International Journal of GEOMATE, July, 2017, Vol.13, Issue 35, pp.156 - 165
Geotec., Const. Mat. & Env., ISSN:2186-2990, Japan, DOI: http://dx.doi.org/10.21660/2017.35.37981

ANALYSIS OF EXTREME RAINFALL-INDUCED SLOPE FAILURE USING A RAINFALL INFILTRATION-INFINITE SLOPE ANALYSIS MODEL

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*Corresponding Author, Received: 11 Sept. 2016, Revised: 29 Jan. 2017, Accepted: 20 Feb. 2017

ABSTRACT: The aim of this paper is to propose the method for analyzing the slope response to rainfall infiltration during the extreme rainfall in a mountainous area by combining Green-Ampt infiltration model and infinite slope analysis model. The Green-Ampt infiltration model is used to calculate cumulative infiltration into the soil slope. The infinite slope analysis model is chosen to represent the shallow soil slope failure and the simplified first order second moment (SFOSM) is used to calculate the probability of failure. The reliability of the proposed model is validated using three landslide history cases in southern Thailand. Considering the result of calculation, it was found that the proposed model can be used the estimating the soil slope failure occurrence time.

Keywords: Slope failure, Extreme rainfall, Soil Infiltration, Green-Ampt Model, Infinite Slope Analysis Model.

1. INTRODUCTION

Slope failure and landslide during the rainy (mid-May to mid-October) are common geo-hazard in Thailand. Slope failure-prone areas are mountainous areas in the northern and southern region of Thailand. The slope failure and landslide occur over 118 times during 1970 to 2015. The slope failure or landslide damaged the properties and caused fatalities, in addition, the total economic losses are over 3,500 million Bath during 1970 to 2006 [30].

In majority of cases the main trigger of landslides and slope failures is rainfall. The slope failures and landslides occur during or immediately after the heavy or prolonged rainfall. When rainwater infiltrates a soil slope, the initial state of soil slope is an unsaturated condition, an increase in the ground water table or a decrease in negative pore-water pressure (matric suction). These changes can lead to slope failure [15], [20], [22], [37]. Therefore, the rainwater infiltration plays an important role in the instability of soil slope. Moreover, a general type of slope failure and landslides occurs in the form of shallow slip and parallel to the slope surface that can be analyzed by infinite slope model.[6], [20], [33]. Numerous researches have been done to study the extreme rainfall induced soil slope failures with several methods such as full scale experiment, field observation, and numerical method [9], [11], [22], [34], [36]. Finite element method (FEM) or Finite difference method (FDM) is numerical method that is widely applied for analysis of water or rain seepage through soil slope. They have been used successfully to perform complex function seepage through the soil slope. However, the numerical method requires many factors as input for performing computation. Full scale experiment is valuable method to study rainfall-induced slope failure mechanism. Moreover, there are a lot of landslide model based on the hydrological model that has been developed to simulate the groundwater or pore water pressure and to assess landslide or soil slope failure [2], [35]. However, this model is only suitable for homogenous soil slope [20].

Hence, this paper presents the deterministic model used to estimate the safety factor and occurrence time of slope failure. The deterministic model is using the Green and Ampt infiltration model, infinite slope procedure and the simplified first order second moment (SFOSM). The purpose of this study also considers the uncertainty of soil properties by SFOSM method. The proposed model was verified and validated by landslide cases histories.

2. RAINFALL INFILTRATION ANALYSIS

The infiltration implies the process of downward flow of water or rainwater into soil. This process is a very important part of the hydrologic cycle which control changing of groundwater table and pore-water pressure. The rainwater infiltration is controlled by many factors, such as hydraulic properties, soil depth, or climate properties. The soil infiltration is controlled by soil's infiltration capacity or potential infiltration. When rainfall rate exceeds the infiltration capacity (maximum rate of the soil to absorb water), the excess rainfall becomes the surface runoff water. There are 3 possible of infiltration cases as shown in Fig. 1. The First case, rainfall intensity is less than the infiltration rate and all the rainwater infiltrates into the soil or slope. Moreover, there is no water ponding at the soil surface. The Second case, the rainfall intensity is less than the infiltration rate at the beginning of time interval, after that, rainfall intensity is more than the infiltration rate and the water pond at soil surface occurs. The third case, the rainfall intensity is more than the infiltration rate and is occurs the water ponding over soil surface at the beginning of time interval. [10], [28]

