An alternative slope design methodology to prevent slope failures due to rainfall infiltration

Une méthodologie de conception inclinée alternative pour empêcher des échecs inclinés en raison de l'infiltration d'averse

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ABSTRACT

Qutie frequent slope failures have been occurred not only in natural slopes but also in engieered slopes. Although engineered slopes such as excavated and compacted slopes were carefully designed and well constructed, unexpected rainfall storms cause many slopes to failure. Nevertheless, we have to do our best to properly consider the real situations in the design. The state of slope safety changes as the rainfall infiltrates into the slope. It induces the pore-water pressure to increase. At present, there is no standard slope design methodology to properly consider the effects of rainfall infiltration. In the current specification of slope design, the surface water-table condition is suggested to prevent the slope failures in case of rainfall condition. However, the surface water-table condition is not relevant to present the real situation, in which only near the surface of slope becomes saturated unless the slope is highly permeable and has initially high water-table. Moreover improper saturated soil properties are generally used in the slope design process. Therefore the design results do not assure the slope stability during or after the rainfall. In this paper, an alternative slope design methodology is suggested to consider the real infiltration condition. It combines not only the local rainfall characteristics but also local permeability of slopes. This suggested slope design methodology includes the main factors affecting the slope stability such as; (1) reasonable initial profile of matric suction, (2) soil-water characteristic curve (SWCC) and permeability function, (3) prolonged rainfall condition, (4) nonlinear shear strength criterion, (5) shallow or deep (circular) slope failure mode, etc.

RÉSUMÉ

Des échecs très fréquents de pente ont été produits non seulement dans les pentes normales mais également dans engieered des pentes. Bien que des pentes machinées telles que les pentes excavées et compactes aient été soigneusement conçues et bien construites, les précipitations inattendues donnent l' assaut à la cause beaucoup de pentes à l'échec. Néanmoins, nous devons faire notre meilleur pour considérer correctement les vraies situations dans la conception. L'état de sûreté de pente change pendant que les précipitations infiltrent dans la pente. Il induit la pression de l'pore-eau d'augmenter. Actuellement, il n'y a aucune méthodologie de conception standard de pente pour considérer correctement les effets de l'infiltration de précipitations. Dans les spécifications courantes de la conception de pente, l'état extérieur d'eau-table est suggéré pour empêcher les échecs de pente en cas de condition de précipitations. Cependant, l'état extérieur d'eau-table n'est pas approprié pour exposer la vraie situation, dans laquelle seulement près de la surface de la pente devient saturé à moins que la pente soit fortement perméable et ait la haute eau-table. D'ailleurs des propriétés saturées inexactes de sol sont généralement employées dans le processus de conception de pente. Par conséquent les résultats de conception n'assurent pas la stabilité de pente pendant ou après les précipitations. En cet article, la méthodologie de conception alternative de pente est suggérée pour considérer le vrai état d'infiltration. Elle combine non seulement les caractéristiques locales de précipitations mais également la perméabilité locale des pentes. Cette méthodologie de conception suggérée de pente inclut les facteurs principaux affectant la stabilité de pente comme ; (1) profil initial raisonnable d'aspiration matricielle, (2) courbe caractéristique de l'sol-eau (SWCC) et fonction de perméabilité, (3) état prolongé de précipitations, (4) critère non-linéaire de résistance au cisaillement, (5) mode de défaillance de pente, etc.. (circulaires) peu profonds ou profonds.

Keywords : unsaturated soil slope, rainfall infiltration, slope design, slope instability evaluation, 1-D infiltration model

1 INTRODUCTION

Many slope failures have occurred in Asian region during rainy season. Especially, the intensive rainstorms and typhoons induced sudden slope failures and these disasters brought the great economical loss and casualties.

A few Korean public institutions suggested conservative slope design guidelines that assume a fully saturated soil condition. In spite of this conservative assumption, many slopes have continued to fail, as this assumption is irrelevant to real natural phenomenon and sometimes soil properties are misread in the slope design method. Therefore, a more relevant slope stability evaluation method is necessary to take into account the real rainfall infiltration phenomenon.

