Influence of the spatial variability of hydraulic parameters on rainfall-induced landslides

Thanh Son Nguyen[1,2] and S. Likitlersuang[3]

[1] Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand.
[2] Department of Civil Engineering, Faculty of Engineering, Mien Trung University of Civil Engineering, Phu Yen, Vietnam.
[3] Centre of Excellence in Geotechnical and Geological Engineering, Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand.

ABSTRACT

The effect of rainfall-induced landslides is usually characterised by hydraulic parameters of soil such as saturated permeability (k_s) and soil water characteristic curve (SWCC). The main objective of this paper is to investigate the influence of spatial variability of hydraulic parameters on slope stability of unsaturated soil during rainfall infiltration. The spatial variability of k_s and van Genuchten parameters (a, n) are simulated by random field theory using the Cholesky decomposition technique. An infinite unsaturated soil slope model is employed for stability analysis. A transient seepage analysis is conducted by random finite element method (RFEM) to obtain the pore water pressure distribution. Next, a stability analysis is performed to indicate the failure mechanism of slope. A numerical procedure for a probabilistic analysis of slope is performed based on Monte Carlo simulation. The results show that the failure probability of slope is highly influenced by the spatial variability of SWCC.

Keywords: Random field, Probabilistic analysis, Permeability, Soil water characteristic curve, Rainfall infiltration, Slope stability.

1 INTRODUCTION

In recent years, several research have studied the influence of spatial variability of hydraulic parameters on slope instability due to rainfall infiltration. Fenton and Griffiths (2008) conducted steady state seepage analysis with spatially random saturated permeability. Srivastava et al. (2010) implemented the influence of spatially variable permeability properties on steady state seepage condition and slope stability. Santoso et al. (2011) presented a probabilistic framework for evaluating unsaturated soil slope stability under rainfall infiltration by modelling the saturated hydraulic conductivity. Cho (2014) discussed various failure patterns of weathered residual soil slope caused by the spatial variability of saturated hydraulic conductivity in the rainfall infiltration of an infinite slope model. The results of these research studies indicated that the saturated permeability had an important role for seepage and slope stability analysis. Recently, Nguyen et al. (2017) and (2018) employed case studies of rainfall-induced slope failure to validate the effect of spatial variability of soil shear strengths and root cohesion due to infiltration.

This research presents an extension of the original work from Cho (2014), in which the saturated permeability and soil water characteristic curves fitting parameters are incorporated in the probabilistic analysis of rainfall-induced landslides. The random field of hydraulic parameters are modelled by Cholesky decomposition and Monte Carlo simulation (MCS). The SEEP/W module of Geo-Studio (2012) is used to perform the distribution of pore water pressures. An infinite slope model is adopted to investigate stability analysis of rainfall-induced landslides.

2 INFINITE SLOPE STABILITY ANALYSIS UNDER RAINFALL CONDITION

2.1 Seepage analysis

The governing equation for one-dimensional flow in saturated-unsaturated soil is given by

$$\frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z}\right) + q = \frac{\partial \theta}{\partial t} \qquad (1)$$

where z is the depth of soil layer (m), h is the total pressure head (m), k_z is the hydraulic conductivity in the vertical direction (m/h), θ is the volumetric water content, q is the applied flux boundary (m/h), and t is time (h).

The volumetric water content and the hydraulic conductivity are defined based on the van Genuchten model (van Genuchten, 1980)

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left[1 + (ah)^n\right]^m} \qquad (2)$$

$$k_z = k_s S_e^{1/2}\left[(1 - S_e^{1/m})^m\right]^2 \qquad (3)$$

where S_e is the effective water saturation, θ_r is the residual volumetric water content, θ_s is the saturated volumetric water content, k_s is the saturated permeability (m/h), and a, n, m are the fitting parameters (m = 1-1/n).

2.2 Infinite slope stability

The infinite slope stability model (Fig. 1) is adopted to analyse the rainfall-induced landslide (Lu and Godt, 2008; Li et al. 2013); therefore, the factor of safety of infinite slope can be expressed as

$$FS = \frac{c' - u_w tan\phi'}{(\gamma_d + \theta\gamma_w) zsin\beta cos\beta} + \frac{tan\phi'}{tan\beta} \quad (4)$$

where c' is the effective cohesion, ϕ' is the effective angle of internal friction, u_w is the pore water pressure, γ_d is the dry unit weight of soil, γ_w is the unit weight of water, z is the depth of soil column, and β is slope angle.