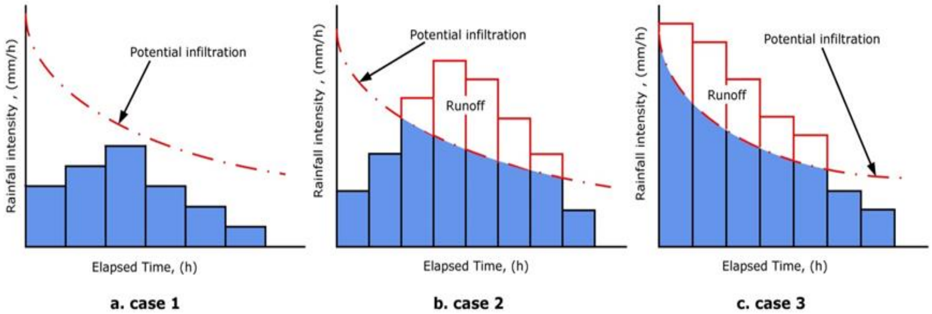

Fig.1 Rainwater infiltration, rainfall intensity, and runoff

The Green-Ampt model is a simplified analytical model of infiltration process of a dry and uniform column of soil which is widely used and modified in numerous researches [1], [15], [19]. The model is derived by applying Darcy's law and was developed based on two main assumptions: 1 the soil suction head at the wetting front is constant, and 2 the volumetric water content and the coefficient of hydraulic conductivity are also constant, moreover the coefficient of hydraulic conductivity equal to saturated hydraulic conductivity. Fig. 2 shows soil and infiltration profile for Green-Ampt model. Originally, the model was developed for horizontal infiltration of ponding water. Reference [3] extended the Green-Ampt equation for sloping ground surface. [15], [19]-[20]

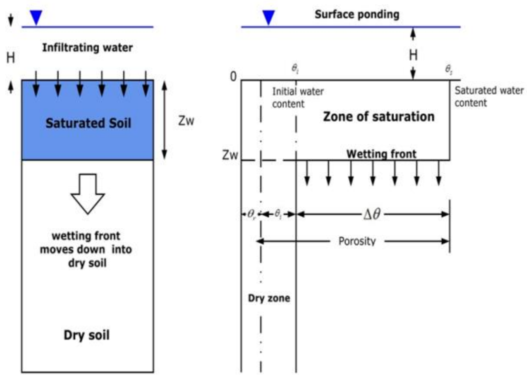

Fig.2 Soil and infiltration profile for Green-Ampt model

Infiltration rate can be calculated using Eq. (1) and cumulative infiltration at the time can be calculated using Eq. (2).

$$f(t) = k\left[\cos\beta + \frac{(\psi_f \cdot \Delta\theta)}{F(t)}\right] \tag{1}$$

$$F(t) - \frac{(\psi_f \cdot \Delta\theta)}{\cos\beta}\ln\left[1 + \frac{F(t)\cos\beta}{(\psi_f \cdot \Delta\theta)}\right] = k \cdot t \tag{2}$$

Where $f(t)$ is potential infiltration rate at time t, k is coefficient of hydraulic conductivity, β is slope angle, ψ_f is suction head at wetting front, $\Delta\theta$ is volumetric water content deficit, and $F(t)$ is cumulative infiltration at time t.

The depth of wetting front can be estimated using Eq. (3).

$$z_w = \frac{F(t)}{(\theta_s - \theta_i)\cos\beta} \tag{3}$$

Where z_w is depth of wetting front, $(\theta_s - \theta_i)$ is volumetric water content deficit ($=\Delta\theta$)

Reference [17] extended the Green-Ampt model for consideration of infiltration when the soil becomes fully saturated and the surface ponding begins. The infiltration rate is equal to rainfall intensity if the rainfall intensity is less than the infiltration rate or infiltration capacity as shown in Eq. (4). An equation 4 yield at surface ponding begins and transform to Eq. (5). Table 1 shows the parameters for Green-Ampt infiltration model.

