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Predicting of Shallow Slope Failure Using Probabilistic Model: a Case Study of Granitic Fill Slope in Northern Thailand

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Abstract

Slope failure occurred during rainfall in September 2009 near the peak of Doi-Inthanon national Park, Northern Thailand. Progressive studies have been conducted to monitor the pore water pressure variation during the monitored rainfall in September 2011. Lack of data for back analysis generated uncertainties in slope failure analysis. This paper presents probability analysis of the slope failures. The analysis considers the uncertainties of the influencing factor such as rainfall intensity, hydraulic and strength parameter of the soil. The probability analysis was calculated using Monte Carlo Simulation method (MCS). The slope failure was modeled using the infinite slope. Infiltration analysis was analyzed using Green – Ampt model. Three models of the rainfall hyetographs, including hourly rainfall, 15 minutes rainfall, and 5 minutes rainfall, were used to analysis the probability of failure. The simulation results show that the probability of failure (P_f) ranges about 0.36-0.38 for the corresponding rainfall. The highest probability of failure was obtained when daily rainfall was simulated. The probability of failure was strongly affected by the variability of the input parameter.

Keywords: rainfall, probability, shallow slope failure, factor of safety, residual soil

1. Introduction

This paper presents the extensive field monitoring results of pore-water pressure and rainfall of a granitic soil slope near the peak of Doi-Inthanon national park, Northern Thailand. Jotisankasa et al.[1] did back analysis of the soil slope that failed in 2011. The study was performed to determine the critical pore-water pressure at failure based on laboratory shear strength. The study also involved laboratory determination of the saturated-unsaturated shear strength and Soil-Water Characteristic Curves (SWCC). Although the early study has been successfully estimated the critical pore water pressure at the site, lack of data for back analysis generated uncertainties in slope failure analysis. Hence, continuous research needs to be conducted to determine the triggering rainfall. This paper presents a probability analysis of the slope failures. The analysis considers the uncertainties of the influencing factor such as rainfall intensity, hydraulic and shear strength parameter of the soil. The effect of rainfall intensities and the uncertainty of soil properties on the probability of failure of the slope is the primary objective of this research. In slope - probabilistic analysis, the establishment of the probability distribution of every random variable is a fitting process based on the limited data from measurements or tests. Therefore, there are three major sub-categories introduced: site characterization uncertainty, model uncertainty, and parameter uncertainty [2,3,4].

2. Method of Analysis

2.1. Rainfall Infiltration and Slope Stability Model

Instability of unsaturated soil slopes after rainfall is common in many countries, and these failures are generally shallow and are usually parallel to the slope surface. The stability of these slopes can be analyzed by a simple infinite slope analysis. The model slope stability analysis in combination with infiltration analysis was adopted from the model developed by Muntohar and Ikhsan [5]. The model incorporated one-dimensional infiltration analysis and infinite slope stability analysis. The infiltration analysis was developed from Green – Ampt infiltration model. Time-varying and unsteady rainfall intensity was considered in the model.

The slope stability can be expressed by calculating the factor of safety as written in Equation 1.

$$FS(t) = \frac{c' + \left[\gamma_t \cdot z_f(t)\cos^2\alpha - u_w(t)\right]\tan\phi'}{\gamma_t \cdot z_f(t) \cdot \sin\alpha \cdot \cos\alpha} \tag{1}$$

Where, u_w is the pore water pressure, γ_t is saturated unit weight of soil, c' and ϕ' are cohesion and internal friction angle respectively, z_f is depth of sliding-plane that is equal to depth of wetting front (z_w*). The depth of wetting front is limited by the depth of impermeable layers or bedrock. In this case, the maximum z_w* is the depth of bedrock (H_b). The pore water pressure is calculated in two condition: $u_w = \psi_f.\gamma_w$, if the ground surface is unsaturated, but if the surface is saturated the pore water pressure $u_w = z_w^*.\gamma_w$. [5].

