Landslide Prediction and Time Dependent Slope Safety Factor

by

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FINAL YEAR PROJECT REPORT

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CERTIFICATION APPROVAL

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Approved by,

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(Assoc. Prof Dr Indra Sati Hamonangan Harahap)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 2014

CERTIFICATION OF ORIGINALITY

I hereby declare that the research paper titled "***Landslide Prediction and Time Dependent Slope Safety Factor***" is my own work. The content of this report is the product of my own work, except as specified in the references and acknowledgements and that the original work contained herein have not been submitted to any other institution or undertaken by unspecified sources.

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NUR AMANINA BINTI KHAIRU

ABSTRACT

Landslide is a natural disaster which may influences by climate change such as rainfall. Most of the landslide events occur during rainstorm. The rainfall infiltration may promote the movement of soil at the slip surface and cause decrease slope stability factor as time dependent. Likewise, the rainfall intensity and soil permeability have significant effect in decrease the slope safety factor as time dependent. This research aims to modify existing development of landslide prediction model. Besides that, the effect of the rainfall intensity and soil permeability or soil type were investigated by using this model. In addition, this research also aims to obtain minimum slope stability and occurrences of landslides based on this analysis. The modified landslide prediction model consists of one dimensional Green Ampt infiltrations analysis and circular slope failure of finite slope using slice methods. For this research, three different of soil permeability or soil type were analyzed under low and high rainfall intensity. Overall, slope stability decreases as time increases. The result indicates the soil permeability are significantly affected the slope stability factor as time dependent. The soils which have high permeability which is sand are unstable as time dependent for both low and high rainfall intensity. As a comparison, the low permeability soil, which is clay are stable as time dependent. Under high rainfall intensity, the slopes fail a few hours after the rainfall starts. While low amount rainfall intensity shows that the longer time and intense rainfall need in order for a slope to fail.

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LIST OF SYMBOLS

$c^{'}$ effective cohesive soil (kPa)

$F(t)$ cumulative infiltration at time t (mm)

$f(t)$ infiltration rate at time t (mm/h)

I(t) rainfall intensity at time (mm/h)

k hydraulic conductivity coefficient (mm/h)

t elapsed time (h)

T_f critical time of failure (h)

T_p time at maximum rainfall intensity (h)

t_p ponding time (h)

Δt time interval (h)

ΔT time interval of rolling rainfall (h)

β slope angle

□' effective friction angle

h_n depth from failure surface to water table (m)

H depth of soil (m)

b_n width of the soil (m)

W weight of soil (kN/m)

θ_i initial moisture content

θ_s volumetric moisture content at saturation

σ_n normal stress parallel to failure plane (kPa)

□$_f$ section head at wetting front (L)

z_w depth of wetting front (m)

γ unit weight of soil (kN m^{-3})

CHAPTER 1
INTRODUCTION

1.1.Background of study

Landslide is downslope movement of soil or rock due to gravitational forces. Landslides can occur anywhere in the world such as on the land in example, in bedrock of soils, barren slopes and also underwater.

Landslides are associated with the natural factors in example, excessive precipitation and earthquakes. Landslides triggered by excessive precipitation may due to wide variety of climatic, geologic and topographic. The humid area causes by high intensity of rainfall lead to shallow slope failure.

While, landslides trigger by excessive earthquake may result in the movement of soil and it can relates with some geological aspect. In addition, human activities could cause landslides like cutting slope, road excavation, and agriculture and hillside development. The slopes at this area are very unstable especially during the rainfall and earthquakes event.

Landslide event is natural disasters which affect the human activities, economic and may threaten human life. In Malaysia, landslides event occur every year especially during the monsoon season where the amount of rainfall is highest. Most of the landslides event that occur in Malaysia located at the hilly slope where the slope is modified.

Landslides are unpredictable events because the locations and occurrences time of this event are hardly to estimate. Till now, there is a lot of research involve with landslide prediction. Besides that, the studies of geologic and hydraulic parameters of slope or soil at hilly area were studied to investigate how these parameters could contribute to the occurrences of landslides event.

Based on past research, a finite element or one dimensional approach model developed based on the failure mechanism of landslide and evaluation of slope safety factor (Muntohar, 2008). The research by Muntohar (2008) also proves that the landslide prediction model can be developed by combination of rainfall infiltration and infinite slope stability analysis using numerical simulations. This landslide prediction model is proven to give the expected result as this model were compared with SLOPE/W and SEEP/W. However, for analysis the circular slopes failure of landslide, the landslide prediction model proposed before could not be used as it is considering the failure of slopes along the plane. In order to predict the time of landslide and stability of slope of the circular slopes failure, the landslide prediction model used by Muntohar (2008) were modified. Instead of using infinite slope stability, another method was adopted here which is using slices method of finite slope stability.

The hydrological and geological of the soil could be one of the parameters which might contribute and affect the slope stability factor. The analysis between these parameters such as the rainfall intensity and soil permeability on the slope stability is applied on the rainfall infiltration and modified slope stability model which is considering the finite circular failure of slope using slices method.

1.2.Problem Statement

The main problem that motivates in conduct this research is to predict the landslides during the rainfall period as time dependent. In relation to this problem, there are two main issues that need to be resolved as follows:

i. The landslide events are unpredictable. The occurrences of landslides are estimated by having the landslide prediction model which incorporates the rainfall infiltration with slope stability analysis.

ii. The effect on rainfall intensity and soil permeability might influence the landslide or slope stability factor as time dependent. The analysis is done to know the significance of this parameter could contribute to the landslides.

1.3.Objectives of study

The objectives of this study are:

i. To develop landslide prediction model consists of Green Ampt infiltration model and circular slope failure of finite slope analysis by using slice methods.

ii. To determine the time dependent relationship of rainfall intensity and soil permeability on slope stability.

iii. To obtain minimum slope safety factor and occurrences time of landslides.

1.4.Scope of study

The scopes of the landslide prediction and time dependent slope factor study consists several scopes as states below:

i. Modification on the existing rainfall infiltration and slope stability model. A modified landslide model adopted here consists of one dimensional Green Ampt infiltration model and circular slope failure of finite slope analysis by using slice methods.
ii. The analysis effect of different amount rainfall intensity and soil permeability or soil on the slope stability factor as time dependent.

1.5.Relevancy and feasibility of the project

The rainfall amount as time dependent is one of the factors that led to landslides in Malaysia. It is related to the geotechnical aspect which is crucial to investigate as the landslides cases are increase especially during rainy period. This also related to civil engineers as geotechnical engineers need to aware about the landslides which could bring disaster and predict high susceptibility of landslide area. It is because landslides not only cause loss of the property but also the loss of people life.

CHAPTER 2
LITERATURE REVIEW

2.1.Type of Landslides

Downslope movement of soil led to landslide can be classified into a few categories. This can be categorized according to the material involved and the movement of the soil (Muntohar, 2008) and Lu and Godt (2013). According to Varnes (1978), the landslide classification can be classified based on slope movements as shown in Table 1.

Table 1: Classification of slope movements (after Varnes, 1978)

Type of Movement	Type of Materials		
		Predominantly Soil	
	Bedrock	Coarse-grained	Fine-grained
Falls	Rock fall	Debris fall	Earth Fall
Topples	Rock topple	Debris topple	Earth topple
Slides: Rotational Translational	Rock slide	Debris slide	Earth slide
Lateral Spreads	Rock spread	Debris spreads	Earth spreads
Flows	Rock flow	Debris flow	Earth flow
Complex	Combination more than one types of movement		

These types of movement are explained below (Das, 2010):

Falls: The large amount of soil mass or rock fragment that slide down a slope.

Topples: The soil mass or rock slide about an axis below center of gravity of mass exerted by adjacent units.

Slides: The downward movement of soil mass occurs on a surface of rupture.

Spreads: The sands and silts which are in liquefied state slide on a very gentle slope.

Flow: The downward movement of soil mass having the viscosity of liquid.

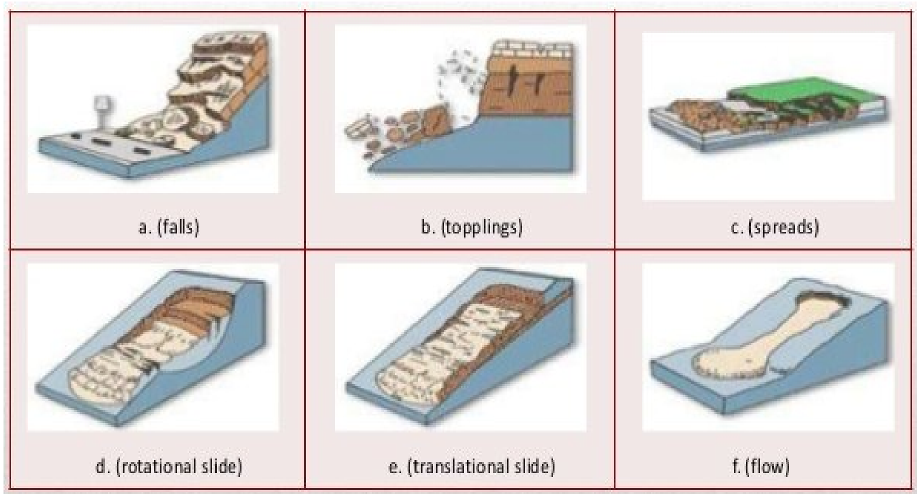


Figure 1: Types of landslides (Varnes, 1978)

2.2.Trigger Factor of Landslides

There are many factors that might triggers landslide such as earthquake shaking, volcanic eruption, heavy rainfall and typhoon (Lu and Godt, 2013).One of the major factor that triggers landslides in Malaysia is rainfall. The landslides trigger by rainfall in Malaysia usually happens during monsoonal seasons where there is increase in amount of rainfall (Matori et al, 2011). Rainfall-induced landslide usually occurs on the top slope in development area (Lee and Chi, 2011). This landslide is initiated on steep slopes during the periods of intense rainfall. Hence, the natural factor is one of the factors that induce the landslide event. The heavy rainfall, earthquake, typhoon and volcanic eruption have greater contribution in promote the movement of the soil especially at the unstable hilly slope area.

Research conducted by Lu and Godt (2013) find that the landslides due to rainfall can be simply explained by understanding these two conceptual models on the occurrence of slope failure above water table which are:

1. Slope failure when the surface is saturated.
2. Compressive pore water pressure

During rainfall events, the soils become saturated. The saturated soils have high pore water pressure. Increase in pore water pressure cause the soil becomes heavier and led to slopes failure. Increase in pore pressures during or shortly after the period of intensive rainfall will reduce the soil strength (Muntohar and Liao, 2010). This rainfall process may trigger the landslide by increasing the pore water pressure in soil.

