ISBN No. : 978-602-17221-3-8

HIMPUNAN AHLI TEKNIK TANAH INDONESIA
INDONESIAN SOCIETY FOR GEOTECHNICAL ENGINEERING (ISGE)
MEMBER SOCIEY OF INTERNATIONAL SOCIETY FOR SOIL MECHANICS
AND GEOTECHNICAL ENGINEERING (ISSMGE)

Proceedings

10th Indonesian Geotechnical Conference and 19th Annual Scientific Meeting

"Geotechnical Role in Mega Structure Construction"

Bidakara Hotel [illegible] 2015

Supported by:

Proceeding *10th Indonesian Geotechnical Conference and 19th Annual Scientific Meeting*
Jakarta - INDONESIA, 24-25 November 2015

"Geotechnical Role in Mega Structure Construction"

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Influence of the Soil-Water Retention Curve Models on the Stability of Residuals Soils Slope

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ABSTRACT: The study is focused on the investigation of effect the characterization of SWRC model and its effect on the slope stability on a simple infinite slope. The SWRC models were fitted to the laboratory test using mini tensiometer and filter paper. In particular, four unimodal SWRC models were evaluated for comparison in this study, i.e. van Genuchten model (VG), modified van Genuchten model (MVG), Brooks-Corey model (BC), and Kosugi log-normal model (KLN). The slope stability analysis was conducted in terms of Factor of Safety (FS) by applying the infinite slope model incorporating infiltration model. The infiltration model was analyzed by Richard's one-dimensional infiltration equation. The analysis resulted that The VG and KLN models produced lower estimation of safety factor than BC and MVG models. The distribution of pore water pressure varied with the SWRC models. Hence, different SWRC model contribute different FS values. The results indicate that the SWRC model shall be applied carefully since the model will have a different conclusion to the slope instability.

Keywords: rainfall, infiltration, soil water retention curve, slope stability, residual soil

1 INTRODUCTION

The mechanisms of rainwater infiltration causing slope instability had been analyzed and reviewed in many scientific works. Rainwater infiltration into the unsaturated soil increases the degree of saturation, hence affecting the shear strength properties and thus the probability of slope failure. It has been widely proved that the shear strength properties change with the soil water suction in unsaturated soils. Therefore, the accuracy to predict the relationship between soil water content and soil water suction, parameterized by the soil-water retention curve (SWRC), has significant effects on the slope stability analysis. The common method to obtain SWRC is by laboratory test by using mini tensiometer, pressure plate, and filter paper. However, sometimes, the data obtained need to be fitted to have a general equation of SWRC model. There are some SWRC models that commonly used for infiltration analysis such as van Genuchten (1980), Brooks and Corey (1964), Fredlund and Xing (1994), log-normal (Kosugi, 1996a), etc.

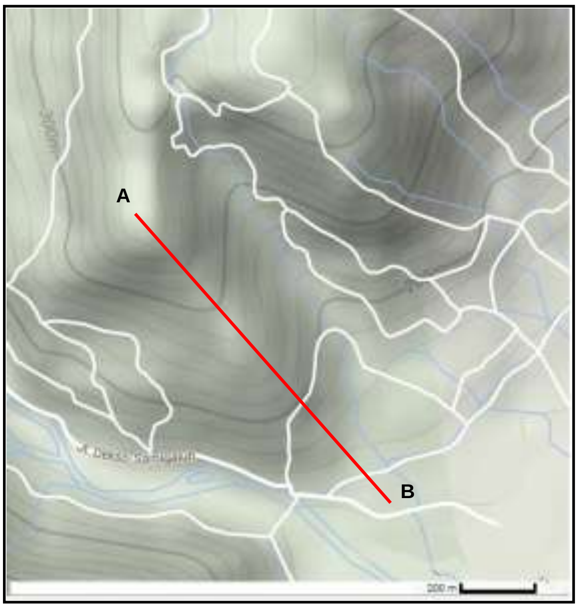
The study is focused on the investigation of effect the characterization of SWRC model and its effect on the slope stability on a simple infinite slope. The SWRC models are fitted to the laboratory test using mini tensiometer and filter paper. In particular, four unimodal SWRC models were evaluated for comparison in this study, i.e. van Genuchten model (VG), modified van Genuchten model (MVG), Brooks-Corey model (BC), and Kosugi log-normal model (KLN). The slope stability analysis is conducted in terms of Factor of Safety (FS) by applying the infinite slope model incorporating infiltration model. The infiltration model is analyzed by Richard's one-dimensional infiltration equation.