2.2. Reliability and failure probability

Reliability is the probability of an object (item or system) performing its required function adequately for a specified period under stated conditions [6]. As it applies in the present context, the reliability of a slope is the probability that the slope will remain stable under specified design conditions. In slope reliability analysis, the performance function $g(X)$ of slope stability can be stated by a factor of safety equation in equation 1, and is always defined as in equation 2.

$$g(X,t) = \frac{R(X,t)}{L(X,t)} \tag{2}$$

where, $X = \{x_{1\ldots n}\}$ are n input uncertain variables which impact the slope reliability. The variables are $X_i = \{\alpha_i, c_i', \phi'_i, \gamma_{t,i}, H_{b,i}, k_{s,i}, \psi_{f,i}, \Delta\theta_i\}$. The function $g(X,t)$ reflects the performance or state of the slope as time dependent function. The slope will be safe when $g(X,t) > 0$; unsafe or failure when $g(X,t) < 1$; limit state when $g(X,t) = 1$, which is also called the limit state function of slopes.

In this study, Monte Carlo Simulation (MCS) method was performed to obtain the failure probability. Values of each uncertain variable are generated randomly as an identically-independent distribution (i.i.d) from the probability distribution function (*PDF*) for each N simulation cycles. A lognormal PDF was used in this study. Each set of samples and the resulting outcome from that sample was recorded. In reliability theory, the reliability index β of the slope

stability can be represented by Equation 3 if the probability density function of safety factor is normally distributed.

$$\beta = \frac{\mu_{FS(X,t)} - 1}{\sigma_{FS(X,t)}} \tag{3}$$

where $\mu_{FS(X,t)}$ is the mean of the safety factor and $\sigma_{FS(X,t)}$ is the standard deviation of the safety factor. If the probability density function of safety factor is log-normally distributed, the reliability index of slope can be given as Equation 4 [7].

$$\beta = \frac{\ln\left[\mu_{FS(X,t)} \Big/ \sqrt{1+\left(\sigma_{FS(X,t)} / \mu_{FS(X,t)}\right)^2}\right]}{\sqrt{\ln\left[1+\left(\sigma_{FS(X,t)} / \mu_{FS(X,t)}\right)^2\right]}} \tag{4}$$

For this reason, the distribution of the factor of safety will be evaluated. Then, the probability of failure can be calculated from the reliability index by Equation 5.

$$P_f = 1 - \Phi(\beta) \tag{5}$$

where, $\Phi(\beta)$ is the cumulative probability density function for the given β.

2.3. Slope and soil properties

Data input for the slope stability modeling of the studied area has been taken from topographic and geotechnical investigations by Jotisankasa et al. [1]. The data collected was determined as the mean value while the coefficient of variance (*cov*) was assumed to be varied by 0.01, 0.02, and 0.005. The geotechnical properties of the soil are presented in Table 1.

The rainfall was recorded from the nearest rainfall station on 1 - 14 September 2011. Originally, the rainfall record was transmitted as 5 minutes rainfall as shown in Figure 1a. The cumulative rainfall for two weeks was about 520 mm. The other rainfall hyetograph was analyzed for hourly rainfall, and daily rainfall as illustrated in Figure 1b and 1c respectively.

Table 1 Soil properties of the slope

Slope angle α	Hydraulic conductivity k_s (mm/h)	Moisture difference $\Delta\theta = \theta_s - \theta_i$	Wetting front suction head ψ_f (mm)	Cohesion c' (kPa)	Friction angle ϕ'	Soil unit weight γ_t (kN/m^3)	Bedrock Depth H_b (m)
33°	2203.2	0.125	300	10.1	26.7^o	21.8	2
Note: The values are mean values (μ). The *cov* was varied by 0.01, 0.02, and 0.005. The Wetting front suction head was estimated from soil water retention curve.							