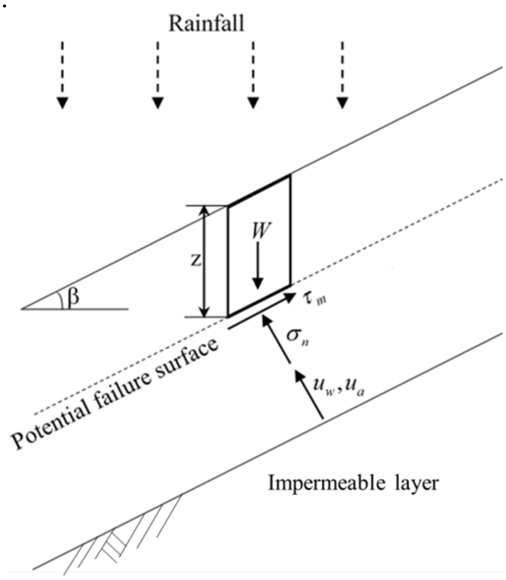


Fig. 1. Infinite slope model for stability analysis

3 PROBABILISTIC ANALYSIS

3.1 Random field model

The spatial variability of k_s and van Genuchten parameters (a & n) are simulated by random field theory using the Cholesky decomposition technique and Monte Carlo simulation (MCS). The details of this approach can be found in Fenton and Griffiths (2008). Table 1 summarises statistical characteristic to generate spatial variability of hydraulic parameters.

Table 1. Statistical characteristic of hydraulic parameters

Parameters	μ	cov	l (m)	$\rho_{a,n}$
k_s (m/s)	3 x 10^{-6}	1.0	0.5 ≤ l ≤ 16	-
a (kPa^{-1})	0.149	1.0		- 0.33
n	1.289	0.14		
θ_r	3.58 x 10^{-4}	-	-	-
θ_s	0.358	-	-	-

3.2 Failure probability

The failure probability can be obtained based on the factor of safety. Since Eq. (4) includes large variability of parameters and is strongly non-linear function; therefore, the MCS was adopted to calculate the failure probability

$$P_f \approx \frac{1}{n_M} \sum_{i=1}^{n_M} FS_i \quad (5)$$

where n_M is the number of realisations, the estimated failure probability of a slope is equal to the number of FS, which is less than 1.0 divided by the total number of realizations.

4 ANALYSIS AND RESULTS

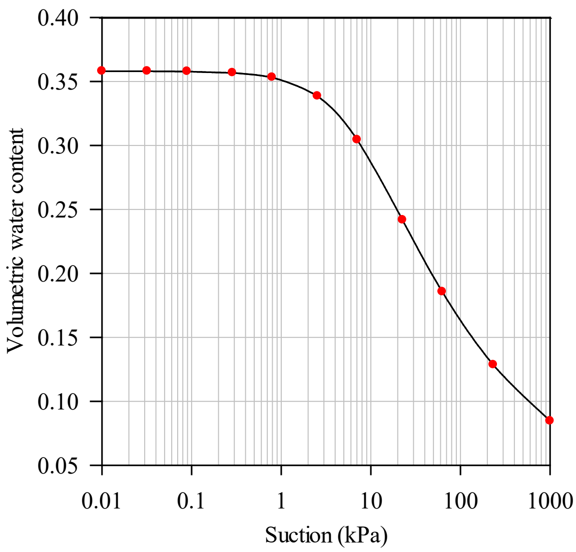
4.1 Deterministic analysis

A hypothetical slope with a 2.0 m thick weathered granite soil layer above the bedrock (Cho 2014) was adopted in this paper. The SWCC (Fig. 2a) was obtained through a pressure plate test, and the hydraulic conductivity function (Fig. 2b) was predicted using Eq. (3). The analysis was conducted for an initial suction of 20 kPa through the depth. Constant rainfall intensity of 3x10^{-6} m/s, equal to the saturated permeability, was assigned as a unit flux boundary in order to simulate the heavy rain that causes the slope failure. The seepage analysis results were used as inputs to the stability analysis. The soil properties used to calculate the factor of safety are presented in Table 2.

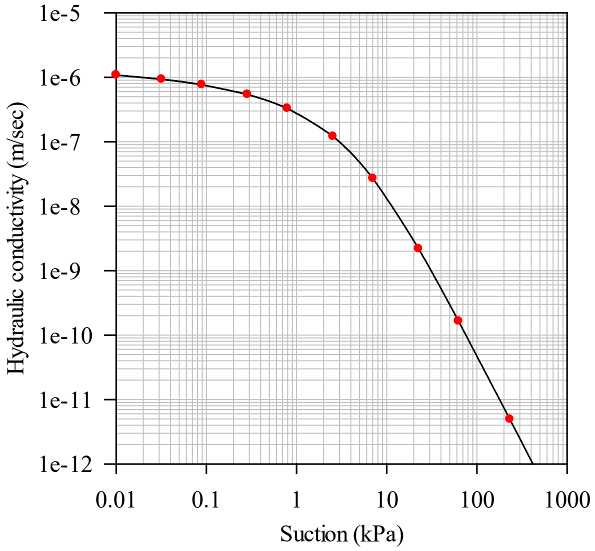
Table 2. Soil properties used for slope stability analysis