2 LABORATORY TEST AND NUMERICAL MODELING

2.1 *Slope properties and rainfall record*

In this study, the studied slope was located at Kedungrong village, in Kalibawang, Kulonprogo. The average slope angle was 22^{o}, while the steepest slope angle was about 40^{o}.

The slope was covered by red residual soil from weathered breccias. The soil thickness (*H*) and unit weight (γ_t) were 8 m and 22 kN/m^3 respectively. The basic properties of the soil are presented in Table 1, while the particle size distribution is shown in Figure 2. Based on the properties, the soil was classified into *SM*.



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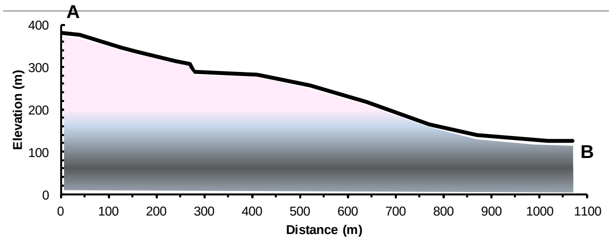

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Figure 1. (a) Topography of the study area, (b) Slope cross section.

Table 1 Properties of the soil layer

Parameter	Unit
Specific gravity, G_s	2.73
Unit weight, γ_t	22 kN/m^3
Particles size:	
Coarse grained: Gravel/sand	86%
Fine-grained: Silt/clay	14%
Liquid limit, LL	50.05%
Plasticity index, PI	19.4%

The rainfall boundary is shown in Figure 7. The precipitation was recorded from the automatic rain gauge station in Kalibawang catchment area. The saturated hydraulic conductivity (k_{sat}) of the soil was 1.0264 x 10^{-1} m/day.

2.2 *Determination soil-water retention*

In this study, soil-water retention curve (SWRC) was determined using miniature KU tensiometer (for ψ < 100 kPa) and filter paper (for ψ > 100 kPa). The filter paper method used Whatman filter paper No. 42 and its calibration curve referred to ASTM D 5298. Figure 4 and 5 presents the schematic cross section of the tensiometer and filter paper apparatus.

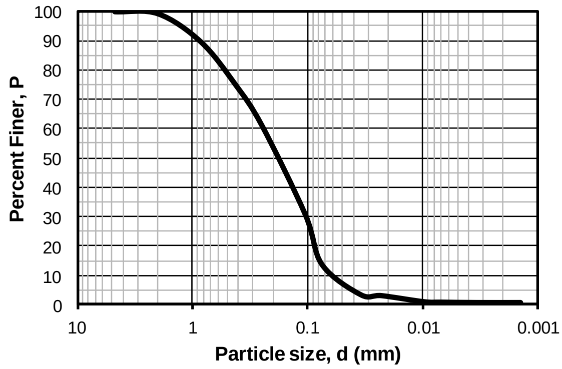


Figure 2 Particle size distribution of the residual soil sample

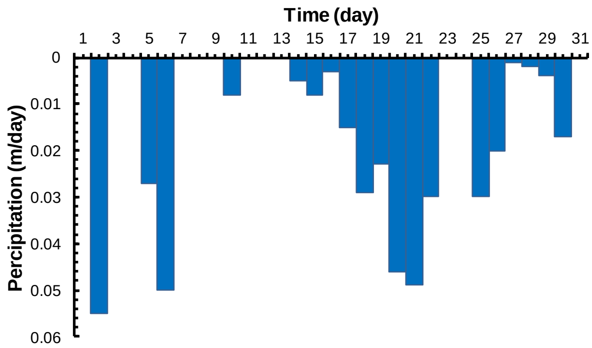
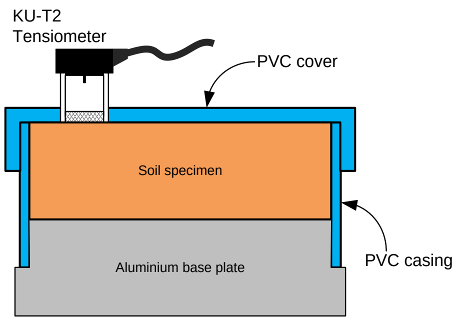