Combined seepage and stability analyses of slopes can be performed using unsaturated soil properties such as shear strength, soil-water characteristic curve (SWCC) and permeability of unsaturated soils for accurate prediction. However, the laboratory tests to obtain these soil properties are troublesome and time-consuming. This difficulty of laboratory tests has prevented from the practical use of unsaturated slope instability evaluation method considering the rainfall infiltration.

In this paper, an alternative slope design methodology to evaluate the rainfall-induced slope instability is suggested by using 1-D infiltration model and wetting depth. The wetting depth is estimated by Mein & Larson's model (1975), which can consider the ponding time and runoff. Three cases of rainfall condition are applied to predict wetting depths and each result is used to calculate the factor of safety of a slope by adopting the nonlinear shear strength criterion.

2 RAINFALL-INDUCED SLOPE INSTABILITY

The mechanism of rainfall induced slope failures is the most fundamental aspect to be considered in the slope stability evaluation. If ground water table is near the surface and the conductivity of soil is high due to cracks and joints, the slope

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can be easily saturated during rainfall events. In this condition, circular and deep slope failures are usually induced. This viewpoint is similar to the rationalization which says that the matric suction in slopes can be ignored when considering the long-term stability of slopes (Fredlund, 1995).

However, most of soil slopes exist in an unsaturated soil condition with a deep ground water table. Negative pore-water pressures develop in the unsaturated condition, and they keep the slope in a more stable state. This negative pore water pressure is also called matric suction. It is difficult to fully saturate the slopes in the case of a deep ground water table condition. The infiltrated rainfall cannot reach the deep depth because the conductivity of the soil in an unsaturated condition is generally very low and the soil has high water storage capacity to store the water in soil pores.

Rainfall infiltrates the slope from the surface and decreases the matric suction as shown in Fig. 1. The wetting depth is affected by many factors such as the rainfall condition, soil conductivity, and soil stratification. In that case, the strength of soil decreases as the matric suction decreases or disappears. Positive pore-water pressure can also develop due to a temporary water table near the slope surface, decreasing the soil strength suddenly. Slope failures occur if the infiltrated rainfall reaches to a critical depth. Most of these failures are shallow or surface types. Therefore, in this type of slope failure, the matric suction and water content inside the slopes have been recognized as the most important soil properties directly related to the instability of the slope.

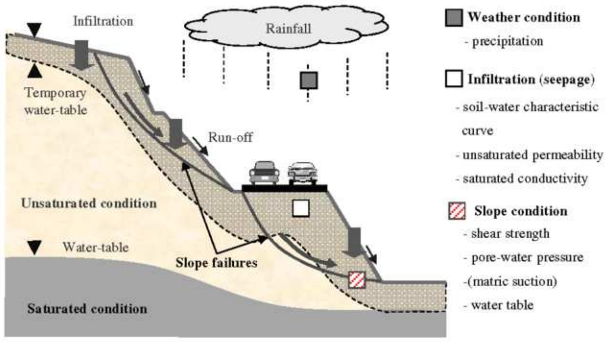

Figure 1. Mechanism of rainfall-induced slope failure

3 AN ALTERNATIVE SLOPE DESIGN METHODOLOGY

3.1 *Problems of current slope design guideline*

To consider the effect of rainfall infiltration, current slope design guidelines recommend that the water-table locates at slope surface or at a certain depth near the surface in case of rainy condition. That is, it assumes that the slope is fully saturated up to the surface. However, it is difficult to satisfy this condition in mountains and man-made slopes. Moreover, the rainfall should continue for very long period since slopes composed of weathered residual soils in Korea have low permeability values. The hydrostatic water pressure in the fully saturated condition also cannot be developed due to the water flow according to the hydraulic gradient. Therefore, it is irrelevant to evaluate the slope stability assuming that the slope is fully saturated.