$$F(t) = i \cdot t \tag{4}$$

$$F(t) = i \cdot t_p \quad (5)$$

The equation for finding time to ponding is as follow:

$$t_p = \frac{k \cdot \psi_f \cdot \Delta\theta}{i(i-k)} \quad (6)$$

The equation at ponding as;

$$F_p(t) - \frac{(\psi_f \cdot \Delta\theta)}{\cos\beta} \ln\left[1 + \frac{F_p(t)\cos\beta}{(\psi_f \cdot \Delta\theta)}\right] = k \cdot t_p \quad (7)$$

and the cumulative infiltration after ponding as;

$$F(t) - F_p(t) - \frac{(\psi_f \cdot \Delta\theta)}{\cos\beta} \ln\left[\frac{F(t)\cos\beta + (\psi_f \cdot \Delta\theta)}{F_p(t)\cos\beta + (\psi_f \cdot \Delta\theta)}\right] = k \cdot (t - t_p)$$

(8)

Where i is rainfall intensity, t is time, t_p is time to ponding, and $F_p(t)$ is cumulative infiltration at ponding time.

3. VERTICAL PROFILE OF PORE WATER PRESSURE

In geotechnical engineering practice, the effect of negative pore water pressure (matric suction) on the slope stability is very difficult to predict and it is sometimes ignored. The matric suction can be ignored because rainwater infiltrates into the slope, and it will generate wetting front. The wetting front causes the disappearance of the soil matric suction. Reference [16] has proposed the wetting front concept after that numerous research develop and widely used method for analysis and considering the changes in the pore water pressure under rainfall condition. Reference [13] studied the effect of steady rainfall on the long-term matric suction condition. The results show that the long-term matric suction will not disappear unless the steady rainfall flux approaches the saturated coefficient of hydraulic conductivity. [8], [10], [13], [21], [28] Reference [14] derived an equation for one-dimensional steady-state seepage condition as follow;

$$\frac{d(u_w / \gamma_w)}{dy} = \left(\frac{q}{k} - 1\right) \quad (9)$$

Where u_w is pore water pressure, γ_w is unit weight of water, q is steady-state flow rate, and k is unsaturated hydraulic conductivity dependent on matric suction.

Table 1 Parameters for Green-Ampt infiltration model [4]

Soil type	Porosity	Effective porosity	Residual porosity	Wetting front soil suction head	Coefficient of hydraulic conductivity, (cm/hr)
Sand	0.437 (0.374-0.500)	0.417 (0.354-0.480)	0.020	4.95 (0.97-25.36)	11.78
Loamy sand	0.437 (0.363-0.506)	0.401 (0.329-0.473)	0.036	6.13 (1.35-27.94)	2.99
Sandy loam	0.453 (0.351-0.555)	0.412 (0.283-0.541)	0.041	11.01 (2.67-45.47)	1.09
Loam	0.463 (0.375-0.551)	0.434 (0.334-0.534)	0.029	8.89 (1.33-59.38)	0.34
Silt loam	0.501 (0.420-0.582)	0.486 (0.394-0.578)	0.015	16.68 (2.92-95.39)	0.65
Sandy clay loam	0.398 (0.332-0.464)	0.330 (0.235-0.425)	0.068	21.85 (4.42-108.0)	0.15
Clay loam	0.464 (0.409-0.519)	0.309 (0.279-0.501)	0.155	20.88 (4.97-91.10)	0.1
Silty clay loam	0.471 (0.418-0.524)	0.432 (0.347-0.517)	0.039	27.30 (5.67-131.50)	0.1
Sandy clay	0.430 (0.370-0.490)	0.321 (0.207-0.435)	0.109	23.90 (4.08-140.2)	0.06
Silty clay	0.479 (0.425-0.533)	0.423 (0.334-0.512)	0.047	29.22 (6.13-139.4)	0.05
Clay	0.475 (0.427-0.523)	0.385 (0.265-0.501)	0.090	31.63 (6.39-156.5)	0.03

