

Full Length Research Paper

Effect of soil water retention model on slope stability analysis

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Understanding of the relationship between volumetric water content (θ) and soil capillary pressure (ψ), and between unsaturated hydraulic conductivity K and ψ is important in the analysis of rainwater infiltration into soil and its effect to slope stability. These relationships are known as the water retention curve and the hydraulic conductivity function, respectively. Much soil water retention-hydraulic conductivity models have been proposed such as Brooks-Corey (BC), van Genuchten (VG) that were derived based on empirical fitting curve, and Lognormal (LN) distribution model derived based on soil pore radius distribution. In this study, numerical simulations were performed using the three models to estimate the extent of rainwater infiltration into an unsaturated slope; the formation of a saturated zone, and the change in slope stability. Comparisons were made in terms of soil moisture, water movement phenomena in a soil slope, and the slope stability characteristic. The results of the numerical simulation shows that although BC, VG and LN models have different value of initial condition, the outcome of soil moisture content, water movement and slope stability characteristic are very similar during rainstorm event.

Key words: Soil hydraulic properties, water retention-hydraulic conductivity mode, slope stability analysis.

INTRODUCTION

Soil water retention curve and hydraulic conductivity function are necessary to describe the physical phenomenon of water behavior characteristic in unsaturated soil. The soil water retention curve is defined as the relationship between volumetric water content, θ and soil capillary pressure ψ while the hydraulic conductivity function is the relationship between unsaturated hydraulic conductivity K and ψ . Many soil water retention-hydraulic conductivity model have been proposed such as Brooks - Corey (BC) (Brooks and Corey, 1964) and van Genuchten (VG) (van Genuchten, 1980) model that were derived base on empirical fitting curve, and Lognormal (LN) (Kosugi, 1996) distribution model based on soil pore radius distribution. The models which are not derived based on soil pore radius distribution actually cannot be effectively used to analyze moisture characteristics in connection with the soil pore radius distribution (Kosugi, 1996).

The mechanism of rainwater infiltration causing instability of slope had been analyzed and reviewed in many paper (Mukhlisin et al., 2006, 2008; Mukhlisin and Taha, 2009; Ray et al., 2010; Pradhan and lee, 2009). The mechanism is as follows: Rainwater infiltration into soil increases the degree of saturation (decreases the negative pore water pressure), hence decreases the shear strength and increases the probability of slope failure. The accuracy in predicting the moisture content of soil will have significant effect on the factor of safety because negative pore water pressure has significant effect in changing the strength properties of soil. Thus, it is important to choose the compatible soil hydraulic properties model in employing to the slope stability analysis.

Numerical simulations were performed in this study using three soil-hydraulic properties models (that is, BC, VG and LN) to estimate the extent of rainwater infiltration into an unsaturated slope, the formation of a saturated zone, and the change in slope stability. The performances of these models were analyzed in terms of soil moisture, water movement phenomena and a slope

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stability characteristic in a soil slope.

THEORETICAL BACKGROUND

Two-dimensional unsaturated flow equation for soil water

According to the Darcy-Buckingham equation, horizontal and vertical water flux (q_x and q_z) in unsaturated soil are expressed as follows:

$$q_x = -K(\psi) \left(\frac{d\psi}{dx} \right) \tag{1}$$

$$q_y = -K(\psi) \left(\frac{d\psi}{dz} \right) \tag{2}$$

where $K(\psi)$ is the hydraulic conductivity as a function of capillary pressure ψ . The equation for continuity of water is expressed as

$$\frac{\partial \theta}{\partial t} = - \left(\frac{\partial q_x}{\partial x} + \frac{\partial q_z}{\partial z} \right) \tag{3}$$

where t is time. Substituting Equations (1) and (2) into Equation (3) yields the two-dimensional, vertical and horizontal flow equation for soil water by Richard's Equation (Richards, 1931):

$$C(\psi) \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial x} \left[K(\psi) \frac{\partial \psi}{\partial x} \right] + \frac{\partial}{\partial z} \left[K(\psi) \frac{\partial \psi}{\partial z} \right] + \frac{\partial}{\partial z} K(\psi) \tag{4}$$

where $C(\psi) = d\theta/d\psi$ (cm^{-1}) is the water capacity function defined as the slope of the soil water retention curve. Solving Equation (4) requires the use of models for soil water retention and hydraulic conductivity.