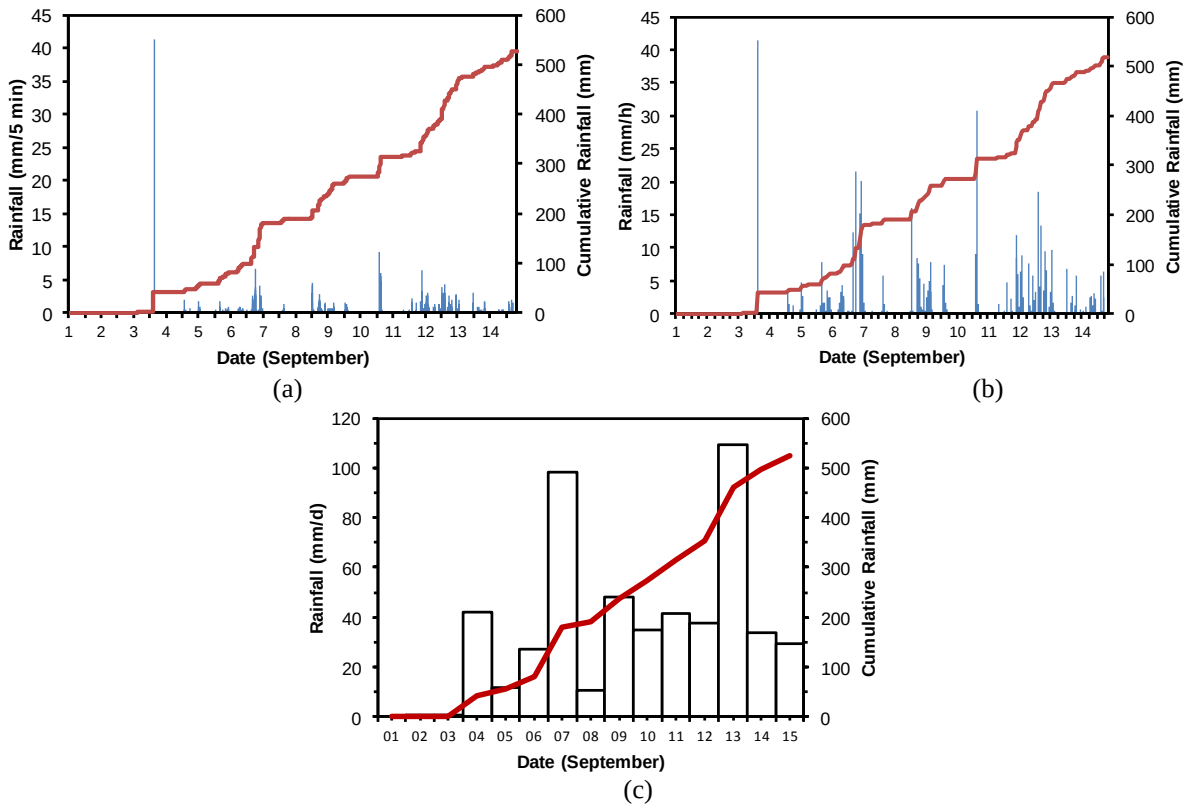

Figure 1 The rainfall hyetograph for the study (a) 5 minutes rainfall, (b) hourly rainfall, (c) daily rainfall

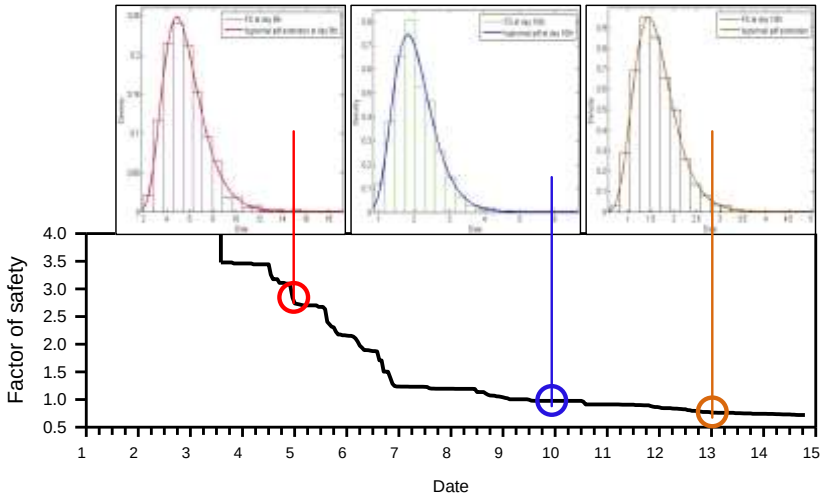

Figure 2 Typical the change of factor of safety and the probability distribution of time for the hourly rainfall