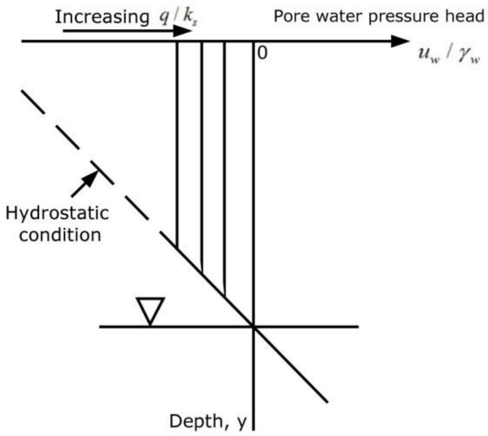

Fig.3. Typical pore water pressure distributions in an unsaturated soil. [37]

Fig. 3 shows the pore water pressure distributions for steady-state seepage condition, according [14] in cases of steady-state condition (water flux in of soil is equal water flux out).

4. METHODOLOGY AND MODEL DEVELOPMENT

4.1 Slope Stability Analysis

Traditional slope stability analysis model of rainfall-induce slope failure is infinite slope model because the model is according to a mode of failure. The characteristic of failure is a shallow failure and parallel to the slope surface. Fig. 4 shows the infinite slope model.

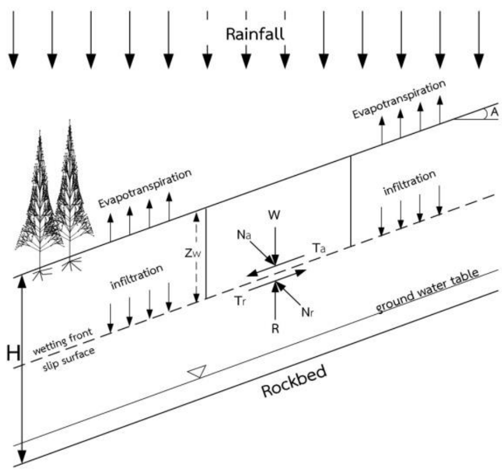

Fig.4. Infinite-slope model.

A concept of stability of hillslope is presented in form of factor of safety (FS) which is a ratio of shear strength to shear stress. If the factor of safety becomes less than 1.0, the hillslope is unstable.

$$\text{FS} = \frac{\text{shear strength of soil slope}}{\text{shear stress developed of soil slope}}$$

The shear strength of soil slope along the potential failure plane can be assessed using the Mohr-Coulomb failure criterion, as follow:

$$\tau_f = c' + (\sigma - u_w)\tan\phi' \tag{10}$$

Where τ_f is shear strength, c' is effective cohesion, $(\sigma - u_w)$ is effective stress, and ϕ' is effective friction angle.

The potential failure plane for analysis is assumed to occur at the wetting front. Hence, the factor of safety can be written as follow:

$$\text{FS} = \frac{c' + (\gamma_t z_w \cos^2 \text{A} - \psi_f \cdot \gamma_w)\tan\phi'}{\gamma_t z_w \cos \text{A} \sin \text{A}} \tag{11}$$

Where FS is safety factor, γ_t is soil unit weight, z_w is depth of wetting front, A is slope angle, and ψ_f is the suction at the wetting front.

4.2 Simplified First Order Second Moment

The probabilistic method provides methods for evaluating uncertainties from soil shear strength, rainfall, and the other parameters. The First-order second-moment method is widely used to analyze the stability of slope [5], [7], [29], [37]. This research used the simplified first-order second-moment method which was improved the approach of calculation by [29]. The probability density function of the random variables and the performance function are assumed to be a normal distribution and the model error and spatial variability is ignored.

The concept of this method is described below:

$$\delta = g(x_1, x_2, x_3, \ldots x_n) + e \tag{12}$$

The expected value of performance variable:

$$E[\delta] = g(E[x_1], E[x_2], E[x_3], \ldots E[x_n]) \tag{13}$$

Taylor's series (first term) approximation of uncertainty:

$$V[\delta] \approx \sum_{i=1}^{k}\sum_{j=1}^{k} \frac{\partial g}{\partial x_i}\frac{\partial g}{\partial x_j} C[x_i x_j] + V[e] \tag{14}$$

Assume that x_i and x_j are uncorrelated (independent random variables):

$$V[\delta] \approx \sum_{i=1}^{k} \left(\frac{\partial g}{\partial x_i} \right)^2 V_t[x_i] + V[e] \tag{15}$$