Soil hydraulic models

The three soil hydraulic properties model used in this study to solve Equation (4) is described in the following. Brooks and Corey in 1964 proposed that the effective saturation S_e is expressed as a power function with respect to matric pressure head ψ :

$$S_e = (\psi_{BC}/\psi)^\lambda \quad \psi < \psi_{BC} \tag{5}$$

$$S_e = 1 \quad \psi \geq \psi_{BC} \tag{6}$$

where ψ_{BC} [cm] is the bubbling pressure and λ [-] is dimensionless soil characteristic parameter (Brooks and Corey, 1964).

Based on Mualem model for relative hydraulic conductivity model K_r [-]. $K_r = K/K_s$ where K_s [cm/s] is saturated hydraulic conductivity, the relationship $K_r - \psi$ for BC model is written as

$$K_r(\psi) = (\psi_a/\psi)^{2+(2+l)\lambda} \quad \psi < \psi_a \tag{7}$$

$$K_r(\psi) = 1 \quad \psi \geq \psi_a \tag{8}$$

Another widely used model which is derived based on empirical fitting curve is van Genuchten model. Van Genuchten (1980) suggested that

$$S_e = \left\{ 1 + (\alpha_v |\psi|)^n \right\}^{-m} \tag{9}$$

where α_v [cm] and n ($n > 1$) [-] represent empirical parameters and m is related to n by $m = 1 - 1/n$. The relative hydraulic conductivity model for VG model is written as

$$K_r(\psi) = \frac{\left[1 - (\alpha_v |\psi|)^{n-1} \left\{ 1 + (\alpha_v |\psi|)^n \right\}^{-m} \right]^2}{\left\{ 1 + (\alpha_v |\psi|)^n \right\}^{ml}} \tag{10}$$

In 1994, Kosugi proposed a new model of soil water retention known as the Lognormal model (LN) (Kosugi, 1994), which was developed by assuming a lognormal soil pore size distribution. This model was modified in year 1996 (Kosugi, 1996). The effective saturation of LN model is expressed as

$$S_e(\psi) = Q \left[\ln(\psi/\psi_m)/\sigma \right] \tag{11}$$

where σ a dimensionless parameter corresponding to the standard deviation of log-transformed soil pore radius, ψ_m is the matric pressure head related to median pore radius, and Q denotes the complementary normal distribution function defined as

$$Q(x) = (2\pi)^{-0.5} \int_x^\infty \exp(-x^2/2) dx \tag{12}$$

The expression of K_r in term of S_e and ψ are (Kosugi, 1999):

$$K_r(\psi) = Q^\alpha \left(\frac{\ln(\psi/\psi_m)}{\sigma} \right) Q \left(\frac{\ln(\psi/\psi_m)}{\sigma} + \beta\sigma \right) \tag{13}$$

