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Numerical Modeling of Rainfall-induced Slope Failure

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ABSTRACT

Slope failure caused by heavy rainfall is an important geotechnical concern in many countries. Geotechnical engineering properties such as soil-water characteristics, strength and stress-strain behaviors of soil as well as climate conditions have become important parameters for reliable numerical simulation of slope stability. In this study, a numerical simulation was performed by considering both the hydraulic (e.g., permeability and soil water characteristic curve (SWCC)) and a strength parameter (i.e., cohesion) to evaluate the stability of unsaturated slopes during rainfall with the finite difference method (FLAC2D). A slope located in Namyangju, Korea was chosen as a testbed. Thus, the geometry, hydraulic and geotechnical properties of the site were used as the input parameters in the numerical modeling. The results suggest that different slope failure modes are generated by different rainfall intensities. The effects of soil permeability, SWCC, and cohesion on the slope stability were also investigated with parametric studies. The permeability and SWCC properties have important roles in the ground infiltration behavior of unsaturated soils, which results in a generation of excess pore water pressure. Moreover, the results showed that cohesion has a significant effect on the safety factor of unsaturated slopes.

1. INTRODUCTION

Slope stability analysis of unsaturated soils is widely used (Fredlund and Rahardjo, 1993; Tsaparas et al., 2002). The role of negative pore water pressure (matric suction) has been considered significant in slope instability induced by heavy rainfall. The mechanism that leads to a slope failure is the loss of negative pore water pressure when rainwater starts infiltrating into unsaturated soils. To have a better

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understanding of the relationship between the mass/volume of water in a soil and the energy state of the water phase, the soil-water characteristic curve (SWCC) is required. To model the water infiltration in an unsaturated soil, besides the SWCC parameter, rainfall scenarios (i.e., rainfall intensity and duration), permeability of the soil and initial conditions within the soil are parameters necessary for numerical modeling of rainfall infiltration in an unsaturated slope. There is a large volume of published numerical studies describing the effects of those parameters such as the role of antecedent and major rainfall (Tsaparas et al., 2002; Lee and Kim, 2013), permeability and initial pore water pressure (Tsaparas et al., 2002; Cai and Ugai, 2004); porosity and soil thickness (Mukhlisin et al., 2008). However, the role of cohesion has not been mentioned in those studies.

A slope located in Namyangju, Korea was chosen as a testbed. Thus, the geometry, hydraulic and geotechnical properties of the site were used as input parameters in the numerical modeling. The results suggest different slope failure modes are generated by different rainfall intensities. Moreover, the effects of soil permeability, SWCC, and cohesion on the slope stability were also investigated through parametric studies. The permeability and SWCC have important roles in the ground infiltration behavior of unsaturated soils which results in an generation of excess pore water pressure. Moreover, soil cohesion also is a significant governing factor in the safety of unsaturated slopes.

2. THE SITE OF INTEREST

The target slope with a height of 30m (Fig.1) is found in Namyangju city, Korea. The highest monthly rainfall intensity, with an average value of 9.28e-2cm/h, mainly occurs in July (Fig.2). Rainwater formed by this rainfall intensity is insufficient to saturate the slope soil considerably, and to cause the soil movement. However, in a study performed by Jung (2015), 35 typhoons affected the Korean Peninsula from 1999 – 2009, which brought heavy rainfall. For example, on September 12, 2003 the Maomi storm had heavy rainfall with a intensity higher than 5.08 cm/h (Ji and Julien, 2005). On July 27, 2011, heavy rainfall with an intensity of 11.25 cm/h over 16 hours (Jeong et al., 2015) caused 151 landslides along Umyeon Mountain (Yune et al., 2013). Thus, there is a possibility that it could happen again, and the Namyangju mountainous area could be at risk of such typhoons.