Figure 3. The daily rainfall hyetograph for the analysis



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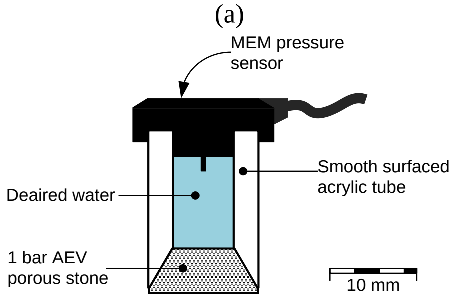


(b)

Figure 4 (a) Cross section of the SWRC test using KU tensiometer, (b) Detail of the KU tensiometer

The compacted soil about 63 mm in diameter and 20 mm thickness, were tested for Soil-Water Retention Curve (SWRC) using the approach as explained by Jotisankasa and Mairaing. (2010). The method involved gradually wetting soil sample, and during each stage suction of sample was monitored until equilibrium was reached. A minimum curing period of about 2-3 days between each increment was allowed for equilibration of the suction throughout the sample, which was carefully wrapped to prevent evaporation. Figure 6 shows the SWRC of the soils.

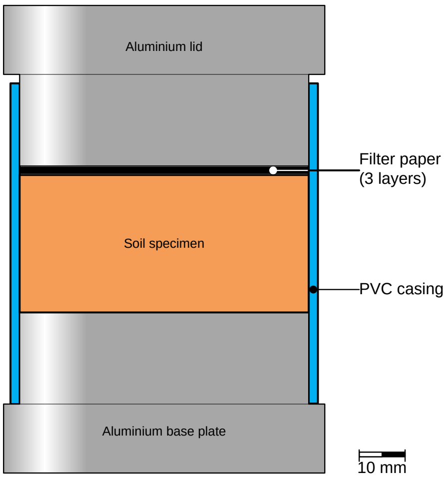


Figure 5 Schemaric cross-section of SWRC test using filter paper

2.3 *Shear strength test*

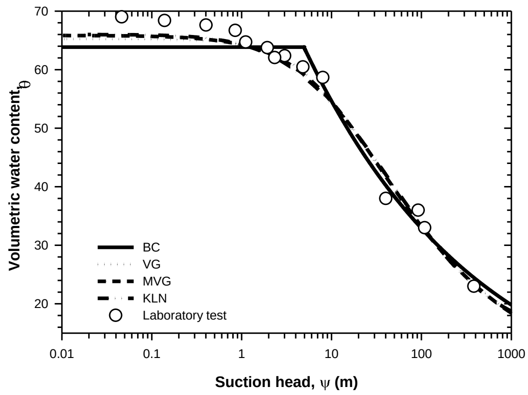
Shear strength characteristic of the soil was investigated in direct shear box. For this purpose, the samples were statically re-compacted in the laboratory to replicate closely the field condition by controlling the void ratios to be within ±5% the value of undisturbed soils. To determine the fully saturated shear strength of the soils, slow multistage-shearing direct shear tests were carried out at normal stresses of 31, 62, and 123 kPa and shearing rate of 0.05 mm/min. This rate was chosen such that no excess pore water pressure developed during shearing. The shear strength parameter was *c'* = 1.7 kPa, ϕ' = 19.6˚.

2.4 *One-dimensional infiltration model*

The one-dimensional infiltration model was solved using HYDRUS-1D code. The model was based on the one-dimensional Richards equation to simulate water movement in variably saturated media, and the equation was solved by numerical method (Šimůnek et al., 2005). The basic water movement equation was described as:

$$\frac{\partial \theta(\psi,t)}{\partial t} = \frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial \psi}{\partial z}+1\right)\right] \quad (1)$$

where ψ is the soil water pressure head, θ is the volumetric water content, t is time, z is the vertical coordinate with the origin at the soil surface (positive upward), and $K(\psi)$ is the unsaturated hydraulic function.