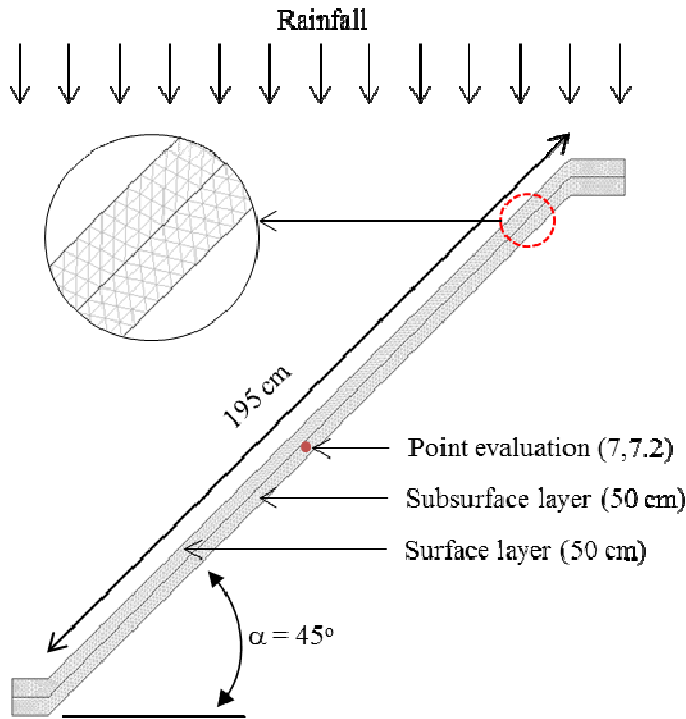


Figure 1. The schematic geometry of slope and the discretizing of system.

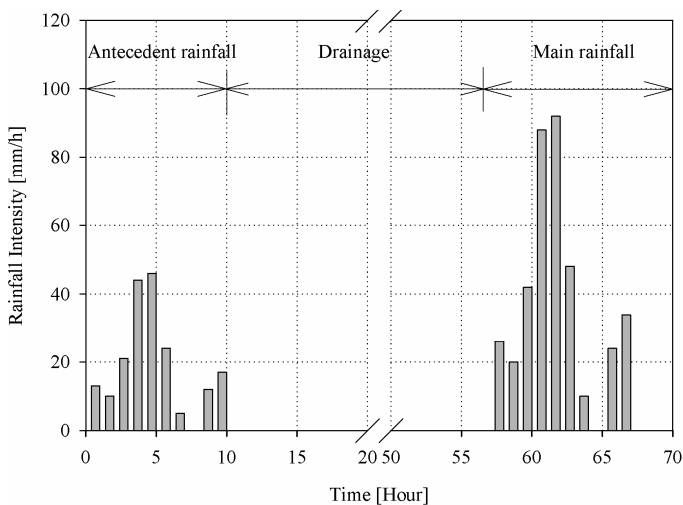


Figure 2. Rainfall intensity

Slope stability analysis with strength reduction technique

In this study, the effect of negative pore water pressure to the stability of a slope was analyzed by employed shear strength reduction technique (SRT). In this analysis, the soil is defined by five parameters, that is, friction angle ϕ , cohesion c_f , Young's modulus E , Poisson's ratio ν and unit weight γ .

The basic idea of this analysis is reducing the shear-strength parameters of soil until the solution of computation stress distribution is non-convergence. The soil strength parameters c_f and ϕ_f used in FEM procedures are defined as the actual shear strength parameters c_i and ϕ divided by a shear strength reduction factor F_t .

$$c_f = c_i / F_t \quad (14)$$

$$\phi_f = \arctan(\tan(\phi) / F_t) \quad (15)$$

The safety factor value can be found when the value of factor F_t will just cause the slope fail (Griffiths and Lane, 1999), therefore $FS = F_t$.

NUMERICAL STUDY

In this study, two step analyses, that is, pressure-head and static analysis was performed. These two analyses were conducted by employing a commercial product, COMSOL Multiphysics v3.4 and Matlab. Pressure-head analysis was conducted to solve the Richard's equation by calculating the pore water pressures distribution, while static analysis was used to compute the safety factor by solving the distribution of the effective stress of a slope.

Soil properties and initial conditions

The slope is assumed to have two soil layers (that is, surface and subsurface layers). Detail explanation of a schematic geometry is as depicted in Figure 1. A no-flux condition was applied in the left and right boundary. The seepage face boundary was applied in top surface geometry. The bottom boundary was assumed as an interface with bedrock. The slope has 45° of inclination and each layer has 50 cm of thickness. The geometry was discretized by triangular mesh as much as 3280 number of elements. For exporting pore water pressure and water content, the data was evaluated at point evaluation in 7 and 7.2.