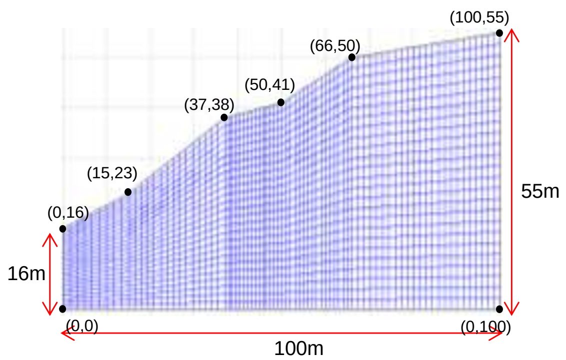

Figure 1. Representative cross-section of the researched slope

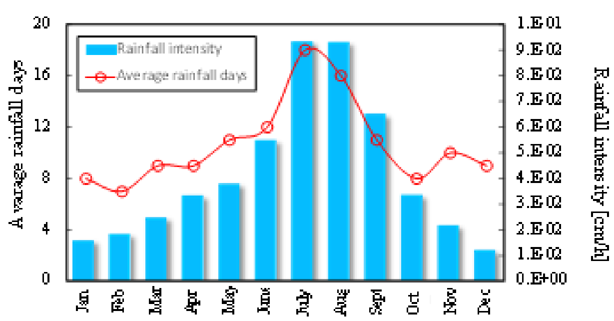

Figure 2. Monthly rainfall infiltration in Namyangju

According to the Unified Soil Classification System, the weathered granite soil of this area can be classified as SM, which is distributed along the slope surface with varying depths of 2 ~ 10 m. Table1 lists the physico-mechanical properties of the soil and SWCC parameters of this area. In this study, the slope was assumed to be a homogenous slope with a weathered granite soil formation.

Table 1. Physico-mechanical properties of the soil and soil-water properties

Soil	**Properties**		
Soil	Dry unit weight	[t/m^3]	1.48
	Eff cohesion	[kPa]	0
	Eff friction angle ϕ	[^{o}]	28.3
	Young modulus	[Pa]	8.4E7
	Position ratio	[-]	0.32
	Initial saturation	[-]	0.5
	Saturated permeability	[cm/h]	1.08
	Porosity	[-]	0.1
Soil – water properties	α	[m^{-1}]	1.91
	n	[-]	1.503

3. THE PARAMETRIC STUDY

The study includes both infiltration analyses and slope stability analyses, which can be simulated simultaneously with the FLAC2D- two-phase flow configuration. Van Genuchten's equation (1980) was used to investigate how rainwater will affect the soil properties of the slope under different rainfall conditions. The shear strength reduction method for unsaturated soils was used to estimate the effects of the amount of rainwater infiltrating into soil on the safety factor (FOS) of the slope.

3.1 Water flow through an unsaturated soil

In FLAC, a set of closed-form equations formulated by van Genuchten (1980), which is based on the Mualem capillary model, was used to represent the hydraulic characteristics of unsaturated soils as follows:

$$S_e = \frac{S_w - S_r}{1 - S_r} = \left[\frac{1}{1+(\alpha\varphi)^n}\right]^m \quad , \tag{1}$$

$$K(\theta) = K_s K_r = K_s S_e^{1/2}\left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2, \tag{2}$$

where S_e is the effective saturation; S_w is the saturation; S_r is the residual saturation; α, n and m are the curve fitting coefficients (m = 1 – 1/n and n >1), and K_s and K_r are the saturated and relative permeability.

Furthermore, to implement the variability in the amount of rainwater infiltration into the soil along the slope surface due to a different slope angle, an adjust-discharge FISH, which is available in FLAC, was edited.

3.2 Shear strength reduction method for an unsaturated soil

Using Bishop's effective stress (1959), the shear strength equation for an unsaturated soil adopted in the stability analysis is written as follows:

$$\tau_{max} = (\sigma - u_a)\tan\phi' + \chi\,(u_a - u_w)\tan\phi' + c, \tag{3}$$

or by Fredlund and Rahardjo (1993)

$$\tau_{max} = (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b + c, \tag{4}$$

where χ is defined by Vanapalli et al. (1996)

$$\chi = (S_w - S_r) / (100 - S_r), \tag{5}$$

with S_w, S_r, u_a, u_w and σ denoting the saturation, residual saturation, air pressure, water pressure and total stress, respectively.