3.2 *1-D infiltration model*

Mein & Larson's infiltration model (1973) has separated the solution for the infiltration before and after ponding during rainfall. Initially, all rainfall can infiltrate soil; however, if the infiltration rate is the same as the rainfall intensity, ponding develops as the pore-water pressure at surface becomes zero. The cumulative infiltration amount can be calculated by the Green-Ampt model (1911) with the assumption that the constant rainfall intensity and the wetting depth are functions of rainfall intensity. Ponding time (T_p) can be calculated from the cumulative infiltration amount (F_p) and rainfall intensity (i).

$$T_p = \frac{F_p}{i} = \frac{k_s \Delta\theta_i \psi_f}{i(i - k_s)} \tag{1}$$

If the rainfall intensity is larger than the infiltration rate, the cumulative infiltration amount can be expressed by Eq. (2).

$$F = F_p + k_s(T - T_p) + \psi_f \Delta\theta_i \ln\left(\frac{F + \psi_f \Delta\theta_i}{F_p + \psi_f \Delta\theta_i}\right) \tag{2}$$

The matric suction at the wetting front can be calculated from the fitting parameters of Brooks and Corey's SWCC (1964) by the following equation.

$$\psi_f = \frac{2+3\lambda}{1+3\lambda}\left(\frac{\psi_b}{2}\right) \text{ (Brakensiek and Onstad, 1977)} \tag{3}$$

where ψ_b = air-entry value; and λ = the pore-size distribution index.

3.3 *Slope stability evaluation technique*

Fredlund & Xing's SWCC (1994) represents the relationship between matric suction and water content using the fitting parameters (s, a, n) as represented in Eq. (4).

$$\theta = \frac{s}{\left[\ln\left(e + \left(\frac{u_a - u_w}{a}\right)^n\right)\right]^{1.7}} \tag{4}$$

Fredlund et al. (1978) also suggested the following equation for estimating the unsaturated shear strength.

$$\tau_f = c' + (\sigma_n - u_a)\tan\varphi' + (u_a - u_w)\tan\varphi^b \tag{5}$$

Lee et al. (2003) suggested a hyperbolic equation to consider the nonlinearity and represented the behavior of apparent cohesion (C_A) as a simple formulation of Eq. (6).

$$C_A = c' + \frac{(u_a - u_w)}{1/\tan\varphi' + (u_a - u_w)/C_{max}} \tag{6}$$

With this nonlinear shear strength of unsaturated soil, the factor of safety of an infinite slope can be calculated by the following equation.

$$FS = \frac{c' + W\cos^2\alpha\tan\varphi' + \dfrac{(u_a - u_w)}{1/\tan\varphi' + (u_a - u_w)/C_{max}}}{W\sin\alpha\cos\alpha} \tag{7}$$

where, W = weight of body considering the degree of saturation of soil; and α = angle of slope.

4 APPLICATION TO AN EMBANKMENT SLOPE

An embankment slope was selected to apply the stability evaluation technique considering the rainfall infiltration effect in the stage of slope design. The new slope will be constructed after excavating the existing embankment to expand the river channel as shown in Fig. 2. The unsaturated soil properties were estimated from basic soil properties and the stability of shallow surface failure was evaluated by the wetting depth according to a rainfall event.