Finite difference approximations of the derivatives are used where close-form derivatives are inconvenient or impossible. The simplification of the original first-order second-moment uses in practice:

$$V[\delta] \approx \sum_{i=1}^{k} \left(\frac{\Delta g}{\Delta x_i} \right)^2 V_t[x_i] + V[e] \tag{16}$$

Reference [7] proposed the step to assess the reliability by using the Taylor series method. It is to use a much larger increment, specifically between point plus and minus one standard deviation from the expected.

$$V[\delta] \approx \sum_{i=1}^{k} \left[\frac{g(x_{i+}) - g(x_{i-})}{2\sigma_{x_i}} \right]^2 \sigma_{x_i}^2 + V[e] \tag{17}$$

Or

$$V[\delta] \approx \sum_{i=1}^{k} \left[\frac{\Delta g(x_i)}{2} \right]^2 + V[e] \tag{18}$$

where , $x_{i+} = E[x_i] + \sigma_{x_i}, x_{i-} = E[x_i] - \sigma_{x_i}$

$$V[\delta] \approx \sum_{i=1}^{k} \left[\frac{\Delta g(x_i)}{2} \right]^2 + V[e] \tag{19}$$

The model error is neglected

$$V[\delta] \approx \sum_{i=1}^{k} \left[\frac{\Delta g(x_i)}{2} \right]^2 \tag{20}$$

The coefficient of variation is calculated using the following relationship.

$$COV = \frac{\sigma(x_i)}{E(x_i)} \tag{21}$$

The standard deviation is calculated using the following equation:

$$\sigma[\delta] = \sqrt{V[\delta]} \tag{22}$$

The reliability index equation can be written as follow:

$$\beta = \frac{E(\delta) - 1.0}{\sigma[\delta]} \tag{23}$$

The probabilistic of failure can be calculated using the following equation:

$$p_f = 1 - \Phi[\beta] \tag{24}$$

Where β is reliability index, $\Phi[\beta]$ is cumulative probability density function for the given β

5. MODEL STUDY AND APPLICABILITY

The proposed model makes some simplifying assumptions. The first assumption is that the initial water content (θ_i) is equal to the volumetric water content at field capacity. The volumetric water contents at field capacity and saturation show in Table 2. The last assumption is that the model of failure is based on the infinite slope model.

Table 2 Volumetric water content at field capacity and saturation [27]

Soil type	VWC at Field cap, %	VWC at Sat, %
Sand	10	46
Silt loam	31	48
Silt	30	48
Silty clay	41	52
Sandy loam	18	45
Sandy clay	36	44

Three landslides cases in Thailand are chosen from literature for verifying the suitability of the proposed model. The landslides cases located in Southern part of Thailand, Khao Luang landslides (1988), Theppharat landslides (2011), Khao Panom landslides (2011). The parameters are collected from the literature and input in the Green-Ampt model for infiltration analysis and infinite slope model for slope stability analysis and a probability of failure. The parameters listed show in Table 3. The coefficients of variation (COV) of soil parameters show in Table 4.

5.1 Description of the Khao Luang landslides

During November 19-23, 1988, the Southern Thailand is situated in a tropical monsoon climate. The extreme rainfall has hit the Nakhon Si Thammarat province. The rainfall in 72 hours was more than 850 mm. which was over more than the average rainfall on November (631.2 mm). The landslides and slope failures approximately occurred 22, November 1988. The geological condition is 0.5-3.0 m of residual soil that is completely the weathered granite rock overlay the moderately, slightly weathered and fresh rock. The debris flow has occurred and destroyed the villages around the base of Khao Luang. [23], [24]

5.2 Description of the Theppharat landslides

During March 22-31, 2011, the abnormal extreme rainfall has occurred in the Southern of Thailand. This event is off-season rainfall. The rainfall in 72 hours was more than 650 mm. The landslides and slope failures have approximately occurred 25-26, March 2011 in Theppharat, Nakhon Si Thammarat. The soil type in landslides area is silty sand and thickness is about 3 - 4 m. The soil is a residual soil which the rock parent is Jurassic-Cretaceous granite rocks. [32]