The research conducted by Rahardjo (2002) states that pore water pressure is one of the factor that can trigger the landslides causes by rainfall. The infiltration of the rainwater will cause the variation in the pore water pressure as time dependent. The variation of the pore water pressure in the soil significantly affected the slope stability. It is because too much water content in the soil causes soils to become heavy and saturated at the surface and might led to shallow landslides. It can be conclude the rainfall could trigger the landslides. It can trigger the landslides as the water that infiltrates through the soil causes the soil to become saturated and increase in pore water pressure. This will cause the instability of the soil.

2.3.Hydrological Geotechnical Model

In analyzing the rainfall induced landslide, the fundamental theory of infiltration of rainfall and slope stability is applied. According to Muntohar (2008) many researchers have established their method in analyze rainfall induced landslide by using the hydrological and geotechnical model. Muntohar and Liao (2008) used this model to predict the rainfall induces landslides during typhoon event in Taiwan. Based on this research proves that the failure time of slope can be determined based on hydrological parameters such as rain intensity, duration, hydraulic properties of soil and the mechanical properties of slope.

There also a study conducted by Yuan et al (2013) have developed time dependent model to analyze the rainfall induced landslides for infinite slope. In his study the hydrological geotechnical model is developed which comprises calculation of:

i. Green and Ampt infiltration
ii. Pore water distribution
iii. Slope stability safety factor

According to the studies conducted by Yuan et al. (2013) analyzing of rainfall induced landslide is conduct by understand the changes on pore water pressure within the wetted zone and below the water table as time changes. This hydrological geotechnical model has sufficient information between elapsed time of rainfall and depth of wetting front which could affect the slope safety factor. According to Muntohar (2008), the field measurement of the hydrological parameters such as such suction head and water content were limited by the depth. Even though, the recent research conducted by Yuan et al (2013) and Muntohar and Liao (2008) could prove that this model could be used to relate the hydrological and stability parameter in rainfall induced landslides.

2.4.Green Ampt Infiltration

The hydrology parameters such as the flow of the fluid and moisture content in hill slope environments very spatially and temporally mainly due to time dependent environmental changes and the storage capacity of soils (Lu and Godt, 2013). Naturally, the soil is unsaturated and some of its void is occupied with air. When rainfall, the water will infiltrates into the soil, then the water will occupy the voids and filled it with water until the soil become saturated. According to Muntohar (2008) the soil surface above the capillary zone always is unsaturated except during rainfall, this part will become saturated conditions temporarily. The water flow can be analyzed by using concept of conservation of mass. The Darcy Law concept states the rate of water loss or gain is equal to the net flux in and out of the element. Thus, by understanding this concept the infiltration rate could be calculated.

The Green Ampt infiltration model is developing to determine the one dimensional flow of water into the soil. Figure 1 shows the idealization of Green Ampt model. Based on the idealization of Green and Ampt infiltration, the Green Ampt profile have sharp boundary which divide the soil of moisture content below initial moisture from saturated soil with moisture content (Muntohar, 2008).

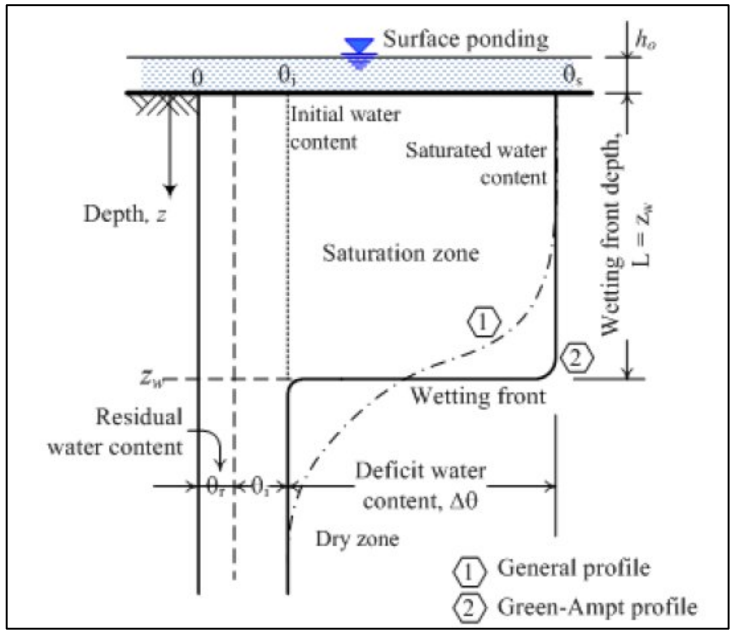


Figure 2: Idealization of Green Ampt model (Muntohar,2008)

Figure 2 shows the infiltration process of a soil unit of cross sectional area. The infiltration processes during rainfall period which cause the wetting front depth to increase as time increase. The increase of wetting front depth exceeds the water table causes slope failure. According to Yuan et al (2013), the infiltration processes are dividing into two distinct phase which consist of:

Phase I: Vertical infiltration during the rainfall period

Phase II: Plug flow driven by the saturated hydraulic conductivity of the soil until formation of the new ground water table.

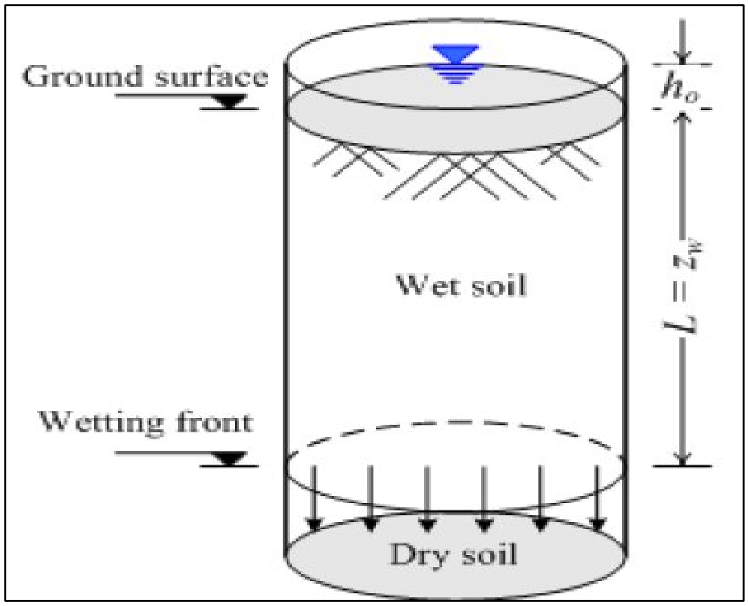


Figure 3: Infiltration of soil unit cross sectional area.
(Muntohar, 2008)

The rainfall will flows in vertical downwards of the soil column and the cumulative depth of water infiltrate could be determined by

$$F(t) = L\,(\eta - \theta_i) = z_w.\Delta\theta \quad (2.40)$$

From equation 2.30, wetting front depth also can be obtained

$$z_w = F/\Delta\theta \quad (2.41)$$

The flux flow can be determined from the Darcy's Law which expressed as

$$q = -k\,\frac{\delta h}{\delta z} \quad (2.42)$$

Assuming the depth of h_0 is negligible. According to Muntohar (2008), this assumption is appropriate it is assumed that ponded water will become surfaces runoff. So assuming $h_0 = 0$.The infiltration rate in equation 2.34 can be determined by substitute equation 2.31 into 2.33

$$f = k(\frac{\psi + z_w}{z_w}) \qquad (2.43)$$

$$f = k(\frac{\Delta\theta.\psi + F}{F}) \qquad (2.44)$$

Since f=dF/dt, by integrating both sides the infiltration rate for horizontal surface could be determined by equation 2.45 while cumulative infiltration can be calculated in equation 2.46

$$f(t) = k(1 + \frac{\Delta\theta\psi}{F(t)}) \qquad (2.45)$$

$$F(t) - \Delta\theta\psi \ln\left(1 + \frac{F(t)}{\Delta\theta\psi}\right) = k.t \qquad (2.46)$$

According Chen and Young (2006), the infiltration rate of the sloping surface could be determined as follows:

$$f(t) = k(\cos\beta + \frac{\Delta\theta\psi}{F(t)}) \qquad (2.47)$$

$$F(t) - \frac{\psi\Delta\theta}{cos\beta} \ln\left(1 + \frac{F(t)cos\beta}{\Delta\theta\psi}\right) = k\cos\beta.t \qquad (2.48)$$

The study conduct by Muntohar and Liao (2008), Yuan et al (2013) have proved using Green Ampt infiltration in their model to predict landslides event.

There several assumptions used for Green Ampt infiltration model. According to Lu and Godt (2013) and Muntohar and Liao (2008) states Green and Ampt provide several assumptions of Green Ampt infiltration model which are:

i. The soil suction head beyond the wetting front is constant in both space and time
ii. The water content and the corresponding hydraulic conductivity of the soil behind the wetting front are also constant in both space and time.

There are three cases of rainfall infiltration will occur during rainfall event (Muntohar and Liao, 2008). The Figure 3, 4 and 5 shows three cases of rainfall infiltration.

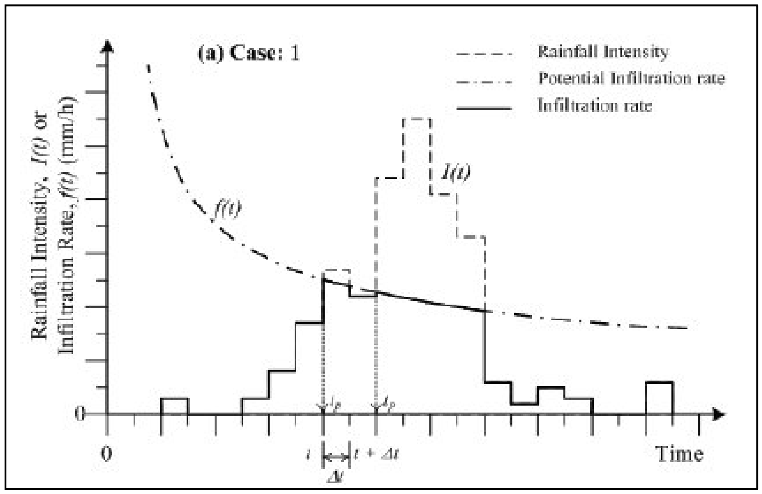


Figure 4: Infiltration Case I (after Chow et al, 1988; Muntohar, 2008)

Case I: It occurs when the infiltration rate is less than the rainfall intensity. The soil becomes saturated.