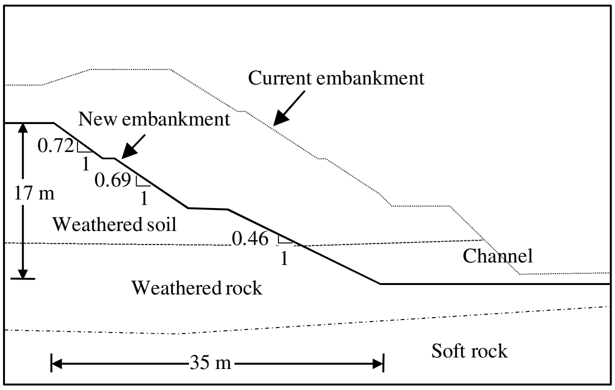

Figure 2. Geometry of new embankment

Table 1 shows the measured soil properties for the undisturbed specimen from the field site. The slope contains a large amount of sand and the field void ratio and unit weight are 0.79 and 18.8 kN/m^3, respectively. The saturated coefficient of permeability is 2.99e-7 m/s and cohesion and friction angle of undisturbed specimen are 34.9 kN/m^2 and 27.8 °, respectively. The water content of specimen was 18.7 %. The unsaturated soil properties such as soil-water characteristic curve, permeability function and shear strength shown in Table 2 were estimated from these basic properties. By using artificial neural network models, parameters of Fredlund & Xing's SWCC [Eq. (4)] shown in Fig. 3 were estimated (Lee, 2004) and the maximum increment of apparent cohesion (C_{max}) in Eq. (6) was obtained to represent the nonlinear behavior of unsaturated shear strength. The saturated cohesion (c') is also required to properly evaluate the slope stability in case of saturated condition near the surface. The field matric suction of undisturbed specimen (ψ_{field}=65.1 kPa) was indirectly calculated from the field water content using SWCC. At first, the saturated cohesion was calculated from the linear shear strength criterion [Eq. (5)] and the value was used as input data to estimate C_{max} value. With C_{max}, a saturated cohesion was obtained again by the nonlinear relationship. By this process, C_{max} and c' were finally obtained as shown in Fig. 4 and Table 2.

Table 1. Measured soil properties

Soil property	Value
Gravel content (%)	0.9
Sand content (%)	93.7
Clay & silt content (%)	5.4
Void ratio (e)	0.79
Unit weight (kN/m^3, γ_t)	18.8
Water content (θ_{field})	18.7
Saturated permeability (m/s , k_s)	2.99e-7
Cohesion (kN/m^2, c)	34.9
Frictional angle (°, φ)	27.8

Table 2. Estimated soil properties

Soil property	Value
s parameter	0.409
a parameter	22.772
n parameter	0.734
Air-entry value (kPa, ψ_b)	1.67
Pore-size distribution index (λ)	0.188
Saturated cohesion (kN/m^2, c')	10.08
Ultimate increment of apparent cohesion (kN/m^2, C_{max})	89.696

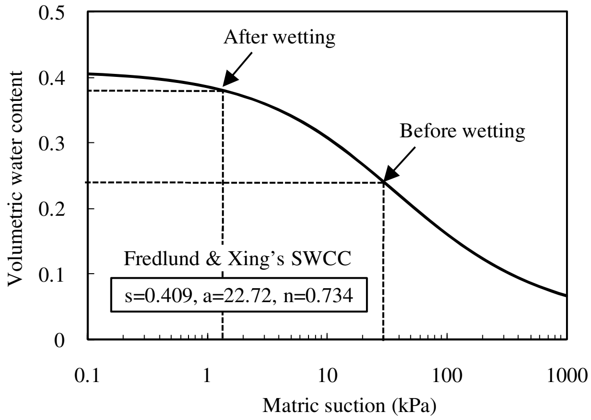

Figure 3. Estimated soil-water characteristic curve

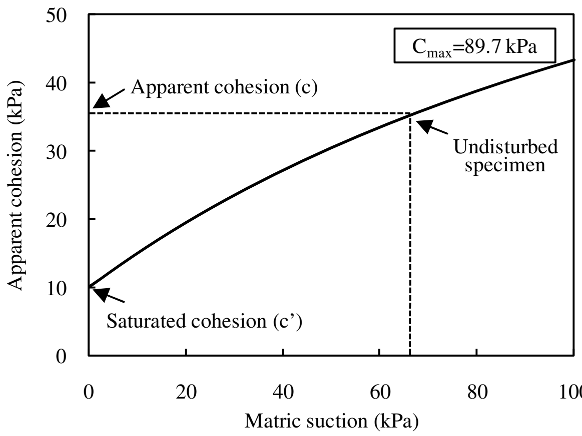

Figure 4. Estimated nonlinear apparent cohesion according to matric suction

Table 3 shows factor of safety values obtained from commercial slope stability software, SLOPE/W (GEO-SLOPE). Case 1 and 2 represent dry and wet conditions considered in current slope design guidelines, respectively. Even if the slope of case 1 and 2 is quite stable according to current, a slope failure can happen in case of fully saturation of embankment in natural environment (real soil property) as shown in Case 4. However, full saturation of slope is difficult due to the low permeability of soil. Therefore, the effect of rainfall infiltration must be obtained by numerical seepage analysis and be used for an optimized slope design.