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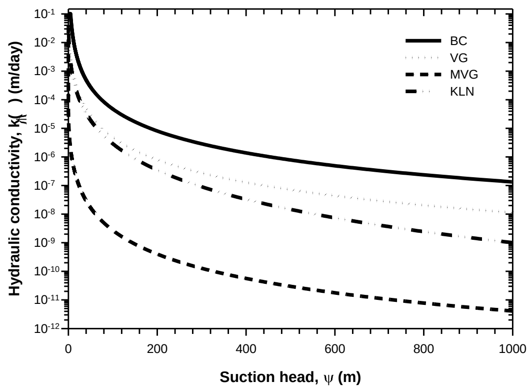


(b)

Soil hydraulic parameter

Models		θ_r	θ_s	α	n	l
BC	:	-	63.848	0.203	0.220	2.0
VG	:	-	65.248	0.127	1.262	0.5
MVG	:	6.211	65.851	0.080	1.005	0.5
KLN	:	14.933	65.997	47.49	2.112	0.5

Figure 6. (a) The soil-water retention curve, (b) Hydraulic conductivity function of the soil.

The unsaturated soil hydraulic properties, $\theta(\psi)$ and $K(\psi)$, in Equation (1) are in general highly nonlinear functions of the pressure head. The hydraulic properties can be presented using analytical models as written by Brooks and Corey (1964), van Genuchten (1980), Vogel and Císlerová (1988), and Kosugi (1996a).

Brooks and Corey Model (BC)

The soil water retention, $\theta(\psi)$, and hydraulic conductivity, $K(\psi)$, functions according to Brooks and Corey [(964) are given by Equation 2a and 2b.

$$\theta(\psi)=\theta_r+(\theta_s-\theta_r)|\alpha\psi|^{-n} \tag{2a}$$

$$K(\psi)=K_s\left[\frac{\theta(\psi)-\theta_r}{\theta_s-\theta_r}\right]^{\frac{2}{n}+l+2} \tag{2b}$$

in which θ_r and θ_s denote the residual and saturated water contents, respectively; K_s is the saturated hydraulic conductivity, α is the inverse of the air-entry value (or bubbling pressure), n is a pore-size distribution index, and l is a pore-connectivity parameter assumed to be 2.0 in the original study of Brooks and Corey (1964). The parameters α, n and l are empirical coefficients affecting the shape of the hydraulic functions.

van Genuchten – Mualem model (VGM)

The soil-hydraulic functions of van Genuchten (1980) used the statistical pore-size distribution model of Mualem [1976]. The expressions of van Genuchten [1980] are given by

$$\theta(\psi)=\theta_r+(\theta_s-\theta_r)\left[1+|\alpha\psi|^n\right]^{-m} \tag{3a}$$

$$K(\psi)=K_sS_e^l\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \tag{3b}$$

where

$$S_e=\left[\frac{\theta(\psi)-\theta_r}{\theta_s-\theta_r}\right] \tag{3c}$$

and, $m=1-1/n$ (3d)

The above equations contain five independent parameters: θ_r, θ_s , α, n, and K_s. Mualem (1976) estimated the pore connectivity parameter l in the hydraulic conductivity function was about 0.5 as an average for many soils.

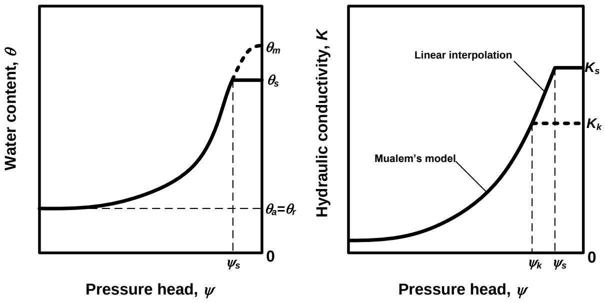
Modified van Genuchten model (MVG)