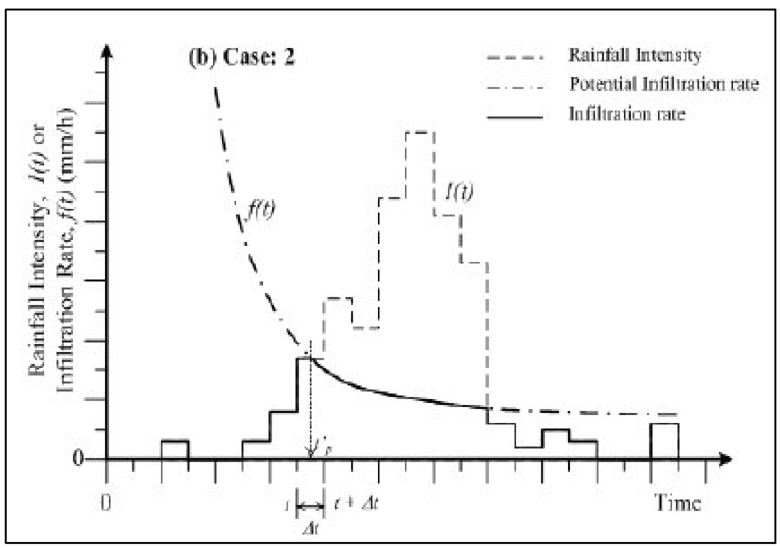


Figure 5: Infiltration Case II (after Chow et al, 1988; Muntohar, 2008)

Case II: It occurs when the soil is unsaturated at the beginning but becomes saturated by the time. Initially, the infiltration rate is more than rainfall intensity but as time increase the soil have become saturated where the infiltration rate less than the rainfall intensity. Thus, the ponding will happen for this case. The ponding time and cumulative rainfall at this time need to be determined

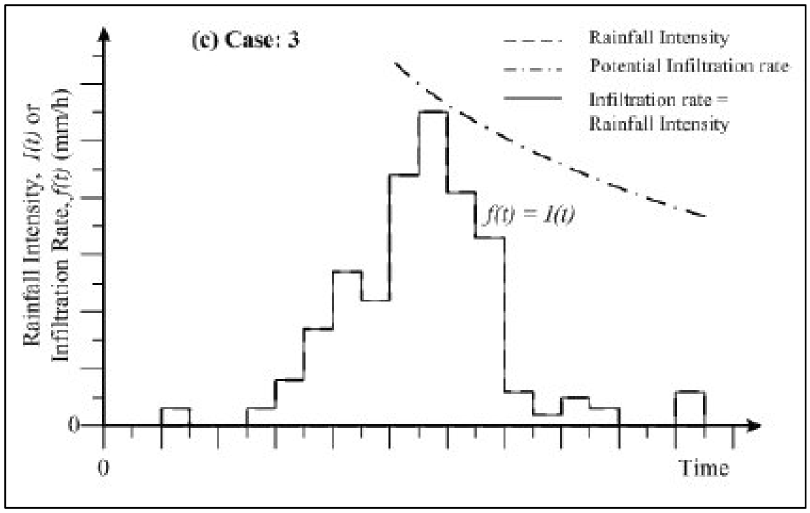


Figure 6: Infiltration Case III (after Chow et al, 1988; Muntohar, 2008)

Case III: It occurs when the soil is unsaturated. The infiltration rate is more than the rainfall intensity. This condition might happen due to higher of soil storage capacity.

The flowchart in Figure 6 will shows determination of infiltration under unsteady rainfall intensity using Green Ampt model (after Chow et al, 1988)

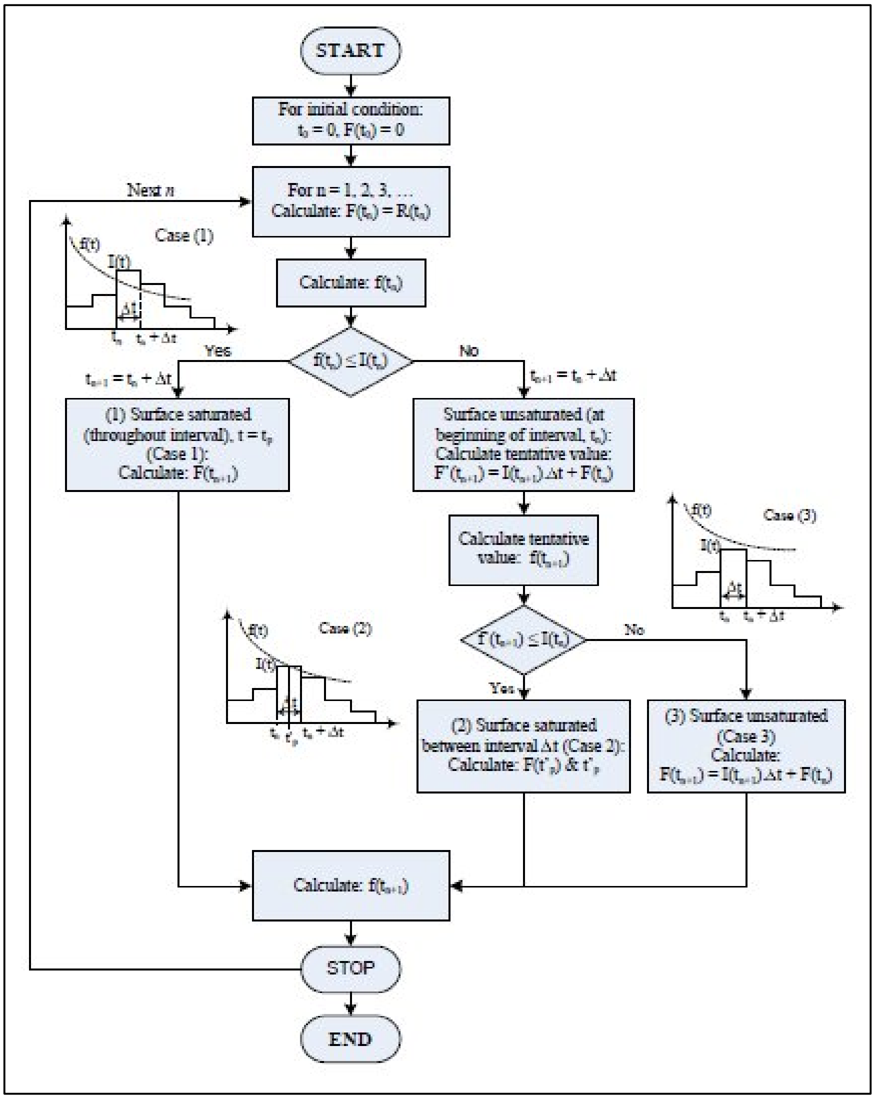


Figure 7: Infiltration under unsteady rainfall using Green Ampt model (after Chow et al, 1988)

2.5. Finite Slope Stability Model – Slice Methods

The stability of the hill slopes can be assessed quantitatively by determining the ratio of shear strength of the soil τ_f to shear stress developed for mechanical equilibrium, τ_d (Das,2010).The slope stability is calculated using Mohr-Coulomb failure criterion. Besides, the slope stability factor also can be expressed in term of shear strength σ', cohesion *c'* and friction angle, ϕ' which stated as below $c_d{}'$ and $\phi_d{}'$ is the cohesion and friction angle of friction that develop along potential failure surface.

$$FS = \frac{shear\ strength\ of\ soil \tau_f}{shear\ stess\ of\ soil, \tau_d} = \frac{c' + \sigma' tan\phi'}{c_d{}' + \sigma' tan\phi_d{}'} \quad (2.50)$$

There are some others methods develop which can be used in the analysis of slope stability for slice methods such as Ordinary Slice method, Simplified Bishop method, Janbu, Fellinius and finite element method. The safety factor for slices method is done by summing each slice resisting forces to summing each slices of driving forces. Overall the slope safety factor of slices method could be determined as equation below:

$$FS = \frac{\Sigma\ Resisting\ forces}{\Sigma\ Driving\ forces} = \frac{\Sigma N\ tan\phi + \Sigma cl}{\Sigma T} \quad (2.51)$$

where

N= Normal forces

l = Length of individual slices

T = Driving forces

According to Das (2010), the slope stability can be calculated using limit equilibrium analysis which can be calculated as follows:

$$F_s = \frac{\sum_{n=1}^{n=p}(c'\Delta L_n + (W_n \cos\sigma_n - u_n \Delta L_n) tan\emptyset'}{\sum_{n=1}^{n=p} W_n \sin\sigma_n} \qquad (2.52)$$

Pore water pressure, u at each slice is determined as

$$u_\mathrm{n} = h_n \gamma_w \qquad (2.53)$$

$$\mathrm{r}_{\mathrm{u(n)}} = \frac{h_n \gamma_w}{\gamma z_n}$$

where

$\mathrm{r}_{\mathrm{u(n)}}$ is a non-dimensional unit, where; $\mathrm{z_n = z_w}$

u = Pore water pressure

ΔL_n = Length of unit soil slice

W_n = Weight of unit soil slice

σ_n = Normal stress of unit soil slice

c' = Effective cohesion soil

$\emptyset'$ = Effective friction angle

γ_w = Unit weight of water

h_n = Height of unit soil slices from ground surface to the failure surface.

According to Lu and Godt (2013), the finite slope stability is suitable to use for modeling the steeply inclined slopes as compared to less steep slopes. A method of slice is one example of the finite slope stability model which is use for calculations factor of safety. This slices method are consider the failure surface geometry of a slope as circular surface. Using finite method, the soil above the surface sliding is divided into a number of vertical parallel slices (Das, 2010). Besides that, the location of the potential slip surface having minimum slope safety factor also can be determined by this slices method. The analysis of slice methods is based on the limit of equilibrium for each slice. Figure 8 shows the forces that acting on a unit of a soil slice.