In the calculation of the safety factor of an unsaturated slope with the shear strength reduction technique, a series of simulations were performed with the reduced shear strength parameters C^{trial} and ϕ^{trial} defined as follows:

$$\mathrm{C}^{\mathrm{trial}} = \frac{1}{\mathrm{F}^{\mathrm{trial}}}\mathrm{C}, \tag{6}$$

$$\emptyset^{\mathrm{trial}} = \left(\arctan\frac{1}{\mathrm{F}^{\mathrm{trial}}}\tan\emptyset\right), \tag{7}$$

where F^{trial} is a trial factor of safety.

Initial shear strength reduction F^{trial} is set to be sufficiently small to guarantee that the system is stable. Then, F^{trial} increases incrementally until a collapse takes place. A critical factor at which failure occurs is taken to be the FOS.

4. VARIABLE PARAMETERES IN THE ANALYSIS

The variable parameters in this analysis were the distribution of rainfall intensity, saturation, coefficient of permeability, SWCC parameters and cohesion of soil.

4.1 Rainfall pattern

Different rainfall intensities were assumed in this study. To estimate the infiltration capacity of the soil, a rainfall intensity that is equal to the permeability of the soil was used, and a rainfall intensity that is similar to the current highest rainfall intensity in Korea was selected (11 cm/h). Rainfall was applied along the slope for 110 hours, and the FOS was estimated at 10 hour increments.

4.2 Saturated coefficient of permeability

Two different permeabilities with respect to saturation were used to investigate their effects on the infiltration process and on the development of positive pore water pressure over time. Of the permeabilities used, one was an experiment value of 1.08 cm/h, and the other was 10 times higher than the experiment data. The latter was approximately the highest rainfall intensity used in this study (10.8 cm/h)

4.3 SWCC parameters

SWCC provides a conceptual understanding between the mass/volume of water in a soil and the energy state of the water phase. From the SWCC experiments, the values of α, n and θ_r are determined and used as input properties for the unsaturated soil in FLAC. The n value is used to calculate the a parameter in Van Genuchten equation, and α (m^{-1}) represents the reference pore pressure Po (kPa). Another fitting parameter is the residual saturation θ_r which relates to the effective saturation used in the calculation of the pore pressure. Sillers (1997) more recently defined residual water content as the water content where the soil-water goes from being held within the soil primarily by capillary action to soil-water being held in the soil primarily by adsorptive forces. In this study, to estimate the effects of this parameter, the FOS obtained values of zero and 0.11 were used, for which zero residual saturation is a special case because the saturation is equal to the effective saturation.

4.4 Saturation

To estimate the effects of the saturation degree on the threshold of slope instability with respect to time, different values for saturation were assumed. These estimated values were 0.4, 0.5 and 0.6, in which 0.5 was an experimental value.

4.5 Cohesion

Cohesion is understood as a force that holds soil particles together. For unsaturated soils, cohesion is the total of the effective cohesion from interlocking, physical, chemical actions and the apparent cohesion controlled by inter-particle force or suction and surface tension (Sako et al, 2001; Cho and Santamarina, 2001). To see the effect of the chosen cohesion on a reasonable prediction of slope failure under rainfall using numerical modeling, five values were assumed. The assumed cohesion values were 0, 5, 10, 20, and 30 kPa.

5. RESULTS AND ANALYSIS

5.1 Effect of permeability

Fig.3 shows the change in pore pressure with depth after 20 hours of 1.08 cm/h rainfall. Two different values of permeability, k1 (1.08 cm/h) and k2 (10.8 cm/h), caused different behaviors of the soil under rainfall. In this case, the cohesion and saturation of the soil were assumed to be 10 kPa and 0.5, respectively. As the permeability was increased, more amounts of water infiltrated into the slope. For a soil with a higher permeability value, positive pore pressure significantly developed near the surface of the slope; meanwhile, there was an insignificant decrease in matric suction for the lower permeability. The figure enables us to estimate the wetting band formed after a given time of rainfall. A wetting depth of approximately 6 m could be estimated for the slope subjected to the rainfall of 1.08 cm/h. The effect of rainwater infiltration on the safety factor of the slope is shown in Fig.4. For a low saturated coefficient of permeability, the negative pore pressure within the slope decreased much more slowly and any changes could only be noticed near the ground surface. This is similar to the result mentioned in a study by Tsaparas et al. (2002). Therefore, the steadily drop of

FOS could be seen in the case with the low permeability. On the other hand, a dramatic decline of FOS was seen in the higher permeability soil subjected to rainfall.