3. Results and Discussion

3.1. Probability density and Probability of Failure

The simulation will result in a variation of factor of safety with the elapsed time. Typical the change of factor of safety and the distribution with time is shown in Figure 2. The calculated factor of safety was not normally distributed but lognormal. Hence, the reliability index was determined using equation 4. As a consequence, the probability of failure was calculated based

on the lognormal probability density function. The variation of the probability density and failure probability with the elapsed time of the 5 minutes rainfall, hourly rainfall, and daily rainfall are shown in Figure 3, 4, and 5 respectively. The failure probability of the slope range from 0.05 to 0.37 due to the 5 minutes rainfall pattern, while the probability of slope failure was 0.04 – 0.36 and 0.05 – 0.038 for hourly and daily rainfall pattern respectively. The results show that the maximum failure probability for the given input parameter was about 0.36 – 0.38 due to the rainfall recorded at the site.

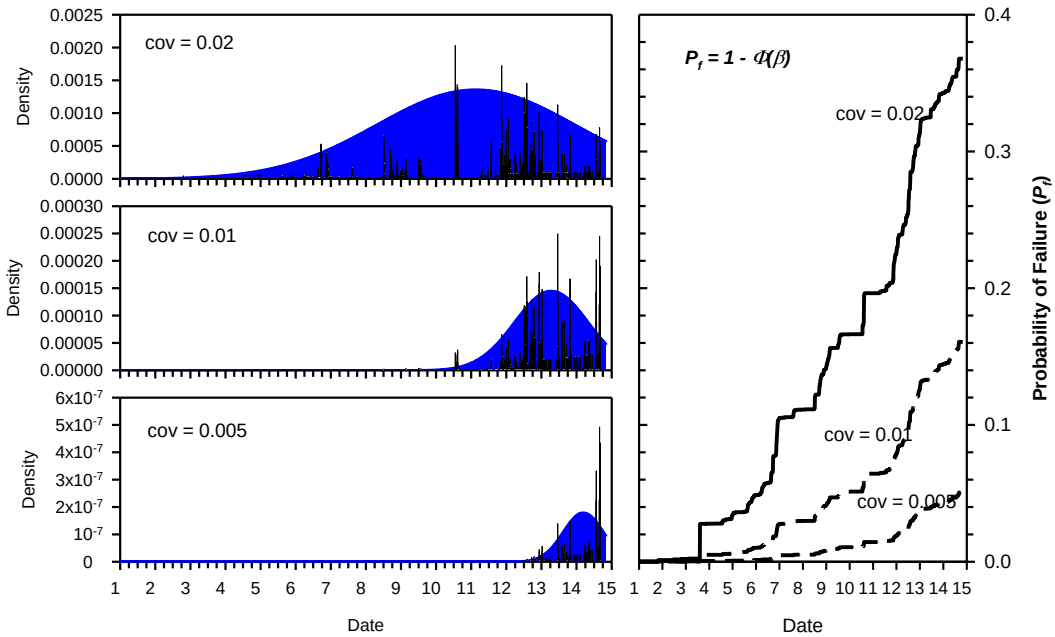

Figure 3 Distribution of failure occurrence and failure probability with the time of 5 minutes rainfall

