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Steep Slope Stability Assessment Based on Hydrological Characteristics*

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Abstract

Each year, steep slope failures occur frequently because inopportune combinations of intensity and duration of rainfall trigger instability of the slopes. An Examination of effects of these two important rainfall factors on steep slope failure is a priority to prevent severe damage of properties and loss of lives resulting from slope failures. Slope failures are often triggered by a wetting band deepening caused by a decrease in matric suction due to water infiltration from the slope surfaces. The existing slope failure warning system in Korea does not reflect mechanical or hydraulic characteristics of unsaturated soils. In this study, geotechnical properties of unsaturated weathered soil, including permeability, soil-water characteristics curve, and shear strength, were examined by a series of experiments to evaluate slope stability. A procedure of steep slope failure risk evaluation is developed to reflect rainfall intensity, rainfall duration, and the mechanical and hydraulic properties of unsaturated soils.

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Ⅰ. INTRODUCTION

In the recent decade, the number of disasters has increased worldwide due to climate changes. Accordingly, the loss of lives and property from domestic natural disaster also has been increased. Steep slope failure is classified as one major category of the natural disaster types. In Korea, the average annual number of fatalities from steep slope failures in recent decade reaches about twenty three.

Rainfall characteristics are important factors of slope stability evaluation. Among many characteristics of rainfall, it is known that its intensity and duration are most influential factors inducing slope instability. When the rainfall intensity and duration become strong and long, respectively, slope failures are triggered mainly by a deepening of the wetting band accompanied by a decrease in matric suction induced by water infiltration.

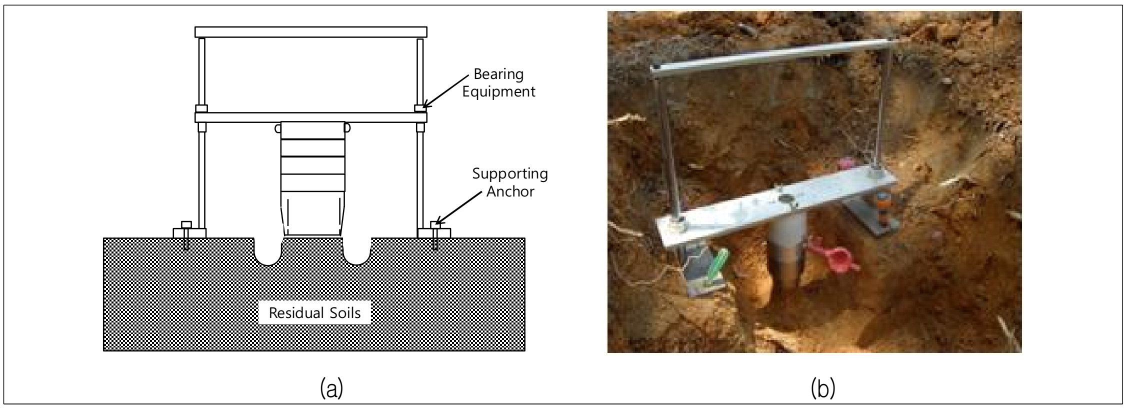
For the prevention or mitigation of loss of lives and properties expected from slope failures, early-warning system of Korea against slope failures was developed with consideration of rainfall intensity and duration and without consideration of the mechanical and hydraulic characteristics of unsaturated soils. In addition, a common design procedure of slope assumes worst-case in terms of water levels within slopes by raising the water levels that may be possible during severe rainy season. Still, the slope stability analyses do not consider the different behavior of slopes under water infiltration from the slope surface. However, the transient behavior of water seepage within the soils varies significantly with the suction profile, where the saturated zone would extend from the slope surface(Iverson, 2000; Collins & Znidarcic, 2004; Lee, *et. al.*, 2009).

In this study, geotechnical properties of unsaturated weathered soils, including the soil-water characteristic curve(SWCC), the unsaturated permeability curve, and the unsaturated shear strength, were assessed from test beds located within areas where slope failures frequently occurred. A procedure for risk evaluation of slope stability is developed, which evaluation method integrates the Factor of Safety(FS) of the infinite unsaturated soil slope, considering both “rainfall intensity and duration” and “mechanical and hydraulic properties of unsaturated soils.”