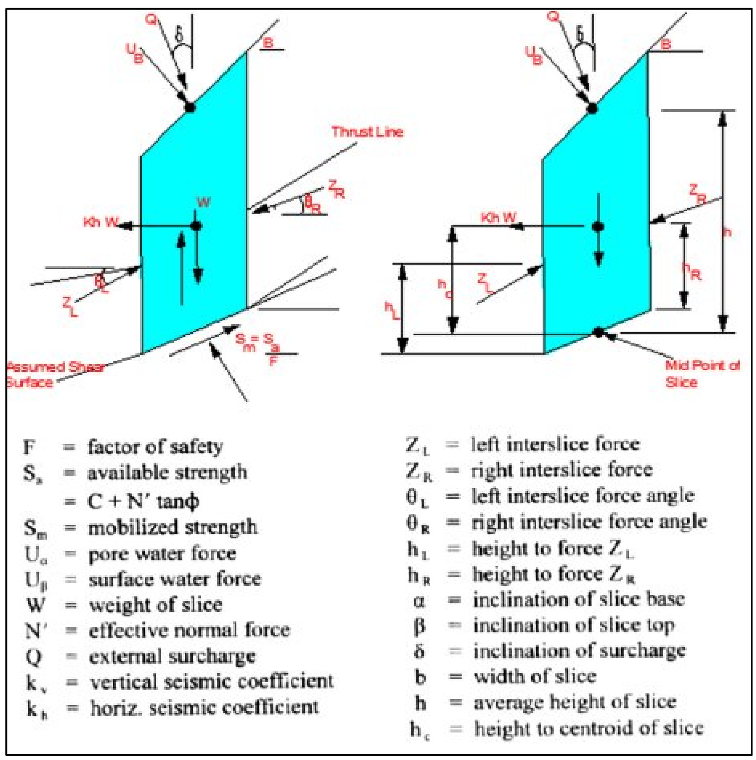


Figure 8: Forces acting on a slice unit of soil (Rabie, 2014)

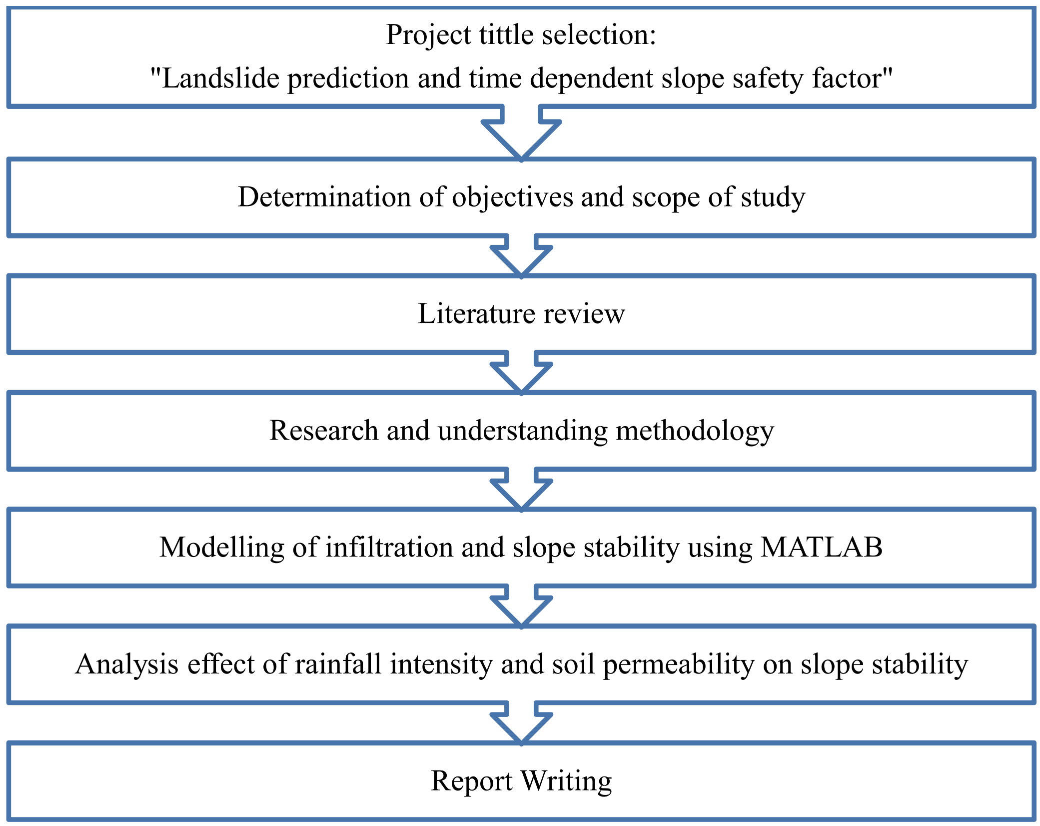
Since there is a rainfall event, rainwater will infiltrate into the layers of soils. According to Rabie (2014) the rainfall event will decrease the cohesion angle, friction angle and matrix suction and increase pore water pressure on the slip surface. While Muntohar (2013) states the increase of pore water pressure along the time have effect on slope safety factor. Therefore, the slopes may become saturated and the cause the rise of water table dependent with the time led to slope failure.

CHAPTER 3

METHODOLOGY

3.1 Research Methodology and Project Activities

The chart below shows sequential activity done during this study:



3.1.1 Assumptions on rainfall infiltration and slope stability model

The Green Ampt infiltration and finite slope stability using slice methods theory are explained in Chapter 2. Based on this understanding, a model of time dependent rainwater infiltration induced circular slope failure is developed. This model aims to relate the relationship of amount rainfall infiltrations under certain period of time which affect the slope stability for circular failure slope.

Thus, several assumptions were made in order to develop this landslide prediction model. An illustration of infiltration model for circular slope failure under rainfall is shown in Figure 9. Based on the figure, there is a layer of the front of infiltration or wetting front depth.

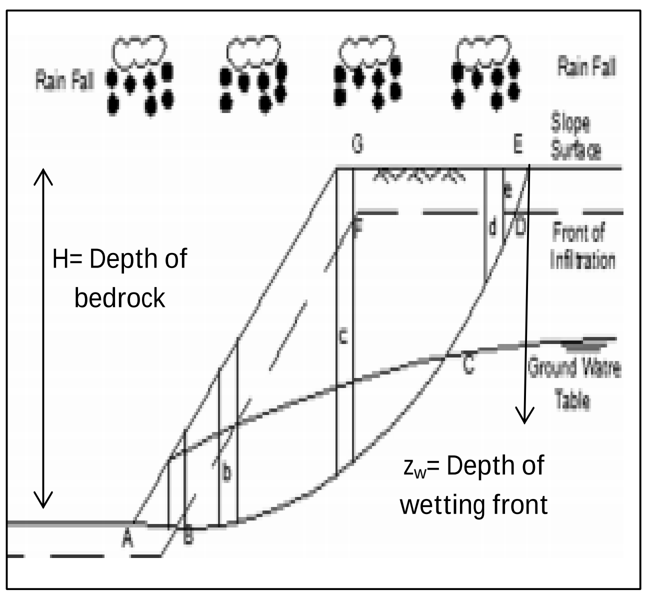


Figure 9: Illustration of circular slope failure under rainfall (Rabie, 2014)

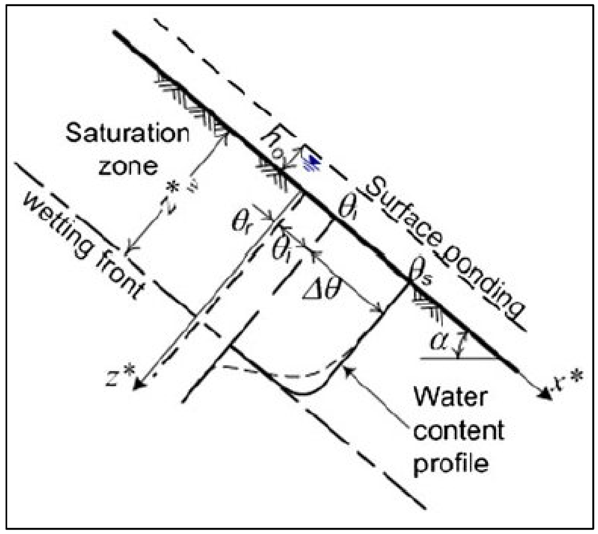


Figure 10: Rainfall infiltration model of a unit of soil slices

(Chen and Young, 2006)

Considering of a unit slice of soil, the determination of the wetting front depth could be illustrated as on Figure 10. There are several assumptions were made in using one dimensional Green Ampt infiltration for sloping ground surface which consists of:

i. The soil suction head beyond the wetting front is constant in both space and time
ii. The soil layer above wetting front is saturated
iii. Assume h_0=0. The ponding surface will become runoff.
iv. For deficit of volumetric water content θ, the value is same before and after the wetting.
v. Coefficient of hydraulic conductivity is equal to the coefficient of saturated hydraulic conductivity ($k=k_s$) and also constant in both space and time.
vi. The direction of seepage is parallel to the slope surface.

The slice unit of a soil for finite slope stability is illustrated in Figure 11 and Figure 12

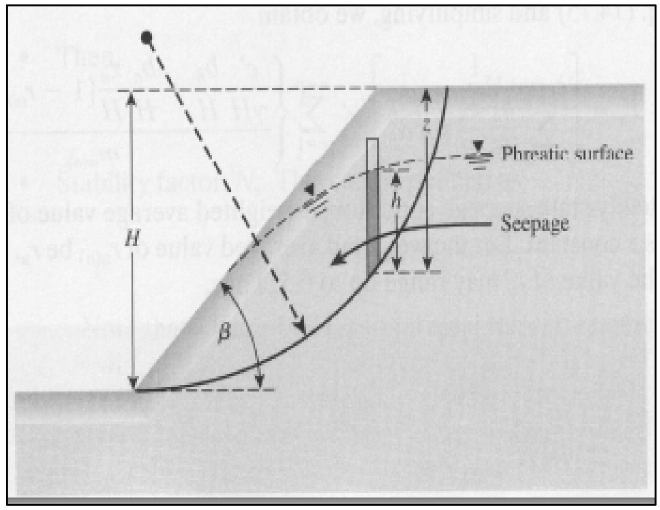


Figure 11: The finite slope stability model (Das, 2010)

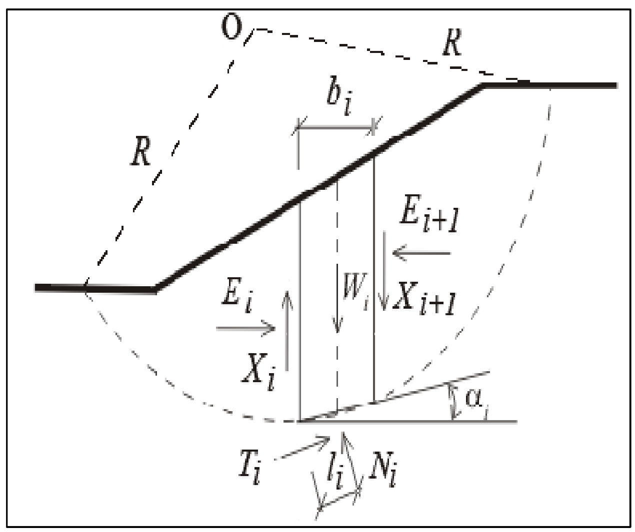


Figure 12: Slices method of finite slope stability model (Das, 2010)

Based on the Figure 11 and 12, the slope stability factor of finite slope stability can be calculated by considering a few parameters such as the pore water pressure, the forces involved in a unit slice of soil. From the slope stability model, the minimum factor safety cause landslides were determined.