Pressure-head analysis

Regarding to solving a Richard's equation in pressure-head analysis, the seepage face boundary (top surface geometry, Figure 1) in COMSOL multiphysics was defined as a general mixed boundary condition (Chui and Freyberg, 2009). In the right and bottom boundary was defined as a Zero flux/symmetry. While, in the left boundary was defined as pressure head boundary condition which as an interface with a head 1 m.

For hyetograph data, localized torrential rainfall in the mid-southern region of Kyushu in Japan triggered a large-scale debris flow along the Atsumari-gawa River in Hougawachi, Kumamoto Prefecture on July 20, 2003 was used in this study. The total rainfall, peak rate, and event duration were established at 379 mm, 91 mm/h, and 10 h, respectively (Figure 2). To establish the initial conditions for the numerical simulation, an antecedent rainfall (that is, 50% reduced the main hyetograph in Figure 2) was applied and whole slope had a constant matric pressure value, ψ_{ini} was fixed at -100 cm. Drainage duration was set as along as 48 h and resulting matric pressure distribution within the whole slope was used for initial condition for the main simulation. A number of data set on the hydraulic properties of weathered granite soils was obtained from

Table 1. Soil hydraulic parameters.

Parameter		Subsurface	Surface
	θ_s [cm ³ /cm ³]	0.456	0.621
	θ_r [cm ³ /cm ³]	0.242	0.370
	ESP	0.214	0.251
	K_s [cm/s]	7.9e-3	32.2e-3
LN	ψ_m [cm]	-33.8	-14.3
	σ	0.98	0.92
VG	α_v [1/cm]	0.051	0.113
	m	0.465	0.49
BC	ψ_{BC} [cm]	-12.936	-6.134
	λ	0.869	0.9607

Mukhlisin et al. (2006). The soil hydraulic parameter and fit parameters value for BC, VG and LN are described in Table 1. While the soil water retention curve for surface and subsurface layers are described in Figure 3. The figures show that VG and LN have similar soil water retention curve, while for BC a bit differ in inflection point.

Static analysis elasto-plastic material

Soil material properties data such as Young's modulus, Poisson's ratio, friction angle and specific weight are required for the analysis of slope stability using shear strength reduction technique. Analysis of slope stability was performed by assuming the dependency of cohesion C_i [Pa] to the negative pore water pressure u_i [Pa] as represented by using equation which was proposed by Sammorri (1994):

$$C_i = C_i' - \chi u_i \tan \phi \quad (18)$$

$$\chi = \text{MIN} (1, 1.25 (\theta/\theta_s)) \quad (19)$$

where c_i' is cohesion under saturated condition and the degree of saturation θ/θ_s . The value of C_i' is assumed as 2 kPa and friction angle ϕ is 35°, value that were used by Suzuki (Suzuki, 1991) as typical values for a weathered granite soils. Other material properties for slope stability analysis that was used in this study are Young's modulus, E is 20 MPa, Poisson's ratio ν is 0.3, and specific weight γ is 10.5 kN/m³.

RESULTS AND DISCUSSION

Comparison study as effect of three models water retention (that is, BC, VG and LM) were performed in this study. Changing of moisture water content, pore water pressure and safety factor were analyzed in three slope angle conditions during rainstorm event.

Soil water infiltration analysis

Figure 4 shows the pore water pressure after 48 h rainfall

infiltration as predicted by BC, VG, and LN models. As shown in Figure 4, the pore water pressure distribution in the whole slope soil differs among the three models. BC model predicts that the unsaturated condition zone wider than the LN and VG models, while the VG model has almost similar result with LN model.

Figure 5 shows the calculation of slope stability analysis during rainstorm event or after 48 h rainfall drainage (Figure 2). The comparison volumetric water content, pore water pressure and safety factor for the three models can be seen in Figure 5 a to c, respectively. Figure 5a and b shows that during the initial stage of rainfall, the moisture soil water content and the pore water pressure value for VG model were greater among other model. Approaching to saturated condition, the LN model result is more similar result with VG model than BC model. Figure 5a shows that VG model has greater initial volumetric moisture water content comparing the other model, while BC has the lower one. Greater moisture soil water content resulted greater the pore water pressure. However the difference of pore water pressure for the three models is not significant during the major rainstorm (Figure 5b).