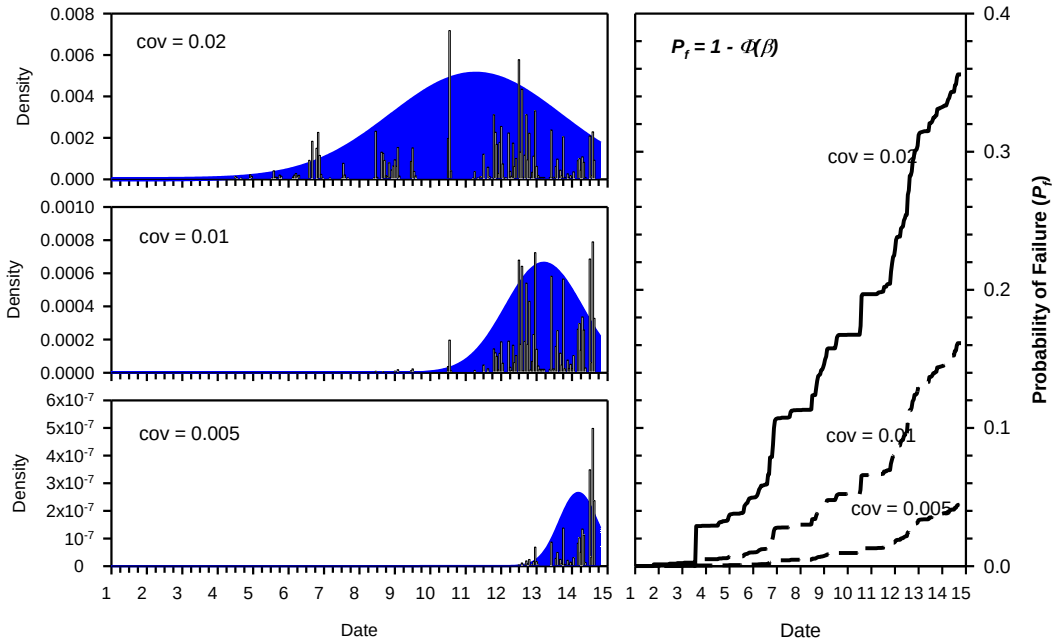

Figure 4 Distribution of failure occurrence and failure probability with the time of hourly rainfall

The relationship in Figure 3 to 5 show that the probability density is widely distributed with the elapsed time if the *cov* is large. In contrast, the probability density is closely distributed if the *cov* is small. In this study, the probability density of occurrence is estimated using the *normal probability density function*. Muntohar [8] proposed the estimated mean time to failure (MTTF) by using the statistical properties of its *pdf* i.e. mean (μ) and variance (σ^2) or standard deviation (σ). The μ value determines the center of the *pdf,* and the value of σ^2 determines the width. A small value of the variance implies that the time to failure is closer to the central value or less uncertain. Table 2 presents the MTTF for the simulated rainfall in this study. Based on this presentation, the slope failure can be estimated to be occurred between 9 to 13 September 2011 that depends on the rainfall patterns and variance of the input parameter. The failure probability for that time interval was about 0.38. For a slope failure in which the knowledge in pore water pressure is poor, the uncertainty in pore water pressure may dominate the analysis [9]. The probability density during the rainfall will present the "degree of belief" to estimate the time of slope failure.

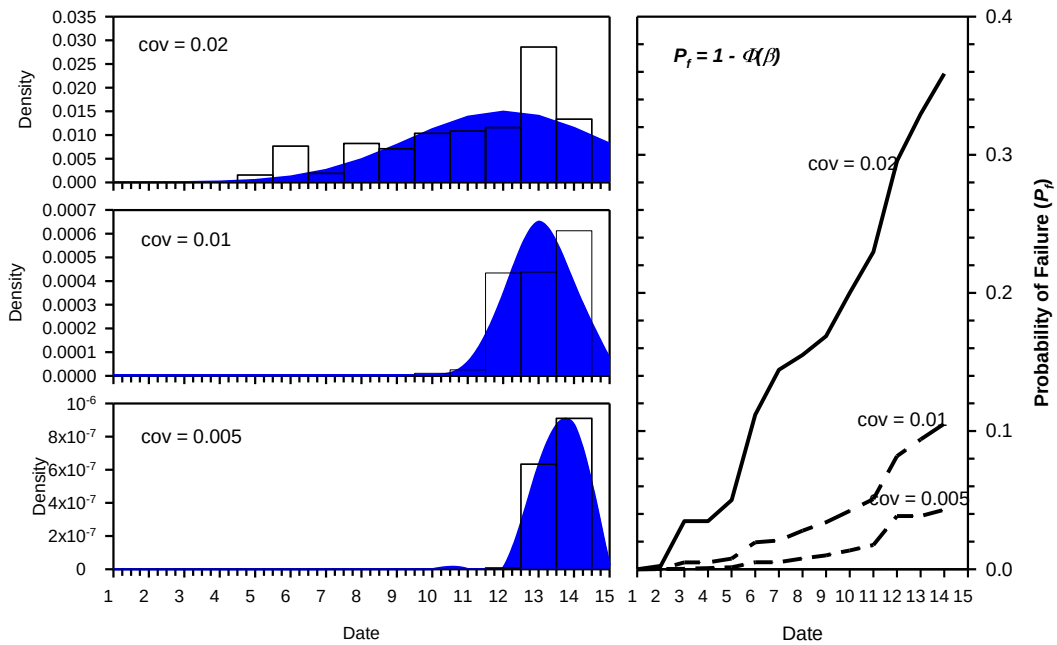

Figure 5 Distribution of failure occurrence and failure probability with the time of daily rainfall