In order to analyze the circular slope failure of finite slopes using slice methods, there are also a few assumptions were made:

i. The critical circular failure plane is at the depth of wetting front
ii. Inter slice normal forces is included (illustrated on Figure 12)
iii. Inter slice shear forces between the slices is neglected.

3.1.2 Rainfall infiltration and slope stability parameters

Green Ampt infiltration and slope stability parameters are not obtained through field and laboratory test for this study due to economic and time constraint. In this study, the synthetic rainfall of the rainfall intensity and accumulated rainfall is created for both high intensity and low intensity. Table below describes the synthetic rainfall data were used in this study:

Table 2: Synthetic rainfall intensity data

	Low Intensity of Rain	High Intensity of Rain
Maximum rainfall intensity (mm/h)	7.2	72
Total accumulated rainfall (mm)	100.8	1000.8

Besides that, the synthetic rainfall intensity of interval 1hour is developed for both low and high intensity of rain. The duration of the period were taken for 48 hours duration. Thus, the data on Table 2 is basically referred for the 48 hours duration of rainfall.

Several assumptions have been obtained by refer to the Green Ampt parameter table. Figure 13 shows the table of Green Ampt parameters and Table 2 show the slope stability parameter used in this study. In order to investigate the effect on the soil permeability, three different soils type is used which are:

i. Sand
ii. Loam
iii. Clay

Table 1 Parameters needed in Green-Ampt infiltration model (adapted from Chow et al. 1988)

Soil type	Range of η	Range of θ_e	Range of ψ_f (mm)	k (mm/h)	ψ_f (mm)	$k_s = 2k^a$ (mm/h)
Sand	0.374 ~ 0.5	0.354 ~ 0.48	9.7 ~ 253.6	117.8	49.5	235.6
Loamy sand	0.363 ~ 0.506	0.329 ~ 0.473	13.5 ~ 279.4	29.9	61.3	59.8
Sandy loam	0.351 ~ 0.555	0.283 ~ 0.541	26.7 ~ 454.7	10.9	110.1	21.8
Loam	0.375 ~ 0.551	0.334 ~ 0.534	13.3 ~ 593.8	3.4	88.9	6.8
Silt loam	0.42 ~ 0.582	0.394 ~ 0.578	29.2 ~ 953.9	6.5	466.8	13
Sandy clay loam	0.332 ~ 0.464	0.235 ~ 0.425	44.2 ~ 1,080	1.5	218.5	3
Clay loam	0.409 ~ 0.519	0.279 ~ 0.501	47.9 ~ 911	1	208.8	2
Silty clay loam	0.418 ~ 0.524	0.347 ~ 0.517	56.7 ~ 1,315	1	273	2
Sandy clay	0.37 ~ 0.49	0.207 ~ 0.435	40.8 ~ 1,402	0.6	239	1.2
Silty clay	0.425 ~ 0.533	0.334 ~ 0.512	61.3 ~ 1,394	0.5	292.2	1
Clay	0.427 ~ 0.523	0.269 ~ 0.501	63.9 ~ 1,565	0.3	316.3	0.6

Figure 13: Green Ampt parameters (Muntohar, 2008)

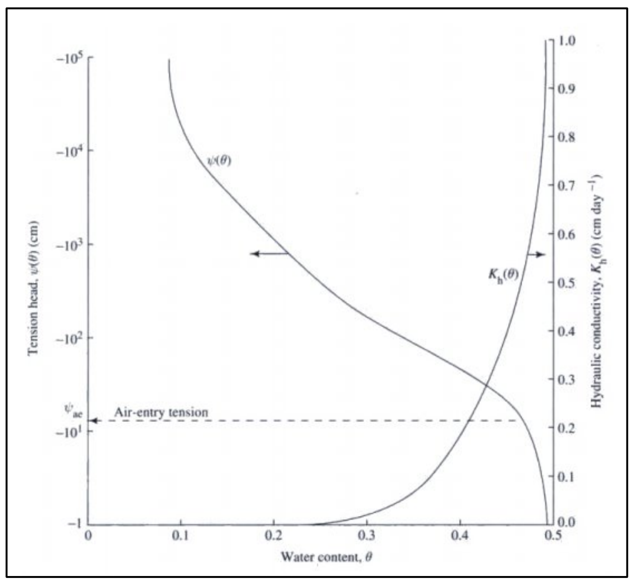


Figure 14: Moisture Characteristic Curve (Dingman, S.L., 2002)

From the moisture characteristics curve illustrated on Figure 14, the moisture content can be obtained and the deficit moisture content could be calculated as follow:

$$\Delta\theta = \eta - \theta$$

where

η = soil porosity

θ = moisture content

Based on the table illustrated on Figure 13, the range of the soil porosity, the effective porosity, suction head at wetting front and coefficient of saturated hydraulic conductivity could be assumed and used for this study.

In this study, the geometric of the soil such as the slope angle is kept constant. Table 3 shows the slope stability parameters values which is used in this study.

Table 3: Geotechnical Parameters

Parameters	Value
Unit Weight Soil, γ (kN m-3)	18
Effective Soil Cohesion, c' (Kpa)	5
Effective Friction Angle, φ'	0.5934
Unit Weight Water, γ_w (kN m-3)	9.81
Topography Slope Angle, B	46
Saturated unit weight of soil, γ_{sat} (kN m-3)	23.8

The soil properties for both high and low rainfall intensity which used in this study can be summarized and presented in Table 4.

Table 4: Summary on hydrological parameters of soils

Parameters/Soil Type	Sand (K=117.8 mm/h)	Loam (K=3.4 mm/h)	Clay (K=0.3 mm/h)
Suction head at wetting front	49.5	88.9	316.3
Porosity	0.5	0.551	0.475
Moisture Content	0.49	0.48	0.37
Deficit volumetric water content	0.01	0.071	0.105
Saturated Hydraulic Conductivity	235.6	6.8	0.6

3.1.3 Rainfall infiltration and slope stability calculation

The wetting front depth can be obtained from Green Ampt infiltration mode as shown in Figure 12. Since the infiltration occurs on the sloping surface, the wetting front depth perpendicular to circular slope failure at t is can be obtained using equation below:

$$Z_w(t) = \frac{F(t)}{\Delta\theta \cos\alpha} \qquad (3.1.3.0)$$

The wetting front depth is used in the slope stability of simplified Bishop's method. This wetting depth is a function of time will give the slope stability with elapsed time. The changes of wetting depth as time changes will affect the slope stability of circular failure.

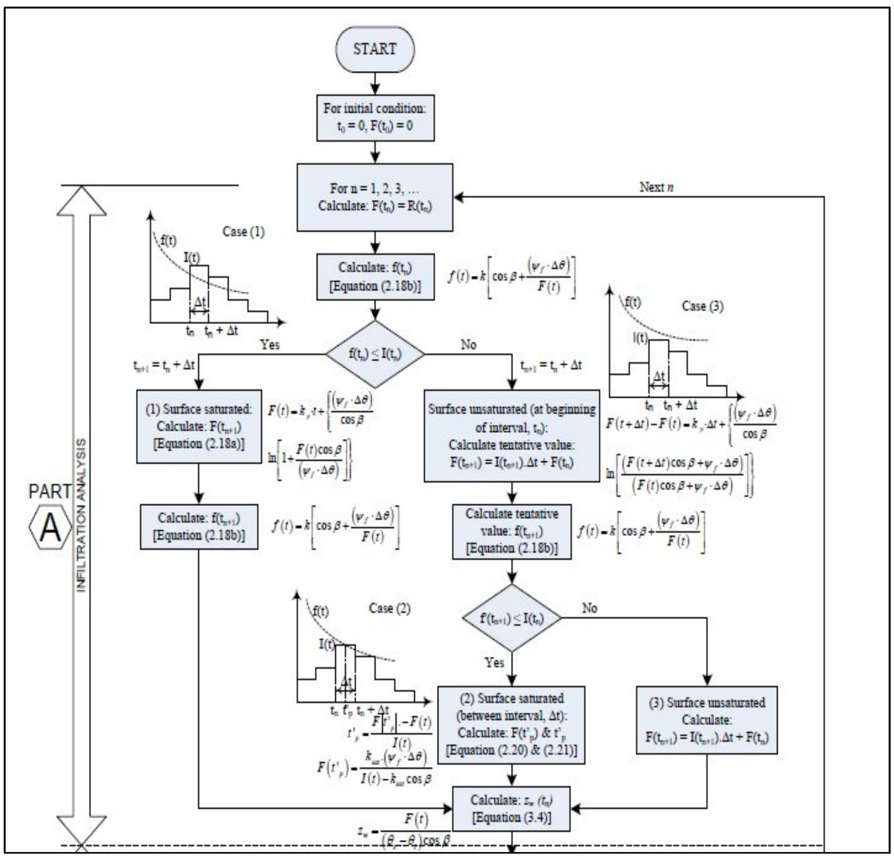


Figure 15: Infiltration framework (Muntohar, 2013)

From the modified Green Ampt infiltration, the infiltration rate and cumulative infiltration rate for sloping ground surface can be determined. According Chen and Young (2006), the infiltration rate of the sloping surface could be determined as follows:

$$f(t) = k(\cos\beta + \frac{\Delta\theta\psi}{F(t)}) \qquad (3.1.3.1)$$

$$F(t) - \frac{\psi\Delta\theta}{\cos\beta} ln\left(1 + \frac{F(t)\cos\beta}{\Delta\theta\psi}\right) = k\cos\beta . t \qquad (3.1.3.2)$$

For Case I, the cumulative infiltration can be determined as in equation 3.1.3.2. While for case III, where the soil is unsaturated, the cumulative infiltration can be determined as follows

$$F(t + \Delta t) - F(t) = k\cos\beta . t + \left\{\frac{(\psi\Delta\theta)}{\cos\beta} ln\left(\frac{F(t+\Delta t)\cos\beta + \Delta\theta\psi}{(F(t)\cos\beta + \Delta\theta\psi)}\right)\right\} \qquad (3.1.3.3)$$

For Case II, the ponding time could be calculated as follows

$$F(t'_p) = \frac{k_{sat.}\psi\Delta\theta}{I(t) - k_{sat}\cos\beta} \qquad (3.1.3.4)$$

$$t'_p = \frac{F(t'_p) - F(t)}{I(t)} \qquad (3.1.3.5)$$

In finite slope stability model, several equations are obtained using limit equilibrium analysis. In this method, the vertical equilibrium of a single slice is shown in equation 3.1.3.1

$$W = N\cos\beta + T\sin\beta + \Delta X \qquad (3.1.3.6)$$

The driving force T is derived using Mohr-Coulomb strength.

$$T = \frac{c\prime L}{F} + (N - uL)\frac{\tan\emptyset\prime}{F} \qquad (3.1.3.7)$$

Where F = Slope Safety Factor

uL = Water uplift force on slice base

N = Normal force

This model is taking into account the horizontal equilibrium for each slice. Horizontal forces differences of inter slice ΔE is zero. Thus the equilibrium of total slice can be calculated as

$$\sum N \sin\beta - \sum T cos\,\beta = 0 \qquad (3.1.3.8)$$

The inter slice force are cancel out and the moment equilibrium of total slice can be calculated as

$$\sum W r_w - \sum N r_N - \sum T r_T = 0 \qquad (3.1.3.9)$$

where r is the radii of rotation and W is the weight of individual slices. Figure 16 and 17 illustrated a slice of a soil unit.