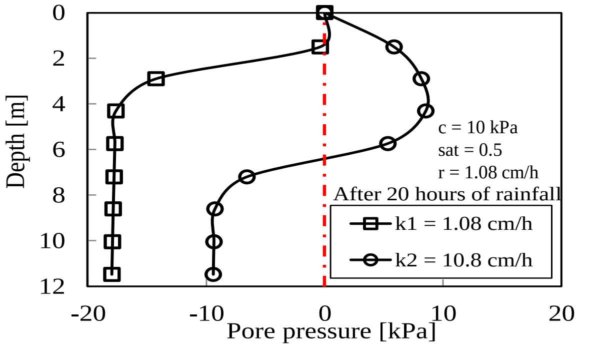

Figure 3. Change in pore pressure after 20 hours of 1.08 cm/h rainfall

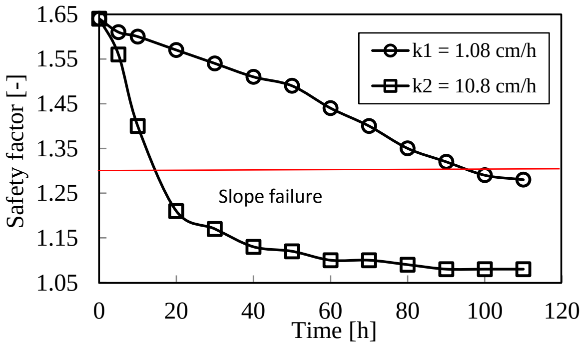

Figure 4. Decrease in safety factor over rainfall time

5.2 Effect of rainfall intensity

To estimate the effect of the rainfall intensity on the FOS of the slope, the soil with low permeability (k1 = 1.08cm/h) was considered. The slope was subjected to different rainfall intensities: r1 = 1.08 cm/h and r2 = 10.8 cm/h. From Fig.5, it can be seen that heavier rainfall causes the slope instability faster through a quicker decrease in the FOS. This phenomenon again can be explained in terms of the change in the negative pore pressure due to rainwater infiltration. The heavier the rainfall was, greater amounts of water penetrated into the slope, which in turn led to a considerable increase in the pore pressure.

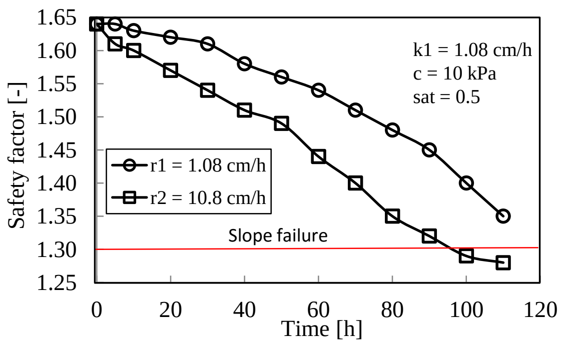

Figure 5. Decrease in safety factor subjected to varying rainfall intensities

5.3 Effect of initial saturation and residual saturation

The saturation of the soil is a primary factor that affects the initial FOS value of a slope. If the coefficient of permeability and the rainfall intensity affect the drop in the FOS during rainfall, then the saturation directly determines the stability threshold of a slopebefore rainfall starts. For different degrees of saturation, different FOSs were obtained. However, the change in FOS during rainfall followed a similar tendency for either a low or high rainfall intensity (Figs.6 and 7). A similar effect could be seen when the residual saturation was considered. When considering the residual saturation, a smaller effective saturation was obtained. The existence of residual saturation suggests that the effective saturation influences the pore pressure distribution and in turn the FOS obtained. The slope was more stable for the lower effective saturation (Fig.8)