Table 2 The statistical properties of *pdf* to determine the day of failure

Rainfall pattern	*cov* input parameter	Estimated time of failure (day)		Maximum Probability of failure (P_f)
		Mean, μ	Variance, σ^2	
5 minutes	0.02	9.725	7.305	0.37
	0.01	11.785	1.007	0.16
	0.005	12.659	0.300	0.05
Hourly	0.02	10.321	5.680	0.37
	0.01	12.241	1.148	0.16
	0.005	13.217	0.289	0.04
Daily	0.02	12.043	7.294	0.38
	0.01	13.051	0.871	0.11
	0.005	13.582	0.253	0.05

3.2 Impact of variability the input variables

The simulation in this study is based on random sampling of the input variables. The effect of variability of the input parameter is evaluated using three different coefficients of variance. A large coefficient of variation indicates that the uncertainty in a variable at failure is substantial in the variation of factor of safety. Hence, the calculated probability of performance function is also a variable. Figure 6 presents the variation of the failure probability with various *cov* of the input parameter. The relationship shows clearly that the failure probability tends to increase with the increases in *cov* value of the input parameter. The failure probability is affected by the variability of the input parameter. El-Ramly et al. [10] explained that the variability of input parameter was more contributed by spatial variability of the soils, rather than statistical sources of uncertainty such as sparse data or the use of empirical correlations and factors. While Zhang et al. [9] stated that the factor of safety changed considerably because of the contribution the greatest uncertainty in the probability distribution of the parameter. This condition is valid if the parameters to be updated are not correlated in the prior distribution.

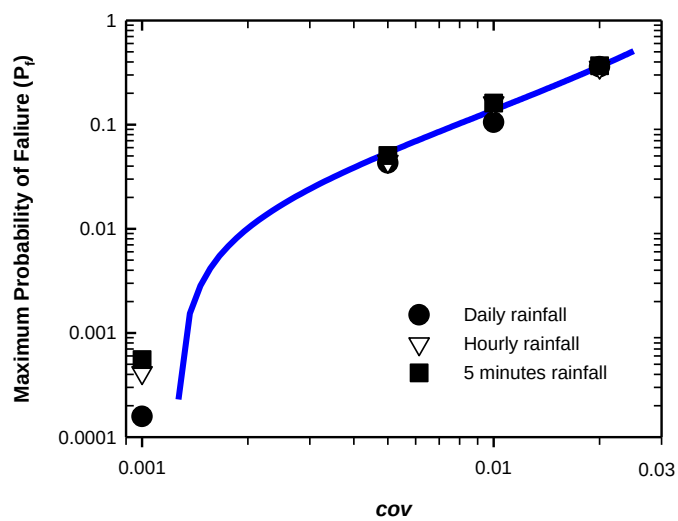

Figure 6 Relationship between failure probability and *cov*.

4. Conclusion

Based on this presentation, the slope failure can be estimated to be occurred between 9 to 13 September 2011 that depends on the rainfall patterns and variance of the input parameter. The results show that the maximum failure probability for the given input parameter was about 0.36 – 0.38 due to the rainfall recorded at the site. The failure probability tends to increase with the increases in *cov* value of the input parameter. The failure probability is affected by the variability of the input parameter. The probability density during the rainfall will present the "degree of belief" to estimate the time of slope failure. The use of a combination of probabilistic and deterministic slope analyses provided a more efficient framework for the investigation and design of remedial measures for the Doi Inthanon park slide in Northern Thailand. However, a probabilistic based back-analyses method need to be developed to obtain an acceptable input parameter at the site.

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