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:

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

or by Fredlund and Rahardjo (1993)

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

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

$$\chi = (S_w - S_r) / (100 - S_r), \quad (5)$$

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:

$$C^{trial} = \frac{1}{F^{trial}} C, \quad (6)$$

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

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.

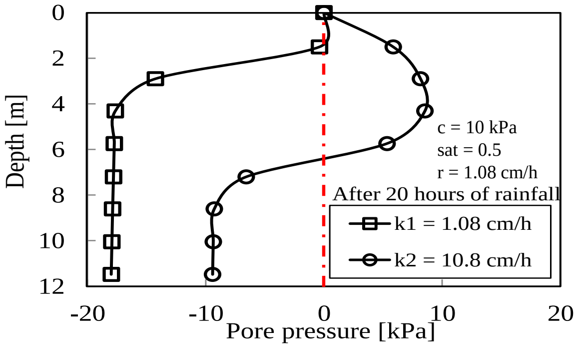

Figure 3. Change in pore pressure after 20 hours of 1.08 cm/h rainfall

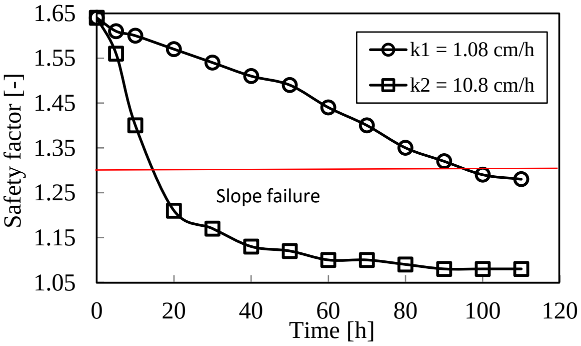

Figure 4. Decrease in safety factor over rainfall time

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.

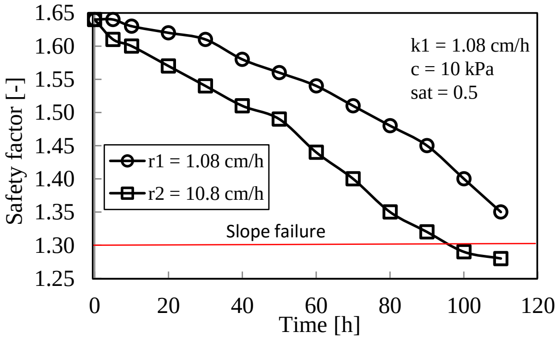

Figure 5. Decrease in safety factor subjected to varying rainfall intensities

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)

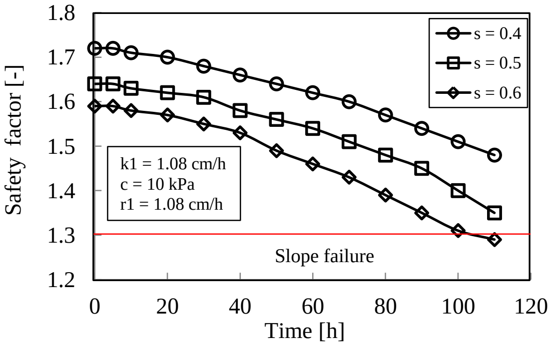

Figure 6. Decrease in the safety factor with a rainfall of 1.08 cm/h

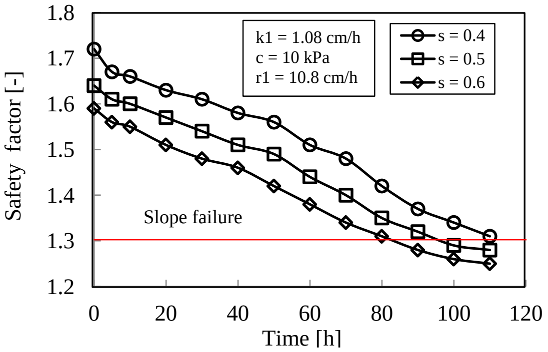

Figure 7. Decrease in the safety factor with a rainfall of 10.8 cm/h

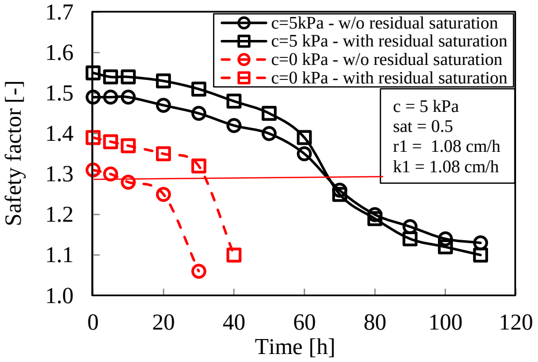

Figure 8. Effects of residual saturation on the safety factor

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.

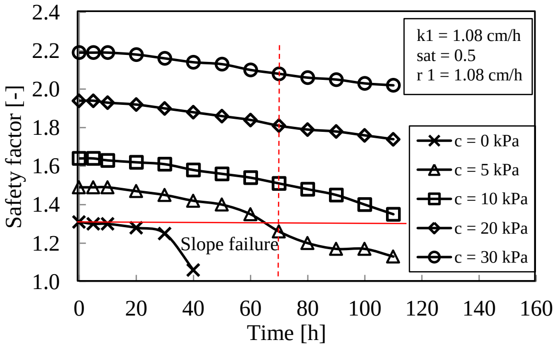

Figure 9. Effects of effective cohesion on safety factor

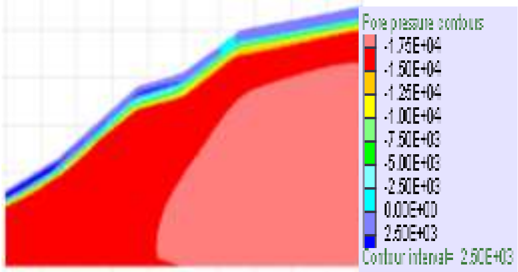

Figure 10. Pore water pressure distribution after 70 hours of rainfall (1.08 cm/h)

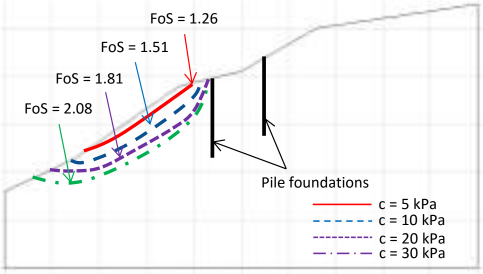

Figure 11. The slope failure mechanisms after 70 hours of rainfall (1.08 cm/h)

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.

ACKNOWLEDGEMENT

This research was supported by a grant from the Korea Electric Power Corporation (KEPCO).

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