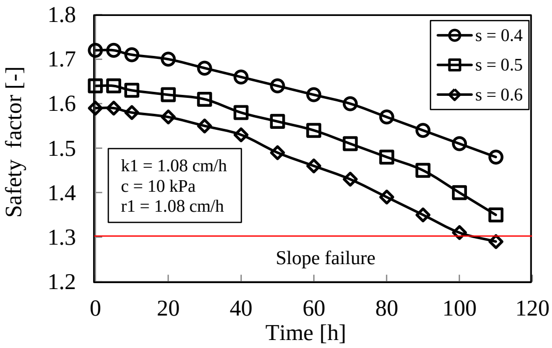

Figure 6. Decrease in the safety factor with a rainfall of 1.08 cm/h

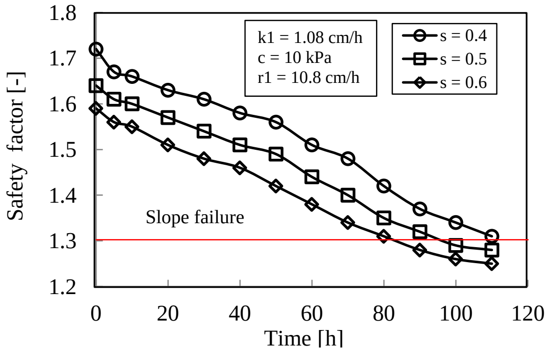

Figure 7. Decrease in the safety factor with a rainfall of 10.8 cm/h

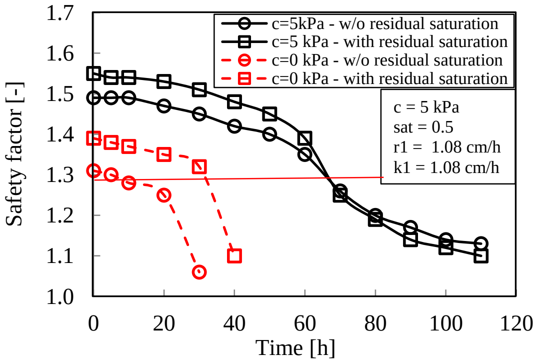

Figure 8. Effects of residual saturation on the safety factor

5.4 Effect of cohesion

A soil with a saturation of 0.5, permeability of 1.08 cm/h and varying cohesion subjected to a rainfall of 1.08 cm/h was considered to investigate the effects of cohesion. Fig.9 shows the decrease in the FOS during rainfall. Under the given rainfall intensity, zero cohesion resulted in instability of the slope after 5 hours with the FOS smaller than 1.3 Meanwhile, it took 70 hours of rainfall to trigger the slope with 5 kPa cohesion to failure. For the higher cohesion, the rate of decrease in FoS was not as drastic. To confirm whether the change in pore pressure plays an important role in this case, the pore pressure distribution after 70 hours was analyzed (Fig.10). Interestingly, for all cases of cohesion, there was a similar distribution of pore pressure. It indicates that the amount of water penetrating into soil for all cases was the same. Fig.11 shows the slope failure surface after 70 hours of rainfall for the corresponding cohesion values. Furthermore, the analysis showed that after 100 hours of rainfall (1.08 cm/h) on the slope, the FOS obtained for 20 kPa and 30 kPa cohesion was still higher than 1.8 to our surprise.

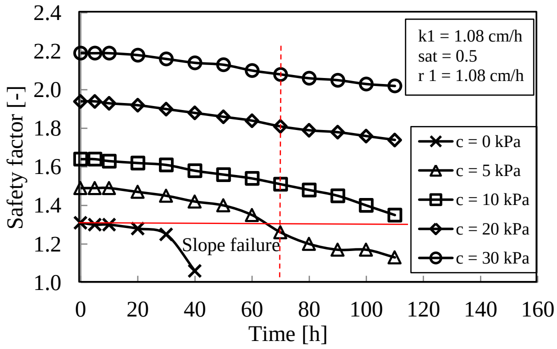

Figure 9. Effects of effective cohesion on safety factor

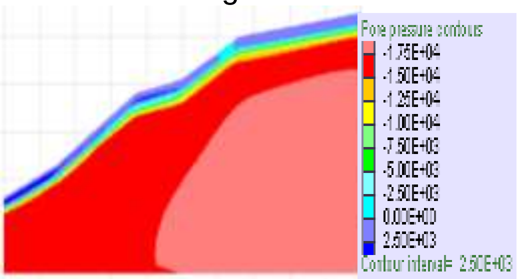

Figure 10. Pore water pressure distribution after 70 hours of rainfall (1.08 cm/h)