Ⅱ. SLOPE STABILITY ANALYSIS

1. Unsaturated Characteristics of Weathered Soils

Undisturbed weathered soils used in this study was sampled using undisturbed sampler from multiple locations. Weathered soils are typically heterogeneous and are mixed with roots of surface vegetation; therefore, sampling of the weathered soils is difficult. In our study, a series of undisturbed weathered soil sampling is performed at Chuncheon area, where steep slope failures were frequently observed. <Figure 1> shows an undisturbed soil sampling equipment and a picture of undisturbed sampling in a field.

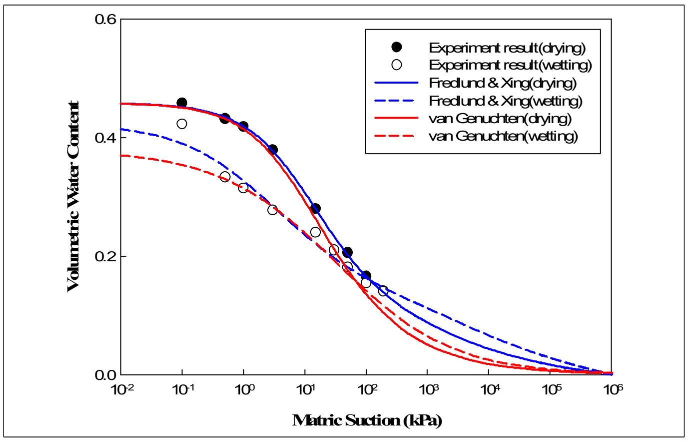


<Figure 1> Undisturbed soil sampling: (a) Sampling equipment and (b) picture of field soil sampling

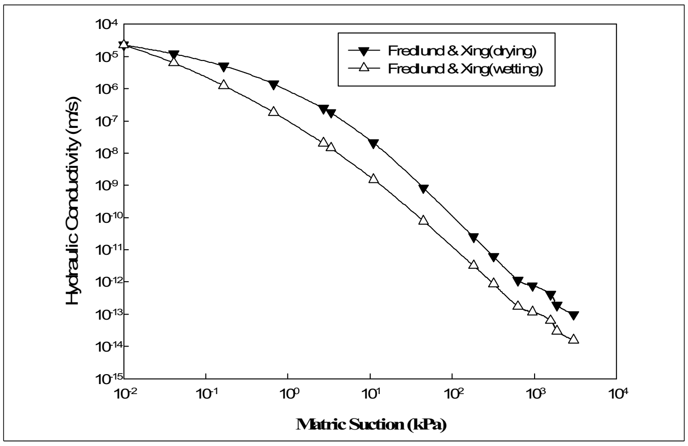
The soil-water characteristic curve(SWCC) was investigated using the SWC-150 SWCC device by Fredlund(1994). <Figure 2> shows the variation of drying and wetting SWCC type of van Genuchten(1980) and Fredlund & Xing(1994). At a given matric suction, volumetric water content is greater for the drying path than for the wetting path.

The permeability function has a close relationship with SWCC because the function varies with water content of soil, which tends to be similar to the SWCC characteristics(Kim, 2003). Therefore, the permeability function and SWCC exhibit a similar shape. <Figure 3> presents the unsaturated permeability curves under drying and wetting conditions. In the practices of slopes, rainfall infiltration induces a decrease of the matric suction or an increase of water content. The strength parameters of unsaturated weathered soils were investigated by an unsaturated triaxial test from undisturbed samples at the study area, Chuncheon.

The weathered soil is classified as SC(symbol indicating clayey sand) based on Unified Soil Classification System (USCS) (ASTM D2487), and its unit weight is 15.98 kN/m3. The cohesion and friction angle are 7.79 kPa and 33.24°, respectively.



<Figure 2> Soil-water characteristic curve (SWCC) under drying and wetting conditions.