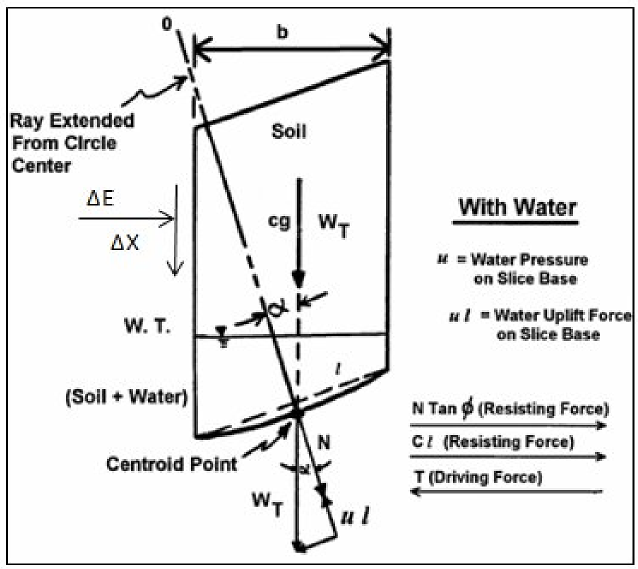


Figure 16: Slice of a soil unit (Das, 2010)

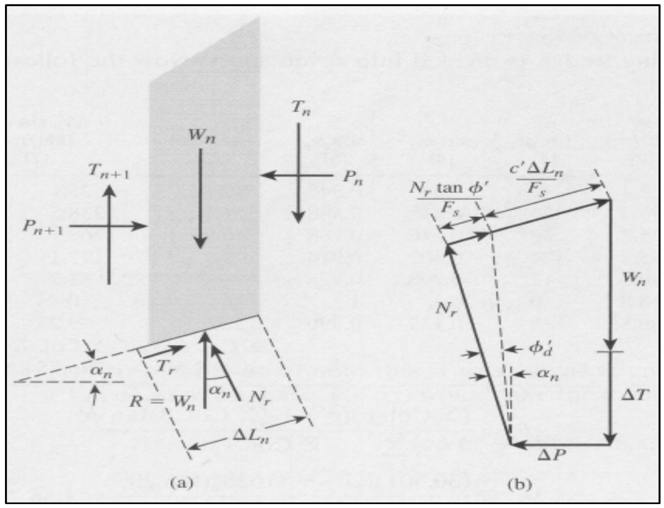


Figure 17: Inter slices forces and equilibrium (Das, 2010)

The slope stability factor could be calculated as follow.

$$F_s = \frac{\sum_{n=1}^{n=p}(c'\Delta L_n + (W_n \cos\sigma_n - u_n \Delta L_n)\tan\emptyset\prime}{\sum_{n=1}^{n=p} W_n \sin\sigma_n} \qquad (3.1.3.10)$$

Pore water pressure at each slice is determined as

$$u_n = h_n \gamma_w \qquad (3.1.3.11)$$

$$r_{u(n)} = \frac{h_n \gamma_w}{\gamma z_n}$$

where

$r_{u(n)}$ is a non-dimensional unit, where; $z_n = z_w$

z_n = height from ground surface to failure plane

b_n = width of each slice

z_w = wetting front depth

H = depth of bedrock

The landslides model development which consists of Green Ampt infiltration model and finite slope stability of circular failure using slice methods could be summarizes in figure 18. By having this model, the analysis effect of rainfall intensity and soil permeability on slope stability as time dependent is done.

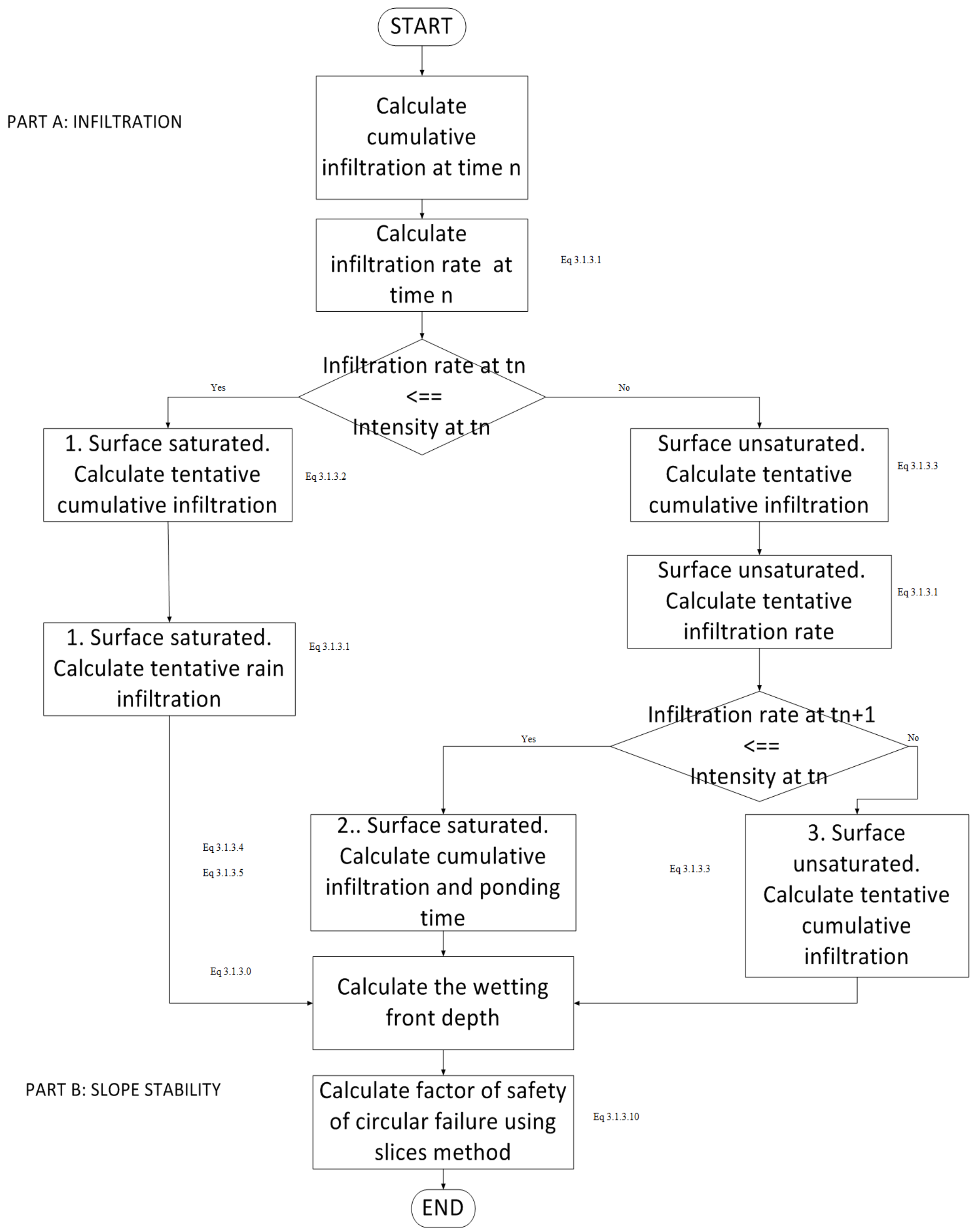


Figure 18: Flowchart of landslide model

3.2 Key Milestone

The Final Year Project (FYP) I and II planning schedules are plan as follow:

	Week	Task Planning
FYP I	1 - 2	Selection of topic
	3 - 5	Literature Review on landslide, Green Ampt infiltration, finite slope stability model
	6	Submission of extended proposal
	7-9	Proposal Defense
	10-12	Data Collection
	13	Submission of Interim Draft Report
	14	Submission of Interim Report
FYP II	1-6	Works on MatLab Infiltration and Slope Modelling
	7	Submission of progress report
	8-13	Continuation of work and final discussion
	10	Pre-SEDEX
	11	Submission of draft final report
	12	Submission of dissertation(soft bound) and technical paper
	13	Viva
	14	Submission of dissertation(Hard Bound)

3.3 Key Milestone

		FYP 1														FYP 2													
No	Details/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Project's Introduction																												
1	Select Project Tittle																												
2	Identify problem statement, objective and scope of study																												
	Literature Review																												
3	-Landslide trigger by rainfall -Green Ampt infiltration - Finite slope stability - Hydrological and geotechnical landslide prediction model																												
	Landslide Model Development																												
4	Develop Green Ampt infiltration programming in EXCEL & MATLAB																												
5	Modify existing slope programming in MATLAB																												
6	Run and test the program using three different soil permeability and rainfall intensity																												
	Analysis and Discussion																												
7	Analysis effect of soil permeability and rainfall intensity on slope stability model as time dependent																												

	Presentation and Report Submission																												
8	Submission of Extended Proposal					■																							
9	Proposal Defense										■																		
10	Submission of Interim Draft Report													■															
11	Submission of Interim Report														■														
12	Submission progress report																					■							
13	Pre-SEDEX																								■				
14	Submission of Draft Final Report																									■			
15	Submission of Dissertation(Soft Bound)																										■		
16	Submission of Technical Paper																										■		
17	Viva																											■	
18	Submission of Dissertation(Hard Bound)																												■

■ Progress work

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Rainfall Intensity and Accumulated Rainfall

The synthetic rainfall intensity and accumulated rainfall data for high and low intensity of rain was developed. The synthetic rainfall hyetograph is created also based on cumulative rainfall amount each day as illustrated in figure below. For low rainfall intensity, the cumulative amount of rainfall for 48 hours duration is 100.8 mm. The highest rainfall intensity, 7.2 mm/hr is occurring at 8 hours of elapsed time. While for high rainfall intensity, the cumulative amount of rainfall for 48 hours duration is 1000.8 mm. The highest rainfall intensity, 72 mm/hr is occurring at 8 hours of elapsed time. Thus, from this data, the pattern of the infiltration rate and wetting front depth as time dependent could be determined by referring to this graph. For both low and rainfall intensity, the maximum intensity occur at 9 hour after the rain starts.