Vogel and Císlerová (1988) modified the equations of van Genuchten (1980) to add flexibility in the description of the hydraulic properties near saturation. The soil water retention, $\theta(\psi)$, and hydraulic conductivity, $K(\psi)$ are given by equation (4a) and (4b) respectively.

$$\theta(\psi)=\theta_a+(\theta_m-\theta_a)\left[1+|\alpha\psi|^n\right]^{-m} \tag{4a}$$

$$K(\psi)=K_k+\frac{(\psi-\psi_k)(K_s-K_k)}{(\psi_s-\psi_k)} \tag{4b}$$

The hydraulic characteristics contain 9 unknown parameters: θ_r , θ_s, θ_a, θ_m, α, n, K_s, K_k, and θ_k . When $\theta_a=\theta_r$, $\theta_m=\theta_k=\theta_s$ and $K_k=K_s$, the soil hydraulic functions of Vogel and Císlerová (1988) reduce to the original expressions of van Genuchten (1980). The parameters are determined as shown in Figure 7.



(a) (b)

Figure 7 (a) Schematics of the soil water retention and (b)hydraulic conductivity functions.

Kosugi lognormal model

Kosugi (1996a) suggested the lognormal distribution model for the soil hydraulic properties. Application of Mualem's pore-size distribution model (Mualem, 1976) leads to the following hydraulic conductivity function.

$$\theta(\psi)=\theta_r+(\theta_s-\theta_r)\frac{1}{2}erfc\left[\frac{\ln(\psi/\alpha)}{\sqrt{2n}}\right] \tag{5a}$$

$$K(\psi)=K_sS_e^l\left\{\frac{1}{2}erfc\left[\frac{\ln(\psi/\alpha)}{\sqrt{2n}}+\frac{n}{\sqrt{2}}\right]\right\}^2 \tag{5b}$$

2.5 *Slope stability analysis*

The methods used in traditional infinite slope analysis must be modified to take into account the variation of the pore water pressure profile that results from the infiltration process. Based on the extended Mohr–Coulomb failure criterion (Fredlund et al., 1978), the safety factor of an unsaturated soil slope with a slip surface parallel to ground surface as shown in Figure 8, can be expressed as written in Equation (6). Consider the model for the shear strength with respect to soil suction by

$$FS = \frac{c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b}{\gamma_t \cdot z_f \cdot \sin\beta \cdot \cos\beta} \quad (6)$$

$$FS = \frac{c'}{\gamma_t \cdot z_f \cdot \sin\beta \cdot \cos\beta} + \frac{\tan\phi'}{\tan\beta}\left[1 + \frac{\psi \cdot \Theta}{\gamma_t \cdot z_f \cdot \cos^2\beta \cdot}\right] \quad (7)$$

where, $$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (8)$$

Vanapalli et al. (1996), the equation can be written as in Equation (7), where FS is the safety factor of slope stability, z_f is the distance from the ground to the slip surface, c' is the effective cohesion, ϕ' is the effective friction angle, β is the slope angle, γ_t is the total unit weight of the soil, u_a is the pore air pressure, u_w is the pore-water pressure, $(u_a - u_w)$ is the matric suction, σ_n is the total normal stress, $(\sigma_n - u_a)$ is the net normal stress on the slip surface; ϕ^b is the angle defining the increase in shear strength for an increase in matric suction.

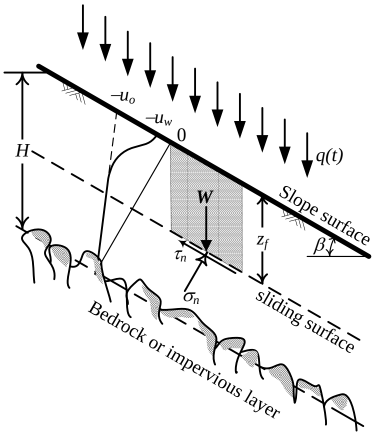


Figure 8. Schematic plot of an infinite slope and boundary conditions of unsaturated soil infiltration.

3 RESULTS

The effect of four models soil-water retention (that is BC, VG, MCG, and KLN) were compared to evaluate their performance in this study. Changing of pore water pressure and safety factor were analyzed during a month period of precipitation event.