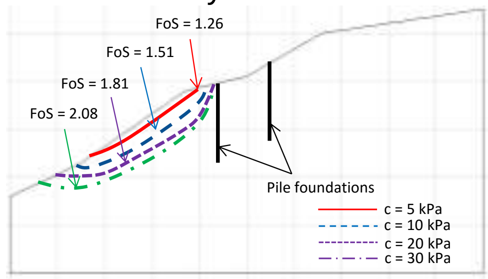

Figure 11. The slope failure mechanisms after 70 hours of rainfall (1.08 cm/h)

6. DISCUSSIONS

The results of this study indicate that water flow through an unsaturated slope is very sensitive to the magnitude of the permeability that controls the rate at which precipitation will infiltrate into the soil. A soil with higher permeability will enable a high rate of flux or rainwater to penetrate deeper into the soil. With rainfall time, the amount of rainwater that can infiltrate into the soil decreases due to a decrease in the permeability capacity of the soil. Furthermore, a high intensity rainfall applied to a low permeability soil has a small influence on the decrease in negative pore pressure. Effective saturation or the relation between initial saturation and residual saturation controls the negative pore pressure distribution at the initial condition. It is undeniable that all those mentioned parameters control the FOS through the change in negative pore pressure.

In FLAC, the relation between matric suction and water content by the SWCC parameters is considered; therefore, the apparent cohesion value will be automatically updated as the FoS calculation process is carried out. The high cohesion results in the high FOS which indicates the safety threshold of the slope. However, these results of the FOS do not reasonably reflect the effect of rainwater infiltration on unsaturated slope instability. From section 5.4, after 100 hours of rainfall (1.08cm/h), the FOS obtained was still higher than 1.8 for the slope with a cohesion of 20 kPa and 30 kPa. The shear strength of the slope was overestimated. The reason for that is the initial effective cohesion taken was too high causing the initial high FoS. Meanwhile, the soil-water characteristics and hydraulic properties of the soil were the parameters determining the change in the pore pressure of the soil or the apparent cohesion during rainfall. Therefore, if the effective cohesion used for the simulation was too high, the effect of the apparent cohesion on the total cohesion used to calculate the FOS during rainfall might not be significant. In other words, there was no large correlation between the shear strength parameter and the hydraulic parameters of the soil used for the infiltration analysis. Due to the major effect of the effective cohesion on the FOS, as the failure surface is shallow, it is suggested that the value for the effective cohesion should be zero or very small in numerical simulations to avoid overprediction in the FoS. Fell et al. (2005) suggests that the initial effective cohesion should be 0 ~ 10 kPa for the peak strength, and 0 or 1 kPa for residual and softened strengths.

7. CONCLUSIONS

Numerical modeling was used to investigate the influence of several hydrological parameters and the shear strength parameter on rainfall-induced slope instability for a typical residual soil slope in Korea. The slope gradient was 3.3:1 with a height of 30 m. The parameters were permeability, rainfall intensity and duration, saturation and cohesion of soil.

The analyses showed the role of saturation, permeability, and cohesion in controlling the initial FOS and in the infiltration process. Saturation, permeability, and rainfall intensity have a role in water infiltrating into the soil and in the negative pore pressure distribution. As the permeability becomes higher, the larger amounts of rainwater infiltrate into soil and in turn, increase the positive pore pressure. Serval simulations with different cohesion values showed that a very small or zero value for the effective cohesion should be chosen to avoid overprediction of the FOS. Furthermore, there are significant interactions among all the parameters (i.e., rainfall intensity, rainfall distribution and saturated coefficients of permeability), which highlight the need for proper and realistic choices for the hydraulic properties of a soil when performing a transient analysis with an unsaturated slope. In addition, choosing a cohesion value as an initial property of the unsaturated slope should be taken into account for a more accurate prediction of a shallow slope failure during rainfall.

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