Parameters	Value
γ_d (kN/m^3)	16.0
c' (kPa)	5.0
ϕ'(°)	32
β (°)	40

The results of the deterministic analysis are shown in Fig. 3. Fig. 3a shows the distribution of pore water pressures over times which rapidly increase at the beginning of rainfall. The pore water pressures increase with depth at 6, 12, and 18 hours of rainfall, and no positive pore water pressures is generated in the soil layer. However, when rainfall intensity remains after 24 hours, the pore water pressures reach to the positive value at the ground surface and increase with depth. Fig. 3b shows that the factor of safety varies with depth for the different durations of rainfall. It can be seen that by increasing pore water pressures with depth, the factor of safety first decreases rapidly, increases slightly, and then decreases again for the case of 6, 12, and 18 hours rainfall. However, the factor of safety decreases continuously with depth for the case of 24 hours rainfall since the pore water pressure correspondingly increases as seen Fig. 3a. The factor of safety less than 1.0 appears at approximately 0.5 m depth below ground surface.



a) Soil water characteristic curve



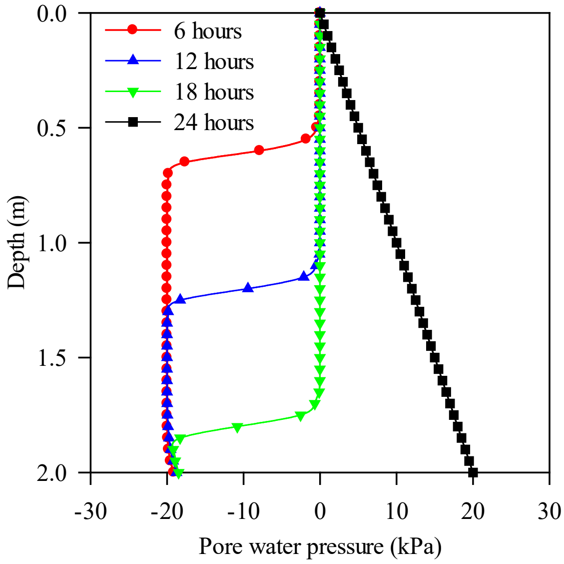
b) Hydraulic conductivity function

Fig. 2. Hydraulic soil properties for analysis

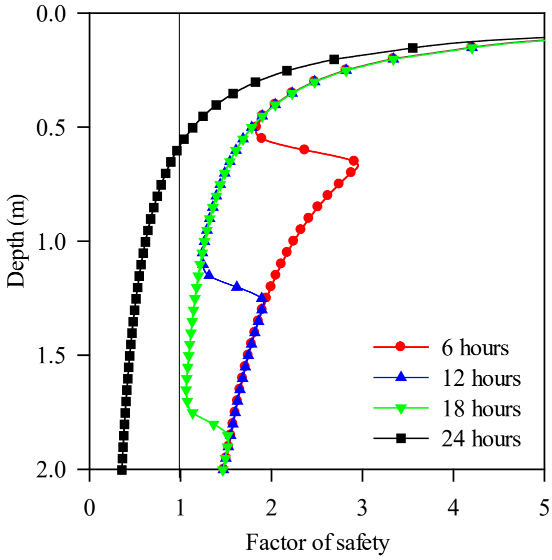
4.2 Probabilistic analysis

To analyse the failure probability of slope, the statistical characteristic of hydraulic parameters are defined as seen Table 1 (Phoon et al. 2010; Cho 2014). The domain of the slope is divided into sub-layers with a size of 0.05 m in vertical direction, including 40 sub-layers. The 1,000 realisations are conducted in various values of hydraulic parameters which generated by Cholesky decomposition technique.

Figs. 4a and b show distribution of critical depths for typical random field of k_s and a & n, respectively. The critical depths distribute from 0.7 to 2.0 m depth. As seen Fig. 4a, about 57% of critical depth developed at the base of slope considering k_s, while only about 21% of critical depth takes on the base considering a & n and about 40% of critical depth occurs from 0.8 to 1.2 m depth. This indicates that k_s is a permeability parameter related to saturated soil condition occurring the deep soil layer, while a & n are fitting parameters related to unsaturated soil condition occurring the shallow soil layer.