5.3 Description of the Khao Phanom landslides

Near the end of March 2011, the off-season rainfall has attacked the Southern of Thailand where located in the Malay Peninsula. The rainfall in 72 hours was over 400 mm. The landslides and slope failures at Khao Phnom, Krabi has approximately occurred 28, March 2011. The characteristic of failure is a shallow landslide on the decomposed soil which the granite rock is an origin of soil. The debris flow length is approximately 2.5-3.0 km and the largest wide is approximately 500m. [31]

Fig. 5 shows location of historical landslides cases

Table 3 Parameters used for Khao luang, Theppaharat, Khao Panam landslide cases

Location/ soil type	Slope angle	$\Delta\theta$	Cohesion , c' (kPa)	Friction angle, ϕ'	Soil unit weight, (kN/m^3)	Coefficient of permeability, (cm/hr)	Reference
Khao Luang landslides	33º	0.08	18	30º	18.5	0.131	[23], [24]
Theppharat landslides	25º	0.17	8	32º	18	1.13	[32]
Khao Panom landslides	35º	0.11	11	25º	16.5	0.087	[31]

Table 4 Summary of variability of soil properties

Parameter	Soil type	COV%	References
Soil unit weight, kN/m^3	Fine grained	9	[26]
Cohesion, kPa	Fine grained	33	[26]
Friction angle, degree	Clay & silt	21	[26]
Slope angle, degree	-	5	[12]
Depth of failure, m.	-	5	[12]

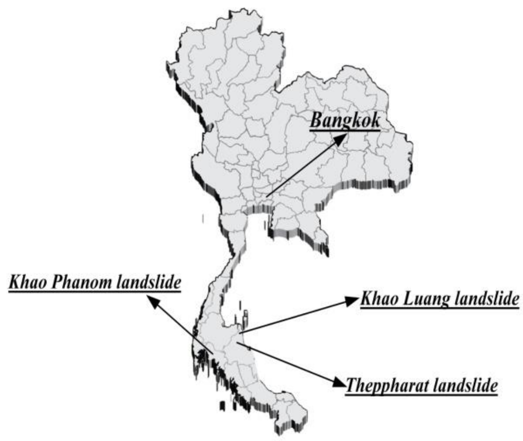

Fig.5. Location of historical landslides cases.

6. RESULTS AND DISCUSSION

6.1 Khao Luang Landslides

The soil at Khao luang landslides is low permeability which the coefficient of hydraulic conductivity is 0.131 cm/hr. Hence, at the beginning of the rainfall, the potential of infiltration rate was higher than the rainfall intensity; hence, the infiltration rate was equal to the rainfall intensity. Ponding time was approximately observed at 24 hours after rainfall; as a consequence, surface runoff was expected to occur due to excess rainfall. The rainwater had infiltrated into the ground which generated the wetting front. At the end of rainfall, the depth of wetting front was approximately 3.5 m. In addition, at the time of landslides occurrence, the depth of wetting front reached about 1.8 m.

The mean factor of safety (MFS) decreases with elapsed time of rainfall. The mean factor of safety is rapid decreases from approximate 2.0 to 1.1 in 24 hours (20-21 November 1988). Considering the accumulation rainfall at this time is 612 mm. and the accumulation infiltration at this time is 40 mm. The mean factor of safety is less than 1 during 21-22 November 1988 which the time of landslides occurrence agrees with the real situation. The time of landslides occurrences is approximately 22 November 1988 (Pantanahiran, 2016). Fig. 6 shows the infiltration rate, rainfall intensity, depth of wetting front, and mean factor of safety in each time. At the time of landslides occurrence, the probability of failure (pf) is approximate 0.7. The probability of failure is rapidly increasing during 21-22 November 1988. Fig. 7 shows the factor of safety and the probability of failure.

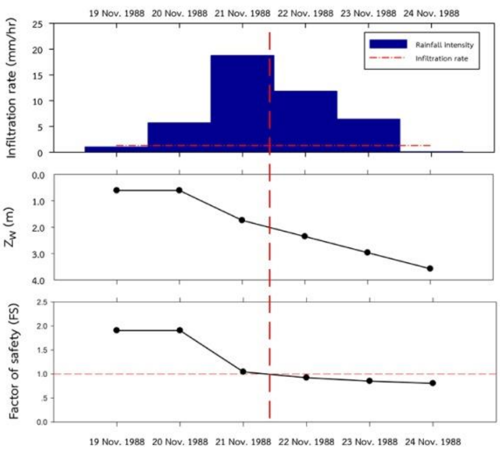

Fig.6. Calculated factors of safety for slope at Khao luang landslides.

