi:10.1007/s10346-007-0112-1.

[17] Saito, H., D. Nakayama, and H. Matsuyama. 2010. Relationship between the initiation of a shallow landslide and rainfall intensity−duration threshold in Japan. *Geomorphology*. 118: 167–175. doi:10.1016/j.geomorph.2009.12.016.

[18] Guzzetti, F., S. Peruccacci, M. Rossi, and C. Stark. 2007: Rainfall thresholds for the initiation of landslides in central and southern Europe. *Meteor. Atmos. Phys*: 98: 239–267. doi:10.1007/s00703-007-0262-7.

[19] Okada, K., Y. Makihara, A. Shimpo, K. Nagata, M. Kunitsugu, and K. Saito. 2001. Soil Water Index. *Tenki*. 47: 36–41 (in Japanese).

[20] Osanai, N., T. Shimizu, K. Kuramoto, S. Kojima, and T. Noro. 2010. Japanese early-warning for debris flows and slope failures using rainfall indices with Radial Basis Function Network. *Landslides*. 7: 1–14. doi:10.1007/s10346-010-0229-5.

[21] Mukhlisin M, Idris I, Salazar AS, Nizam K, Taha MR. 2010. GIS based landslide hazard mapping prediction in Ulu Klang, Malaysia. In: *ITB Scientific Journal* 42A(2): 163–178.

[22] Gue, S.S. and Cheah, S.W. 2008. Geotechnical Challenges in Slope Engineering of Infrastructures, *KLIUC-International Conference on Infrastructure Development* (INCID), Putrajaya, Malaysia. 7–8 May 2008.

[23] Gue, S.S. and Liong C. H. 2007. Is the Ground in Ulu Klang Unstable, *Jurutera*, February. 32–33.

[24] Farisham, A.S. 2007. Landslides in the Hillside Development in the Hulu Klang, Klang Valley. *Post-Graduate Seminar*, *UTM*, Skudai, Malaysia. 6 March 2007.

[25] Low, T.H., Othman, M.A., Ashaari, M., Shabri, S., Mahadzer, M. and Fadli, M. B. 2008. Area Based Slope Hazard Assessment and Mapping in Hulu Kelang – Ampang, *International Conference on Slopes, Kuala Lumpur*, Malaysia. 4–6 November 2008. 409–420.

[26] Lee, M.L., Ng, K.Y., Huang, Y.F., & Li, W.C. 2014. Rainfall-induced landslides in Hulu Kelang area, Malaysia. Natural Hazards. 70(1): 353–375.

[27] Sugawara, M. 1961. Automatic callibration of tank model. *Hydrological Sciences-Bulletin-des Sciences Hydrologiques*. 24(3): 375–388.

[28] Jemec M., Komac M. 2011. Rainfall patterns for shallow landsliding in perialpine Slovenia. *Natural Hazards*. doi:10.1007/s11069-011-9882-9.

[29] Nguyen H.T., Wiatr T., Fernaˊndez-Steeger T.M., Reicherter K., Rodrigues D.M.M., Azzam R. 2013. Landslide hazard and cascading effects following the extreme rainfall event on Madeira Island (February 2010). *Nat Hazards* 65(1): 635–652