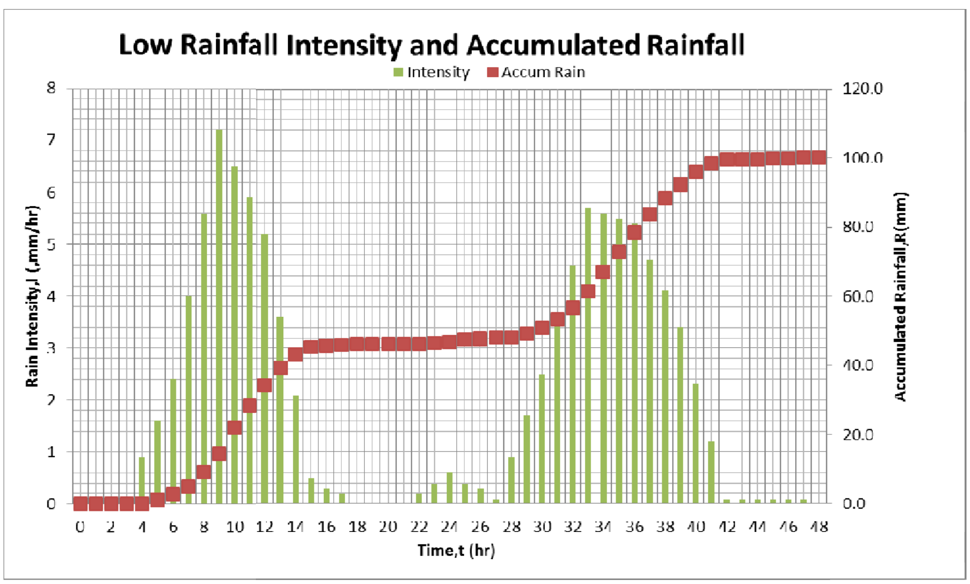


Figure 19: Low rainfall intensity and accumulated rainfall

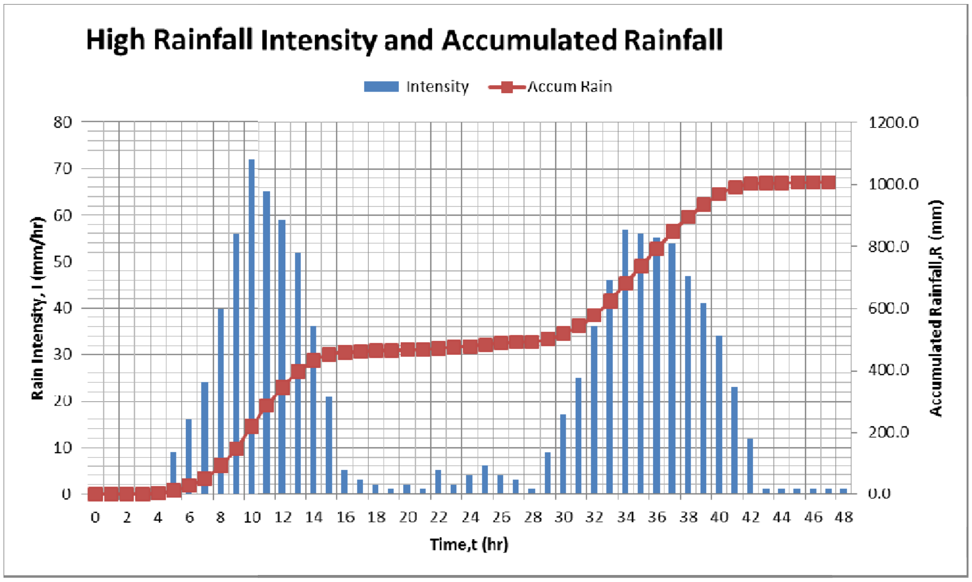


Figure 20: High rainfall intensity and accumulated rainfall

4.2 The effect of low rainfall intensity on slope safety factor

Overall, the minimum safety factors of different soils and occurrences time of landslide could be determined using the landslide prediction model. The effects of low rainfall under different soil permeability or soil type are illustrated in Figure 21, 22 and 23 which consist of:

i. Sand (K =117.8 mm/h)
ii. Loam (K = 3.4 mm/h)
iii. Clay (K = 0.3 mm/h)

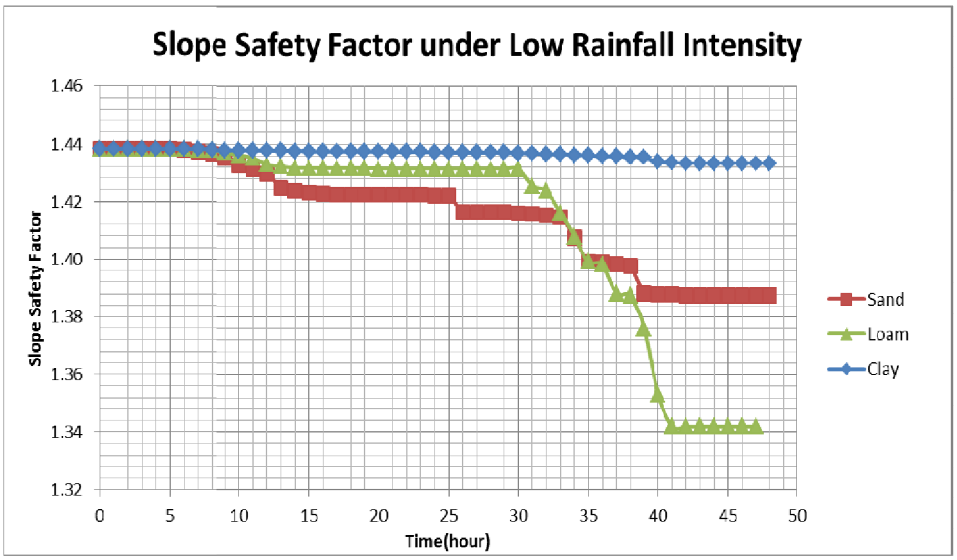


Figure 21: Slope Safety Graph for Sand under Low Rainfall Intensity

Based on Figure 21, the slope stability factors are decreasing as time dependent. For sand, the slope safety factor starts decrease at 9 hours of elapsed time where the slope safety factor is 1.438 where the amount of rainfall at that time is 9.1 mm and rainfall intensity 5.6 mm/hr. For loam slope safety factor starts decrease at 11 hours of elapsed time where the slope safety factor is 1.438 where the amount of rainfall at that time is 21.9 mm and rainfall intensity 6.5 mm/hr. For clay, the minimum slope safety factor is 1.433 at the end of rainfall period where the amount of rainfall at that time is 100.8 mm. The slope safety factor decrease slightly as time dependent. This indicates that this slope is very stable as compare to sand

and loam during the rainfall period. Overall, under low rainfall intensity, the slopes were stable for each of soils type.

4.3 The effect of high rainfall intensity on slope safety factor

For the high rainfall intensity, the pattern on slope stability factor such as the occurrences times of landslide is slightly different than low rainfall intensity. Figure 22 will illustrate the effect of high rainfall intensity under different type of permeability or soil type.

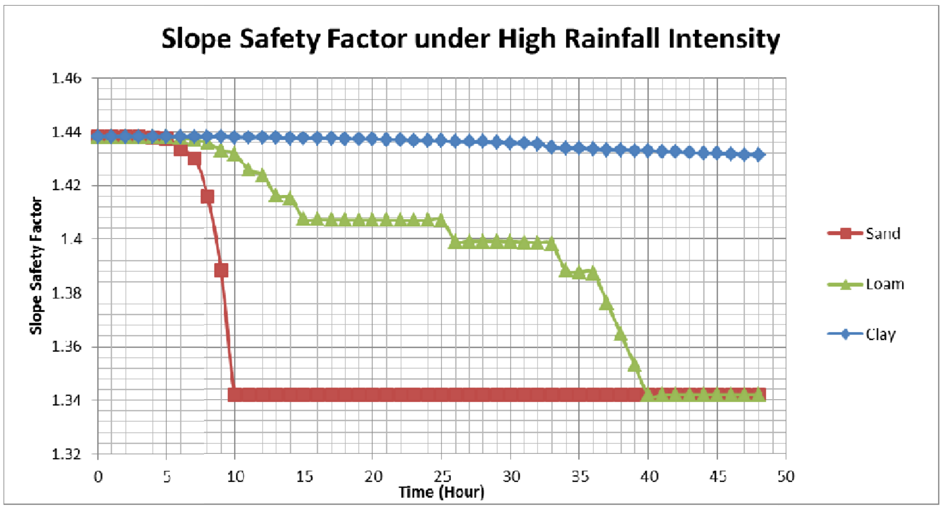


Figure 22: Slope Safety Graph for Sand under High Rainfall Intensity

Based on Figure 22, the slope stability factors are decreasing as time dependent. For sand, the slope starts decrease significantly at 6 hours after elapsed time where the amount of rainfall at that time is 11 mm and rainfall intensity is 16 mm/hr. After 10 hours of elapsed times, the slope stability becomes constant because the sand already reaches its saturations. Even though, the slope have reaches its saturation, the slope safety factor are greater than 1 (FS >1) which is 1.342, means the slope are still stable. The water infiltrates into the sands faster causes the slopes are decreasing significantly.

While for loam, the slope starts to decrease at 8 hours after elapsed time where the amount of rainfall at that time is 51 mm and rainfall intensity is 40 mm/hr where FS= 1.438 . The water infiltrates into the loams slow as compare to the sand as the time for slope safety factor to decrease for loam slow than sand. All slope safety factors for clay under high rainfall intensity are small changes in decrease as time dependent. The slope safety factor of clay throughout the rainfall period is 1.431.This indicates that the slopes are stable and not significantly contribute by rainfall infiltration.

4.4 The comparison of slope safety factor

The comparison of the slope safety factor is based on the rainfall intensity and soil permeability or soil type. In this study, the effect of the rainfall intensity and soil permeability or soil type on slope safety factor as time dependent were investigated. The result of the comparison of slope safety factor as time dependent for two different amount of rainfall intensity is illustrated in Figure 23, 24 and 25. Each comparison is done based on three types of soils permeability or soils type.