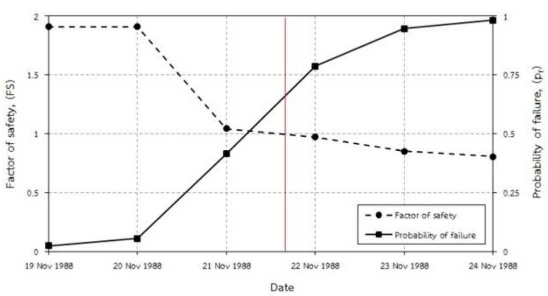

Fig.7. Calculated factors of safety and probability of failure at Khao luang landslides.

6.2 Theppharat Landslides

At the beginning of the rainfall, the all the rainwater infiltrated into the slope at the Theppharat site because the permeability of soil at slopes is 1.13 cm/hr and higher than the rainfall intensity. The first ponding occurred at 96 hours after the rainfall and the second ponding occurred at 168 hours after rainfall. At beginning of rainfall until landslides occurrence, the accumulation rainfall was 710 mm in 120 hours. The depth of wetting front is about 3 meters at the time of landslides occurrence.

According to the calculation, it showed that the mean factor of safety (MFS) is a rapid decrease from over 15 to about 1.2 in 72 hours (22-24 March 2011) after the rainfall. The amount of rainfall in 72 hours is approximately 140 mm. and all the rainfall in 72 hours infiltrated into the slope. The computed factor of safety reduced to 1 on 25-26 March 2011 (the time of landslides occurrence is about 25-26 March 2011). The analysis results, it was showed that the mean factor of safety is quite correlated with the real situation of landslides. Regarding the probability of failure, it was about 0.53 at the time of landslides occurrence. The probability of failure rapidly increases during 24-26 March 2011 and the probabilistic of failure is remaining constant after 26 March 2011. Fig. 8 shows infiltration rate, depth of wetting front, and the mean factor of safety in each time of Thappharat site. Fig. 9 shows the mean factor of safety and the probability of failure.

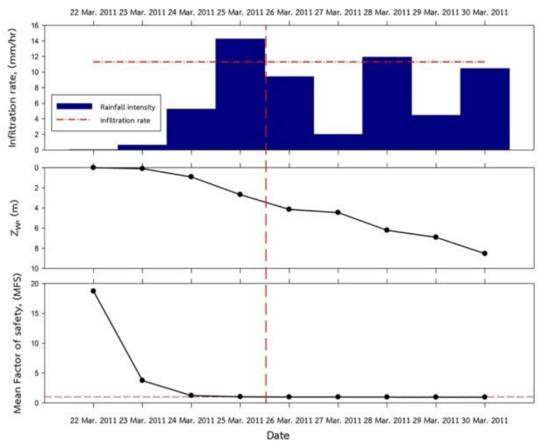

Fig.8. Calculated factors of safety for slope at Thappharat landslides.

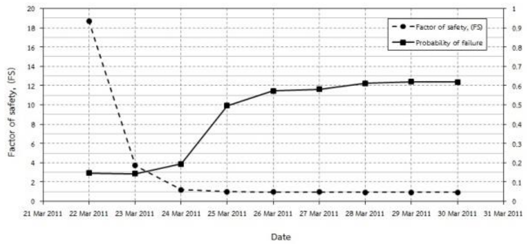

Fig.9. Calculated factors of safety and probability of failure at Thappharat landslides.

6.3 Khao Phanom Landslides

At the beginning of rainfall, the infiltration rate is higher than the rainfall intensity; hence, all the rainwater was infiltrated into the slope. The ponding was approximately occurred and observed at 24 hours after rainfall (26 March 2011) and continuously occurred until 30 March 2011. The excess rainwater becomes the surface runoff water. The rainwater, which seeped into the slope, generated the wetting with elapsed time of rainfall. At the time of landslides occurrence, the depth of wetting front is approximately 0.60 m. In addition, the depth of wetting front is approximately 1.25 m. at the end of rainfall.