In this paper, the rainfall intensity, duration and frequency was obtained by Sherman type based on local rainfall characteristics. 100 years-frequency rainfall represented in Fig. 5 was selected and the rainfall patterns of 25 mm/hr-12 hours, 15 mm/hr-24 hours, and 9 mm/hr-48 hours summarized in Table 4 were applied to estimate the wetting depth.

The slope was assumed to have the matric suction of around 30 kPa before the rainfall from several field measurements (Lim et al., 1996; Lee et al., 2003; Lee & Kim, 2007). Therefore, its water content was 0.239 as shown in Fig. 1. The matric suction (ψ_f) in the wetting front during the rainfall is 1.37 kPa as calculated by Eq. (3) and its water content is 0.379. The deficit of water content ($\Delta\theta_i$) is 0.14. The wetting depth calculated by Mein & Larson's infiltration model from each rainfall condition is shown in Table 5. Case 3 has the largest wetting depth of 60.1 cm. Even if the rainfall intensity is the lowest, the duration is the longest and hence the total rainfall amount is the largest. Moreover, the saturated permeability is lower than all rainfall intensities. Accordingly, the rainfall intensity has little effect on the infiltration.

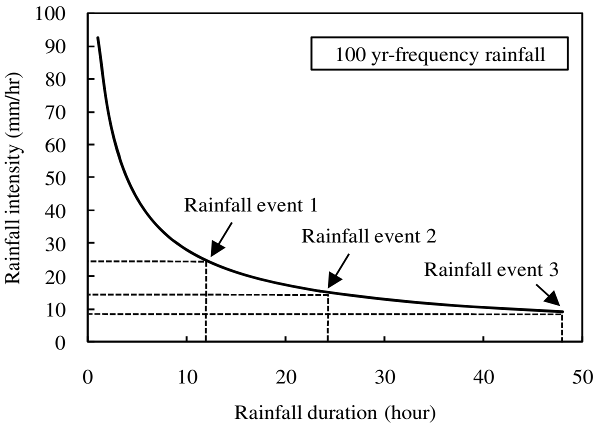

Figure 5. Rainfall intensity-duration curve for 100 yrs frequency

Table 3. Factor of safety obtained from SLOPE/W

Case	Cohesion (kN/m^2, c)	Pore-water pressure condition	Minimum factor of safety
1	34.9	-	2.722
2	34.9	Water table at surface	1.898
3	10.309	-	1.598
4	10.309	Water table at surface	0.886
5	10.309	Seepage analysis	2.088

Table 4. Applied rainfall condition

Case	Rainfall intensity (mm/hr)	Rainfall duration (hour)	Total rainfall amount (mm)
Case 1	24.7	12	296
Case 2	15.1	24	363
Case 3	9.1	48	438

Table 5. Estimated wetting depth according to rainfall condition

Case	Ponding time (hour, T_p)	Cumulative infiltration amount (mm, F)	Wetting depth (cm, z_w)
Case 1	0.036	31.77	22.7
Case 2	0.099	50.84	36.3
Case 3	0.287	84.16	60.1