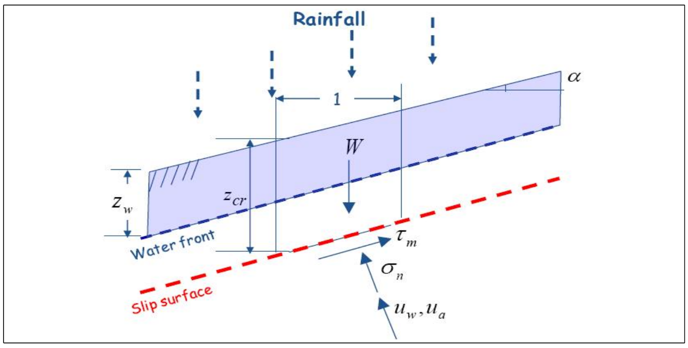


<Figure 3> Unsaturated permeability curve

2. Analysis of Unsaturated Infinite Slope

The shear strength of a potential soil sliding mass to resist against driving shear stress depends on the effective stress. Rainfall on the slope surface saturates unsaturated soils. As the soils become saturated, loss of capillary suction in the soil mass causes a decrease in the effective stress as well as its normal stress acting onto potential failure plane. Therefore, the reduction in shear strength and the increase in soil unit weight reduce the FS of the unsaturated infinite slope during rainfall (Li, *et. al.,* 2005).

The slope stability is evaluated by the FS equation for unsaturated infinite soils with consideration of the capillary suction loss and the soil unit weight gain during the rainfall. The geometries of unsaturated infinite slope and the stresses required for the slope stability analysis of this problem are shown in <Figure 4>.



<Figure 4> Geometries, Forces, and Stresses required for force equilibrium calculation for a potential failure surface (Shin, *et. al.,* 2013)

When the wetting front exists above the potential failure surface (zcr > zw), the FS of the unsaturated infinite slope can be evaluated using the following equation.

$$FS=\frac{\tau_f}{\tau}=\frac{\tau_f(\sigma_n,u_w)}{\tau} \qquad (1)$$

where σn = normal stress (=σz cosα = W cos2α); τ = shear stress (= σz sinα = W sinα cosα); and uw = initial suction (= − so).

Based on the force equilibrium per unit width, the total weight above the slip surface is W = ɣ satɣw + ɣw (zcr−zw), and length of slip line is cosα = 1/L. The total vertical stress on the surface is σz = M/L = W cosα. FS of the unsaturated slope is the ratio of shear strength to shear stress along the potential failure surface.

There are three important factors influencing the FS of unsaturated infinite slopes: (1) A one-dimensional infiltration model [which determines the depth of the wetting front (zw) for a given rainfall intensity and duration, assuming that vertical gravity driven infiltration is dominant even in the two-dimensional flow]; (2) The effective stress carried by the soil skeleton (which determines the shear strength of unsaturated soil); and (3) The advance of the wetting front during rainfall (which controls pore-pressure distribution in soils).

The slope stability analyses of unsaturated infinite steep slopes were conducted using the infiltration model by Mein & Larson(1973) and the shear strength model by Lu & Likos(2006) accounting for suction stresses. In these analyses, the suction profile, which is expressed in terms of positive pore water pressure within the seepage profile exerted from precipitation, is adapted based on the results of infiltration model tests and the research by Rahardjo, *et. al.*(1995). A series of infinite unsaturated slope stability analysis was conducted to estimate the effect of rainfall intensity-duration, slope angle, permeability, and infiltration depth on FS. Input parameters and analysis conditions for unsaturated infinite slopes are listed in Tables 1 and 2.