Regarding the accuracy of predicting the moisture content near at saturated condition, van Genuchten and Nielsen (1985) concluded that VG model performed better than BC model because the $\theta-\psi$ curve has an inflection point. Comparing the three model, Kosugi (1996) mentioned that the models which are not derived based on soil pore radius distribution, nor do they emphasize the physical significance of their empirical parameters are not necessarily suitable models for evaluating the effect of the soil pore radius distribution on the water movement in the soil.

Soil slope stability analysis

Figure 5c shows the comparison safety factor yielded

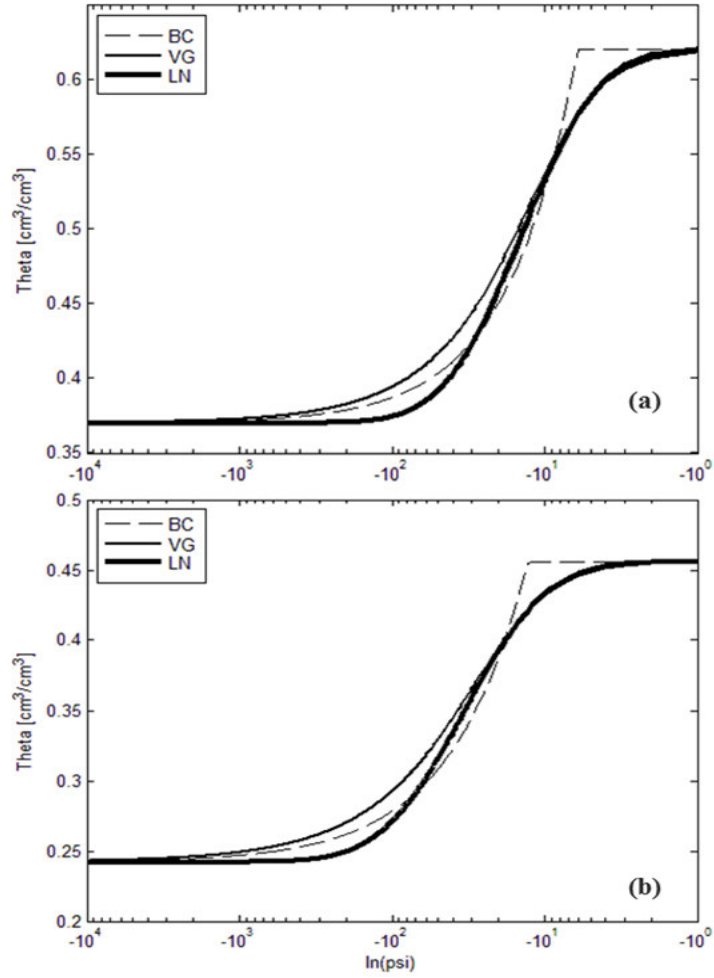


Figure 3. Soil water retention curve for (a) surface and (b) subsurface layer.