Pore water pressure profile

Figure 9 show the changing of pore water pressure with depth for various time of rainfall. The initial suction at surface and bottom layers is 490 kPa and 410 kPa respectively. The suction decreased with the elapsed time of rainfall. The suction propagates to a deeper wetting front. Comparing pore water pressure profile in Figure 9a and 9c with Figure 9b and 9d, it can be observed that the rates of downward movement of the wetting front are comparable. The BC and MVG models have similar suction distribution profile, while the VG and KLN models show a similar suction profile. The results indicate that different SWRC model affect the pore water pressure profile. In general, the suction varies with the elapsed time of rainfall which corresponds to the rainfall intensity.

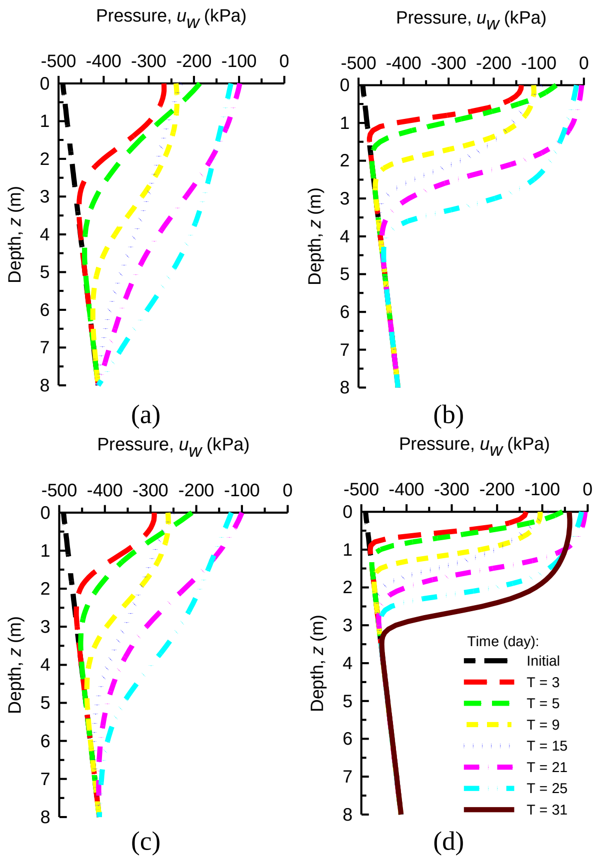


Figure 9 Pore water pressure profile, (a) BC, (b) VG, (c) MVG, (d) KLN models.

Variation in Slope stability

Figure 9b and 9d show that the deepest wetting front depth reached 5 m and 3 m for VG and KLN models respectively, while the wetting front depth goes to a deeper for the other models. Use equation 7, Figure 10 illustrates the variation of safety factor (FS) profile with the depth for various time of precipitation. At the beginning of the rainfall events, the initial safety factors at all depths of the potentially unstable soil layer are significantly higher than 100 (Fig. 10) at near ground surface, as a consequence of high suction values. The safety factor decreased with the depth. The lowest safety factor was 2.05, 1.59, 2.10, and 1.89 for BC, VG, MVG, and KLN models respectively. At the end of rainfall event, the potential sliding depth Z_f can be estimated as 5 m, 2.5 m, 7 m, and 1.7 m for BC, VG, MVG, and KLN models respectively.