Regarding the slope stability, it was found that the safety factor is approximately 1.5 at the beginning of rainfall and it continuously reduced into 1.0 during 27-28 March 2011. The cumulative rainfall at the time of landslides occurrence was 400 mm. The result of calculation agrees with the observation data. Considering to the probability of failure, it was found that the probability of failure continuously increases from about 0.35 to 0.65. At the time of landslides occurrence, the probability of failure was about 0.55. Fig. 10 shows infiltration rate, depth of wetting front, and the mean factor of safety in each time of Khao Phanom site. Fig. 11 shows the mean factor of safety and the probability of failure.

7. CONCLUSION

The results found from this study could be concluded as follows;

The capacity of infiltration is controlled by the ability of the soil to absorb water. Some of the rainfall is infiltrated into the soil and the excess rainfall becomes the runoff surface. Hence, debris or woody debris flow usually occurs along with the landslides in many times.

The probability of failure at the time of landslides occurrences in each landslides case are approximately 0.7 for Khao luang landslides, approximately 0.58 for Theppharat landslides, and

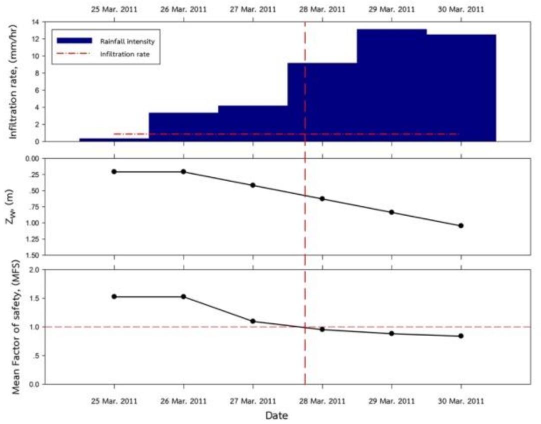

Fig.10. Calculated factors of safety for slope at Khao Phanom landslides.

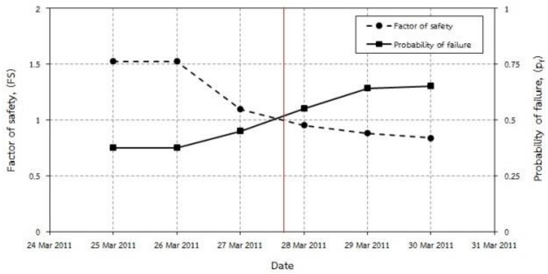

Fig.11. Calculated factors of safety and probability of failure at Khao Phanom landslides.

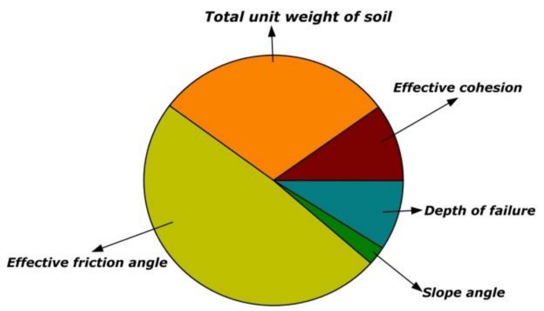

Fig.12. Percentage contribution of each parameter for infinite slope model.

0.55 for Khao Phanom landslides. When considering the sensitivity of infinite slope model, it was found that the friction angle has the most effect on the model as in Fig. 12.

The proposed method integrates the Green-Ampt infiltration model and infinite slope stability model for studying the extreme rainfall-induced shallow slope failures. The model used the SFOSM for consideration the uncertainty and variance of soil properties. The proposed method is capable of estimating the time of landslides occurrence which has been verified by the recorded data on the landslides cases in southern of Thailand. The estimated time of landslides occurrence from the proposed method is in good agreement with the real observation data. The depth of sliding plane can be estimated by this method but the depth of sliding plane cannot be confirmed because of the limitation of recorded data. The SFOSM can be applied for estimation of the probability of failure. Hence, the proposed method can be applied to analyze the effect of rainwater on the slope stability.

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