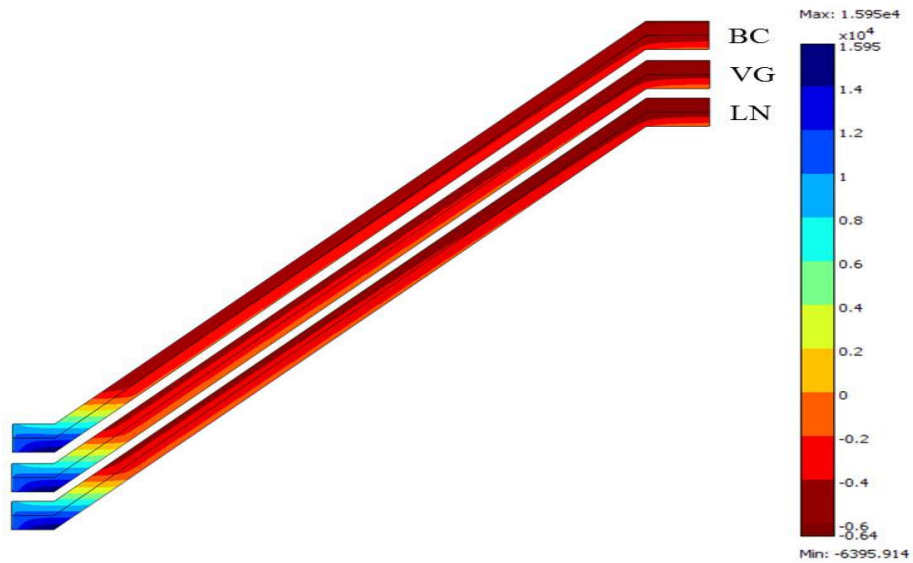


Figure 4. Distributions of pore water pressure (Pa) for initial conditions after 48 h drainage.

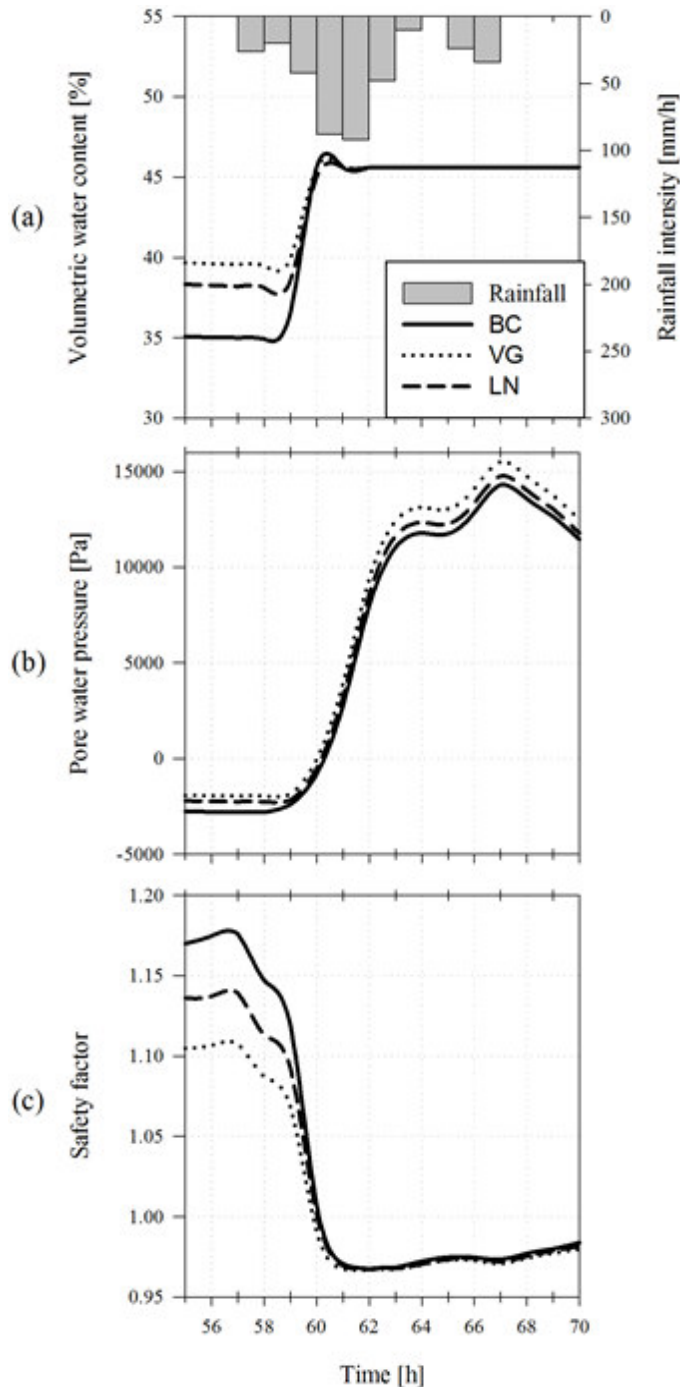


Figure 5. Comparisons of the three soil-hydraulic models; (a) volumetric water content (b) pore water pressure, and (c) safety factor value at the point of evaluation (Figure 1).