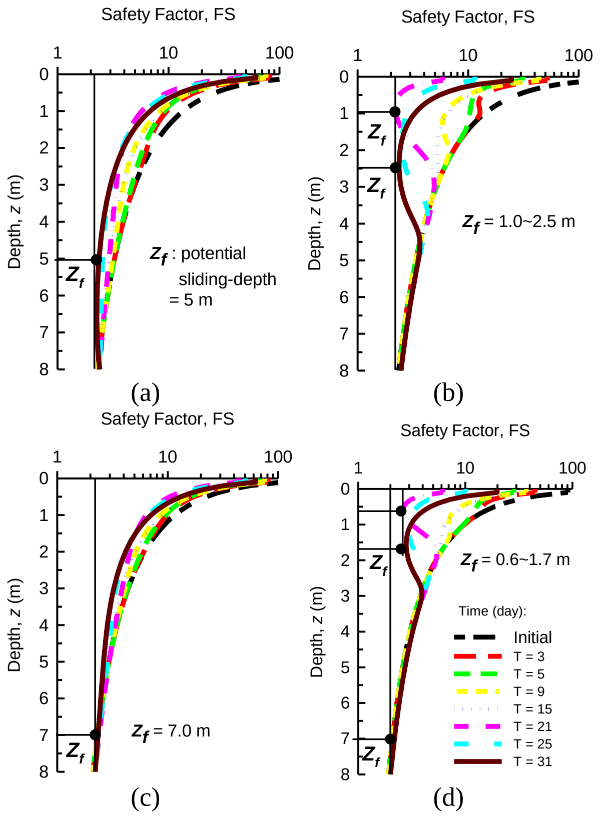


Figure 9 Saftey factor variation with depth for various elapsed time of rainfall, (a) BC, (b) VG, (c) MVG, (d) KLN models.

Figure 10 shows the variation of safety factor with the elapsed time of rainfall event for depth of failure (z_f) up to 3 m. In general, the FS of slope decrease with increasing of time of rainfall for all models. The FS value fluctuates which follow the rainfall pattern. At shallow depth failure, z_f = 1 m, modeling SWRC using VG and KLN yield a lower safety factor that the other SWRC models. A rapid change in FS was observed at shallower failure depth (Figure 10a), while the change was lesser at a deeper failure depth. (Figure 10c). Again, the modeling with VG gained a rapid decreasing of the FS at a deeper failure depth. The rapid decreasing of the FS was gained after intense rainfall at day of 6th and 21st. The lowest FS value is obtained after day of 21st after six days intense rainfall as shown in Figure 10. The results indicated that the ancedent rainfall affect the FS pattern. The characteristics was also stated in Rahardjo and Rahimi (2015).

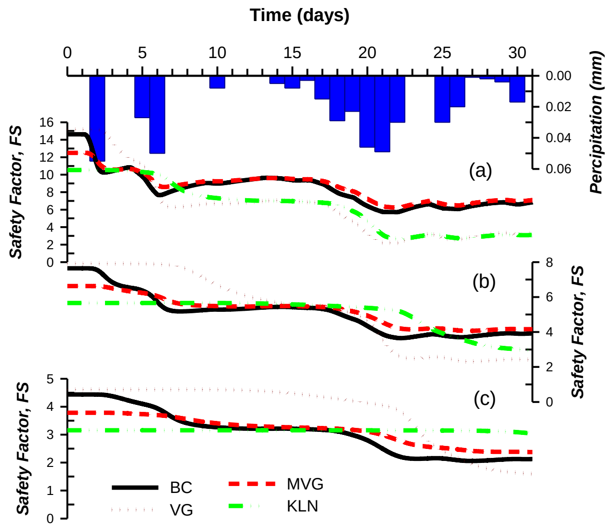


Figure 10 Variation of safety factor of the slope with the elapsed time of rainfall (a) z_f = 1 m, (b) z_f = 2m, (c) z_f = 3 m.

4 DISCUSSION

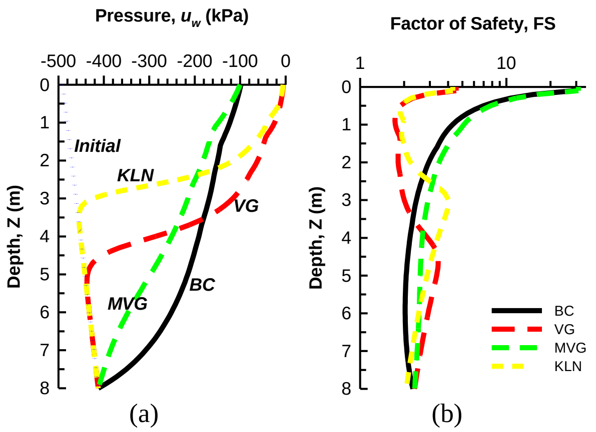
Soil–water retention curve or soil water-characteristics curve (SWCC) is a graphical relationship that shows the relationship between the amount of water in a soi, i.e. gravimetric water content w, volumetric water content θ_w or degree of saturation *S* (Fredlund and Rahardjo, 1993) and matric suction ψ. As introduced by Fredlund (2006), the entire suction range of the SWRC can be divided into three zones such as boundary effect zone, transition zone and residual zone and they are separated by air-entry value and residual suction. Zhai and Rahadjo (2013) mentioned that high variability in water content occurs in the transition zone, suggesting that more data points need to be measured within the transition zone in order to obtain a more accurate SWRC.