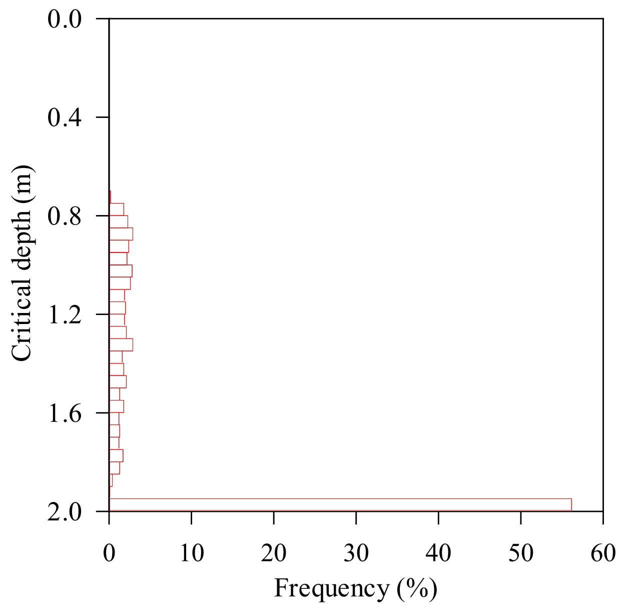
a) Distribution of pore water pressure with depth



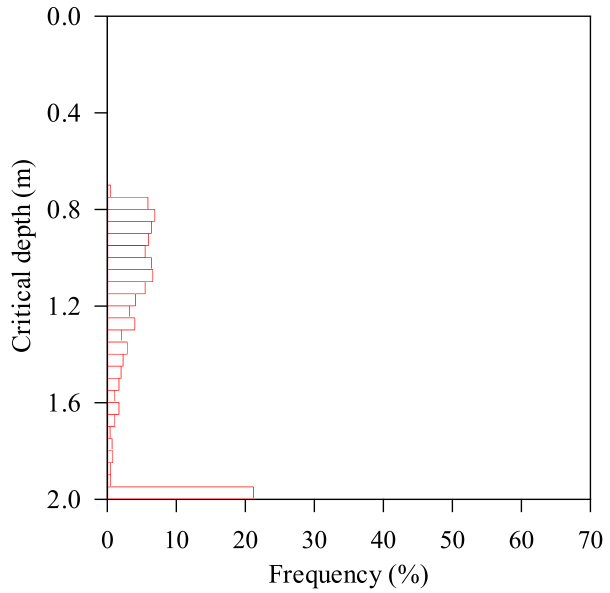
b) Distribution of factor of safety with depth

Fig.3. Results of deterministic analysis

The failure probabilities obtained by random field k_s and a & n are provide in Fig 5. The results indicate that the curves of failure probability estimated from the MCS for the various correlation lengths exhibit different trends. For considering k_s, the failure probability decreases with correlation lengths between 0.5 and 8.0 m, and no longer changes with lager values. While the failure probability increases with correlation length between 0.5 and 8.0 m, and is stable with the lager value considering a & n. The failure probability considering a & n is more than that considering k_s when correlation length is more than 3.0 m. Based on the results in Fig. 5, random field a & n appear to be more important than random field k_s in considering spatial variability of hydraulic parameters.



a) Considering k_s



b) Considering a & n

Fig 4. Distribution of critical depths

5 CONCLUSION

The paper extends the work of Cho (2014) in order to show that the hydraulic parameters exhibit an important role on failure probability analysis of slope stability due to rainfall. The critical depths mainly occurred at the base of slope considering k_s, while the critical depths considering a & n distributed the shallow depth of soil layer. The random field a & n predicted a higher failure probability than the random field k_s for the lager correlation length. The trends of failure probability are different, in which they decrease and increase with respect to random field k_s and a & n, respectively. This seems to be the finding from this study that the spatial variability of random field a & n highly influences on failure probability of slope with the modelling of seepage analysis.

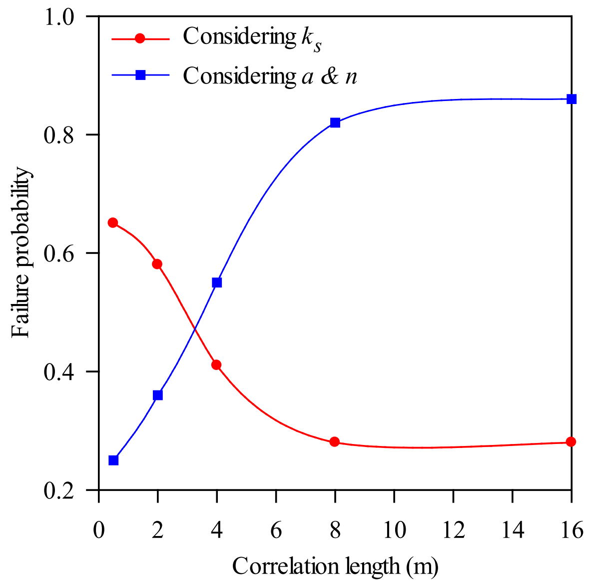


Fig 5. Effect of correlation length on failure probability.

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