from analyses using BC, VG, and LN models. As mentioned previously, VG model has greater initial volumetric moisture water content comparing the other model, while BC has the lower one. Greater moisture soil water content resulted in greater pore water pressure, thus lower factor of safety was expected. However the different of pore water pressure for the three models are

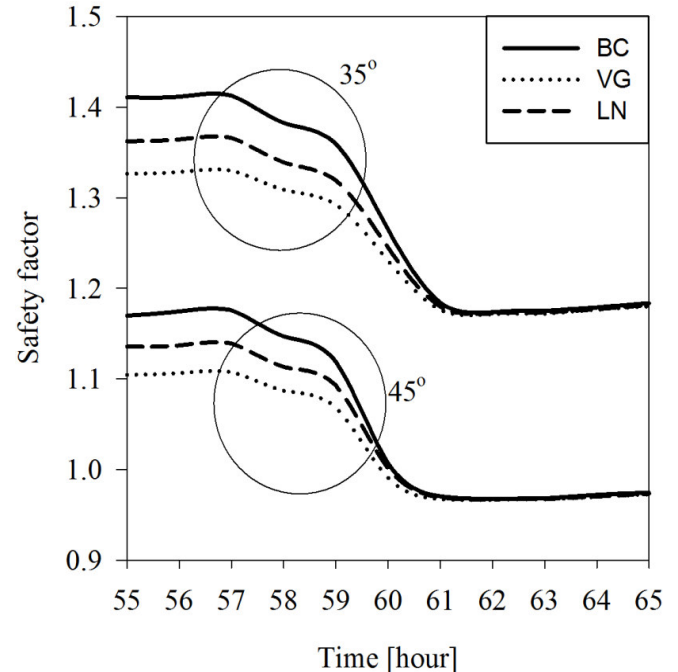


Figure 6. Comparison of safety factor as effect of 35 and 45° slope angle.

not significant during the main rainstorm (Figure 5b). Therefore, although BC model has greater safety factor in initial condition, the safety factor predicted from the three models converges during and after major rainfall. The results show that rainstorm has significant effect on increasing pore water pressure and decreasing safety factor of the slope soil.

All three models show a different safety factor when the slope is in the unsaturated condition. BC model shows a higher value 0.035 from LN model. Meanwhile, VG model turned out to be lower 0.035 than LN model. Approaching to the saturated condition, VG model resulted a slope failure was faster than the other two models (see at hour 60th). The entire model has similar result in the timing of slope failure.

After major rainfall, the slope is still in saturated condition in a while. At some locations, although the pore water pressure has decreases, the cohesion of the soil mass remains constant, that is, 2 kPa. This explains the trend of safety factor in which even 8 h after major rainfall, the safety factor did not increase significantly. The safety factor value had been increased significant at the above hour-75th (the data is not depicted in the figure).

Effect of slope angle

The effect of slope angle was studied by varying the slope angle. Two slope angles was used, that is, 35 and 45°. Figure 6 shows the variation of safety factor from the

three water retention curve model used in this study. The figure shows the consistency of effect of different soil hydraulic properties models where BC model has a higher safety factor while VG model has a lower safety factor than LN model. Increasing of slope angle by 10° decreases the safety factor by about 0.2 for all models.

Conclusion

A numerical simulation was carried out to investigate the performance of three soil hydraulic models, that is, Brooks - Corey (BC), van Genuchten (VG) and Lognormal (LN) on rainfall induced slope instability. In this study, the effect of different soil hydraulic properties models was analyzed. The results show that the position of LN model always in between of BC and VG models in term of changing soil moisture content, pore water pressure and safety factor during rainstorm event. Although the value of initial condition a bit different among the three models, however changing soil moisture content, pore water pressure and safety factor are very similar during saturated condition. This study showed that the shape of S curve as result of water retention fit parameter models has effect on soil slope stability analysis, particularly during unsaturated condition.

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