The wetting front depths are found sharply in VG and KLN models while the others do not show a clear wetting front depth. BC model a power function with respect to the suction which the inflection point was unclear defined. 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 θ-ψ curve has an inflection point (ψ_o). Kosugi (1996b) was shown that the VG model was analogous to the KLN model under the restriction bubling pressure ψ_c = 0, the BC model was similar to the KLN model when air entry pressure close to suction at inflection point ($\psi_c \rightarrow \psi_o$).

Comparing the four models, Kosugi (1996b) 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.

The lowest pore water pressure bound at the end of rainfall event for all SWRC models. Lee et al. (2009) mentioned the lowest bound of suction as suction envelope. The suction envelope indicated the minimum suction existed in the soil slope under various durations of extreme rainfalls. Using the lowest boundary of the pore water pressure, the redistribution of pore water pressure is shown in Figure 11a. Fourie et al. (1999) have identified the key role of suction in maintaining the stability of steep slopes. Use the suction envelope in Figure 11a, the minimum factor of safety for four SWRC models is shown in Figure 11b. The figure is alluding to conclude that the stability of slope is affected by the SWRC models applied for analysis.

The variation of FS (Figure 10) shows that different SWRC model contribute different FS values. Initial suction at slope surface was about 490 kPa. Then, the suction at surface decreases to about 4 kPa during the rainfall (Figure 12). The matric suction can be eliminated only when the ground surface moisture flux is equal to or greater than the saturated coefficient of permeability. It is the possible reason that the hydraulic conductivity function affects the pore water pressure profile. As the result, the safety factor is controlled by the hydraulic conductivity function (Rahimi et al., 2010; Rahardjo et al., 2007). It was found that the range of SWRC measurements greatly affect the estimated permeability functions. Rahimi et al. (2015) found that the effect of the range of SWRC measurements is more significant than the selected best-fit SWRC equation used. The results indicate that the SWRC model shall be applied carefully, since the model will have a different conclusion to the slope instability.



(a) (b)

Figure 11 (a) Pore water pressure envelope, (b) Boundary of factor of safety for various SWRC models.

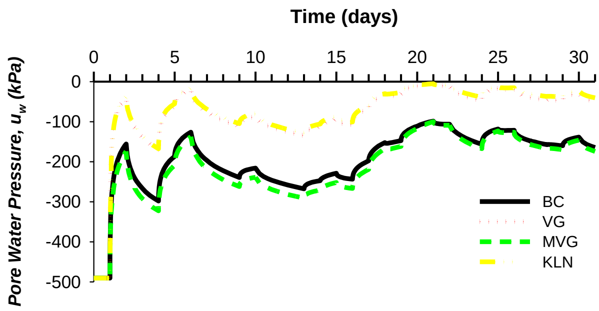


Figure 12 Variation of pore water pressure at the surface for various SWRC model

5 CONCLUSIONS

The result of this study concluded that a good expression for the SWRC is essential to combine with constitutive modeling. Comparisons between measured and modeled SWRCs proved that the models resulted different suction profiles. As consequence, the safety factor of slope was affected by the applied SWRC model. This study concluded that the VG and KLN models produced lower estimation of safety factor than BC and MVG models. Finally, the study indicated that the SWRC model shall be applied carefully, since the model will have a different conclusion to the slope instability. However, further studies should focus on the effect of hysteresis and uncertainty of the SWRC models.

ACKNOWLEDGEMENTS

The author thanks for the financial support from Ministry of Research, Technology, and Higher Education, the Republic of Indonesia under research scheme "Penelitian Hibah Kompetensi" in 2015. Support from Apiniti Jotisankasa, Ph.D., Kasetsart University, Thailand is acknowledged.

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