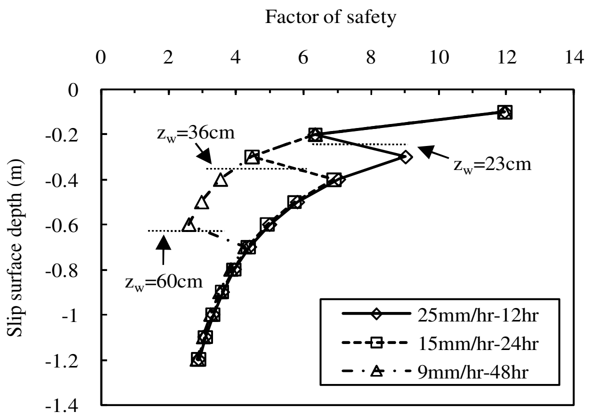

Figure 6. Variation of factor of safety along slip surface

Factor of safety along slip surface can be calculated by Eq. (7) using the wetting depth shown in Fig. 6. The overburden weight of soil along slip surface is used to consider the wetting area and its degree of saturation. As the matric suction decreases due to wetting, the FS also decreases. Besides, the FS decreases as the slip surface depth increases in the range of wetting area. In case of Case 3 (9.1 mm/hr-48 hours), the FS along 60 cm slip surface is lower than that of 120 cm depth. This implies that the shallow slope failure can occur due to the rainfall infiltration before the rainfall infiltrates deeper. However, the slope has sufficient stability after the rainfall infiltration for this embankment. Because the slope has low permeability, most of rainfall is runoff and just a little rainfall can infiltrate the slope. In this case, the wetting depth depends on the rainfall duration, not on the rainfall intensity. In this slope, the shallow slope failure can happen if the rainfall infiltrates up to 4 m depth as calculated by Eq. (7) in case of FS=1.

5 CONCLUSION

An alternative slope design methodology considering the real infiltration characteristics is suggested. To verify the applicability of the method, an example of slope design for an embankment was illustrated. An alternative slope design methodology considering the rainfall infiltration includes: wetting depth estimation by 1-D infiltration model, assumption of infinite slope failure, and estimation of unsaturated soil properties. Although this evaluation technique is based on the theory of geotechnical engineering, it needs to be improved for practical use. For example, the theory of infiltration adopted in this study cannot consider the inclination of slope and unsaturated permeability of soil. Besides, the range of depth for shallow slope failure must be defined by considering the height of slope and characteristics of the soil. The optimized slope design methodology can complement the current specification of slope design after more refinement in the theory and field applications.

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REFERENCES

Brakensiek, D. L., and Onstad, C. A. 1977. Parameter estimation of the Green and Ampt infiltration equation. Water Resource Research, Vol. 13, No. 6, pp. 1009-1012.

Brooks, R. H., and Corey, A. T. 1964. Hydraulic Properties of Porous Medium, Hydrology Papers, Fort Collins, Colorado.

Fredlund, D. G. 1995. The stability of slopes with negative pore-water pressure, Proceedings, Ian Boyd Donald Symposium on Modern Developments in Geomechanics, Monash University, Melbourne, Australia, June 7, pp. 99-116.

Fredlund, D. G., Morgenstern, N. R., and Widger, R. A. 1978. Shear strength of unsaturated soils, Canadian Geotechnical Journal, Vol. 15, No. 3, pp. 313-321.

Fredlund, D. G., and Xing, A. 1994. Equation for the soil-water characteristic curve, Canadian Geotechnical Journal, Vol. 31, pp. 521-532.

Green, W. H., and Ampt, G. A. 1911. Studies of soil physics I. The flow of air and water through soils, Journal of Agricultural Science, Vol. 4, pp. 1-24.

Lee, I. M., Cho, W.S., Kim, Y. U., and Sung, S. G. 2003. In-situ Monitoring of Matric Suctions in a Weathered Soil Slope, Korean Geotechnical Society (KGS), Vol. 19, No. 1, pp. 41-49 (In Korean).

Lee, S. J. 2004. Estimation of unsaturated shear strength and soil water characteristic curve for weathered granite soil, Doctoral thesis, KAIST.

Lee, S. J., Lee, S. R., and Kim, Y. S. 2003. An approach to estimate unsaturated shear strength using artificial neural network and hyperbolic formulation, Computers and Geotechnics, Vol. 30, pp. 489-503.

Lim, T. T., Rahardjo, H., Chang, M. F., and Fredlund, D. G. 1996. Effect of rainfall on matric suctions in a residual soil slope, Canadian Geotechnical Journal, Vol. 33, pp. 618-628.

Mein, R. G., and Larson, C. L. 1973. Modeling infiltration during a steady rain, Water Resource Research, Vol. 9, No. 2, pp. 384-395.