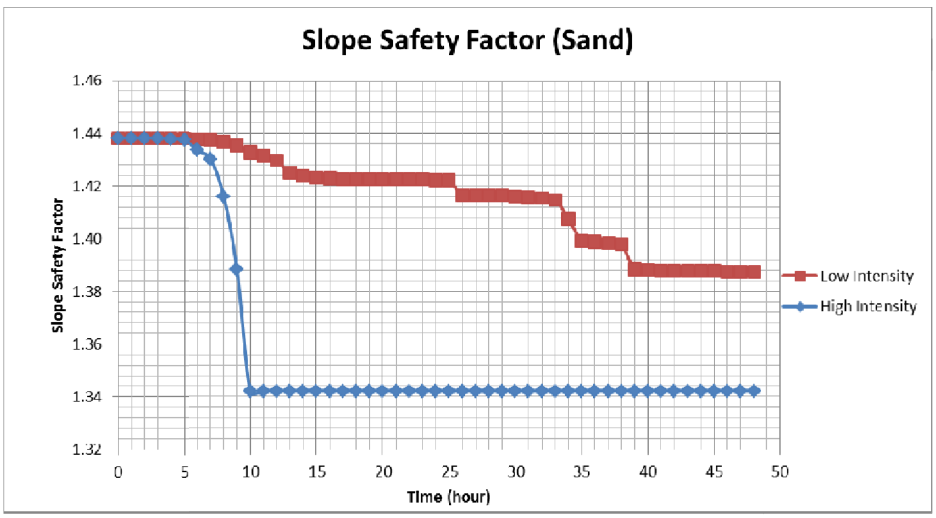


Figure 23: Comparison slope safety factor of sand under different rainfall intensity

Based on Figure 23, for the sands slopes under low rainfall intensity have a greater slope safety factor value as the sands slope under high rainfall intensity. Under high rainfall intensity, this slope is greatly decreased from 1.438 to 1.342 at the maximum rainfall intensity. While, for low rainfall intensity the slope stability factor slightly decrease from 1.438 to 1.387 with time as compared during high rain intensity. This can be said that the sand infiltrates faster as there is a change as time increase.

As the rainfall intensity is too high, the rainfall infiltrates faster in the sand causes the increase in wetting front depth as time dependent. The increase in wetting front depth over the time makes the soils becomes saturated. As the soil becomes saturated, there will be no more water will infiltrates cause the slope stability to remains constant.

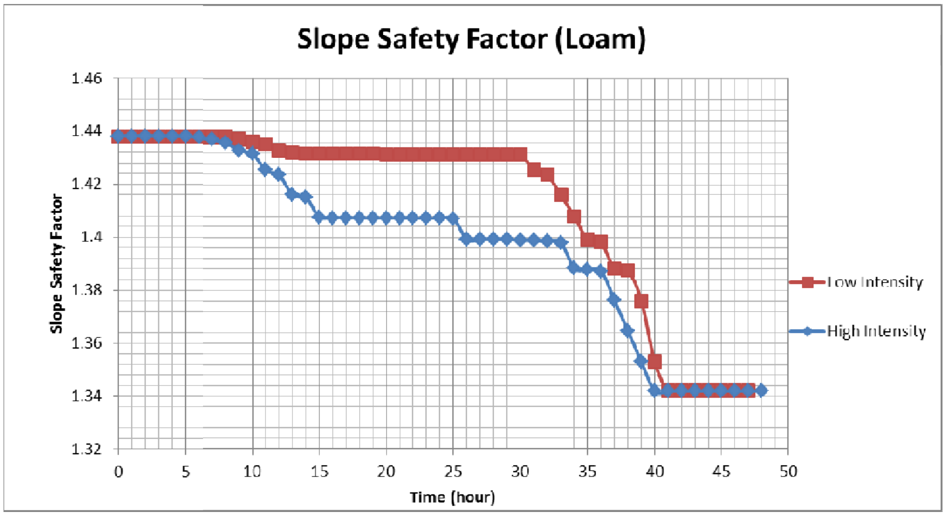


Figure 24: Comparison slope safety factor of loam under different rainfall intensity

Based on Figure 24, for the loam slopes under low rainfall intensity have a greater slope safety factor as the sands slope under high rainfall intensity. The patterns of different rainfall intensity on the loam soil are same. The slope starts to decrease after 2 hours from the maximum intensity under different rainfall intensity where FS = 1.426. Then, the slope stability for high and low rainfall intensity was constant (FS = 1.342) after 42 hours of rainfall elapsed time. The slopes becomes constants as its reach its saturation. After its reach its saturation, the will be no more water infiltrates even at the beginning the slope under high rainfall intensity seems to infiltrate faster as compare to low rainfall intensity.

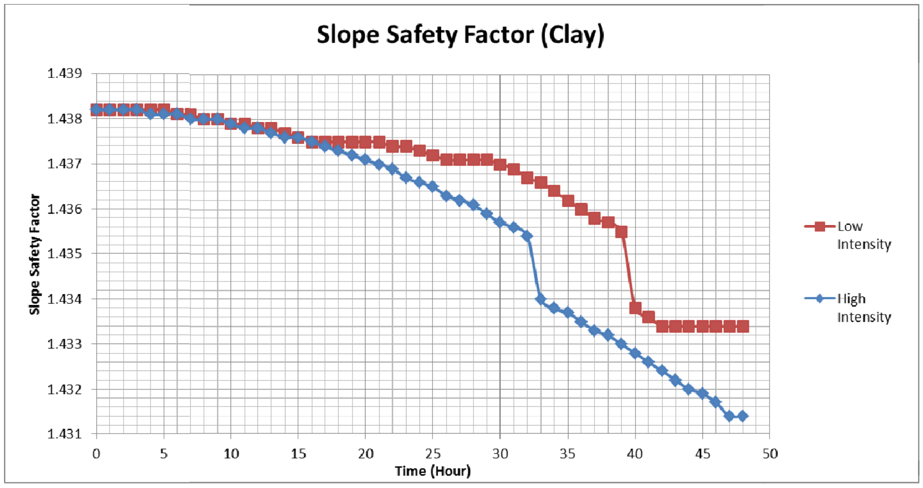


Figure 25: Comparison slope safety factor of clay under different rainfall intensity

Based on Figure 25, the slope stability factors are decreasing as time dependent but the slope remains stable where all slope safety factors is above 1 (FS >1). Both slope starts to decrease after 4 hours of the maximum intensity where slope safety factor is 1.4375 for both rainfall intensity. As for the clay, the slope stability factor as time dependent does not dependent much on the rainfall intensity. It can be observed that, slightly different in change of slope stability factor under different amount of rain intensity. The clay having the lowest permeability of soil which the rate of rainwater to infiltrates is slowest as compared to the sand and loam. The infiltration rate is less and the increase in wetting front depth over a period of time is small.

4.5 Summary on effect of rain intensity and soils permeability on slope stability.

By using the one dimensional Green Ampt infiltration model combines with finite slope stability analysis using slices method, the analysis of the effect on the rainfall intensity and permeability of soil or soil type are investigated and summarizes as below:

i. The high of rainfall intensity and high permeability of soils which are sand have significantly effects the slope stability factor as time dependent. The high soil permeability under high rainfall intensity tends to cause the instability of the slope after short period of rainfall. This is because the slope stability value starts decrease significantly as compare to loam and clay. Whereas, the high rainfall intensity and low permeability of soils such clay, are slightly decreased as time dependent.

ii. The instable of the slope are depends more on the permeability of the soils. It can be seen that, the sand which have higher permeability cause the slope to decrease significantly after a period of rainfall. For high permeability soils, during intense rainfall, rain water will infiltrate faster and reach a deeper saturation depth. Whereas for low permeability of soils, the infiltration is slow and only reach shallow saturation depth.

iii. The amount of rainfall intensity also affected the instability of the slope. From result, the high amounts of rain intensity have lower factor safety as compared to the low rain intensity. Although the amount of rainfall intensity not significantly contribute to the slope failure, combination of both high amount of rain intensity and high permeability of soil may contribute to the slope instability just after elapsed time of rainfall.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

Overall of this study, the slope stability factor could be analyses by using the one dimensional Green Ampt infiltration model with finite slope stability model using slices method. Besides that, the effect on the rainfall intensity and different soil permeability or soil type on slope stability are able to assess using this landslide prediction model. Based on the findings from the analysis of time dependent relationship of rainfall intensity and soil permeability on slope stability, a few conclusions are made as follows:

i. The amounts of rainfall intensity affect the landslide slope stability as time dependent. It was observed that during high rainfall intensity, the slope stability factor is much lower than low rainfall intensity. In addition, the slopes tend to fail much faster during high rainfall intensity as compared to low intensity. It can be say that, that the soil cannot be able to withstand too much of rainfall amount as there is a capacity limitation. After the soils reach its saturation, they will starts to fail.

ii. The different permeability of soil or soil type shows different pattern on the slope stability as time dependent. The soil which has highest permeability which is sand tends to infiltrate faster as compared to the lowest permeability soil which is clay. For clay soil, the slope stability is stable as time dependent for both under high and low rainfall intensity. While for loam soil and sandy soil, the slope safety factor decrease as time increase. It is observed that, for these types of soil, the slope stability is affected also by the rainfall intensity. These soils which having tends to fail due to maximum amount of intensity during high rainfall intensity. Whereas, during the low rainfall intensity, these soil tends to fail after a long time period of rainfall. These soils under low rainfall intensity need more intense rainfall and longer rain period in order for a slope to fail.

iii. For low permeability of soils which is clay, the rainfall intensity does not influence the slope stability factor as time dependent. It is because the rainwater infiltrates is slowest in clay. A longer period of rainfall of intense rainfall may cause the slopes which have lowest permeability to fail.

iv. Based on the modified landslide prediction model, the time of occurrences of landslides and minimum slope safety factor for different rainfall intensity and soil permeability could be determined. To what extents the accuracy of this model is not validate in this study but this model could be used in predicting the landslides.

5.2 Recommendations

The following are the recommendations that can be done for future research or work:

i. This landslide prediction model which consists of one dimensional Green and Ampt infiltration model and finite slope stability model using slice methods need to be validated. It can be done by applied this model in analysis of past event of landslides. Validated whether this model could give exactly the same occurrences of landslides based on the past events.

ii. In this study, the hydrological parameters are determined by estimation from the Green Ampt hydrological parameters for different type of soils and moisture characteristics graph. While, for the geological parameters such as the unit weight of soil, cohesion angle and friction angle is assumed based on the typical values of the soil. The laboratory test and field test need to be conducted to obtain the geological and hydrological parameters of the soil.

iii. For future research, this numerical simulation should be combined with the qualitative approach of landslides prediction in order to develop a landslide early warning system.

iv. Instead of the deterministic approach of the slope failure used in this research, the statistical approach of could be used to investigate the probability of landslide failure.

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