<Table 1> Characteristics of hydro-mechanical properties and suction profile

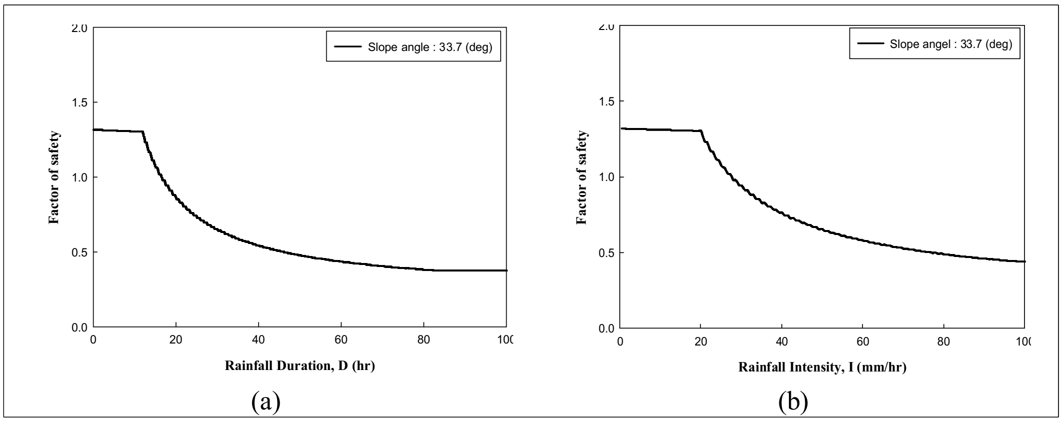
Properties	Parameter values used in the analyses
Hydro property	- SWCC parameter (wetting condition) α = 0.33 kPa N = 0.45 m = 1.06 Δθ = 0.14 - Permeability ks = 2.28E-05 m/s
Mechanical property	α = 10~70 degrees H = 5.0 m ɣt = 15.98 kN/m3 ɣsat = 18.89 kN/m3 c' = 7.79 kPa ϕ' = 33.24 degrees
Suction property	So= 14 kPa wfsh= 1 m

So = initial soil suction (in-situ result); wfsh = water front suction head (evaluated from ASCE, 1996); Dq = volumetric water content change by saturation; and Se= [1+α(ua - uw)n]-m(Genuchten,1980)

<Table 2> Analysis conditions for unsaturated infinite slope

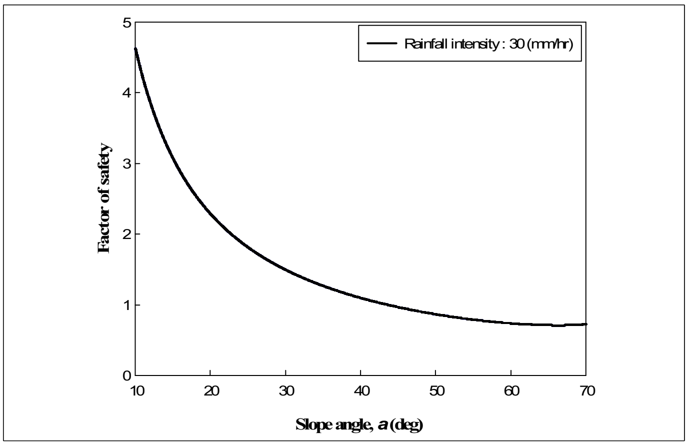
Cases	Rainfall		Slope angle (degrees)	Permeability ks of soil (m/s)
	Intensity I (mm/hr)	Duration D (hr)		
Case 1	20	0~100	33.7	2.28E-05
Case 2	0~100	12	33.7	2.28E-05
Case 3	30	5	10~70	2.28E-05
Case 4-1	100	100	33.7	2.28E-04
Case 4-2	100	100	33.7	2.28E-05
Case 5	20	5, 10, 15, 20	33.7	2.28E-05

The effect of the rainfall intensity and duration on the FS of unsaturated infinite slopes is shown in <Figure 5>. When the rainfall intensity or duration is less than the certain threshold, the rainfall pattern has a minor effect on the FS of the slope. However, an increase in the slope angle rapidly decreases the overall FS in unsaturated infinite slopes, as shown in <Figure 6>. <Figure 7> shows a variation of FS, which has the same soil properties and slope angle, but different saturated hydraulic conductivities. As the saturated hydraulic conductivity of the soil increases, rainfall infiltration is much faster and the rainfall duration becomes shorter to reach the slope failure above a certain threshold of rainfall intensity. Furthermore, <Figure 8> shows the variation of FS with respect to infiltration depth.

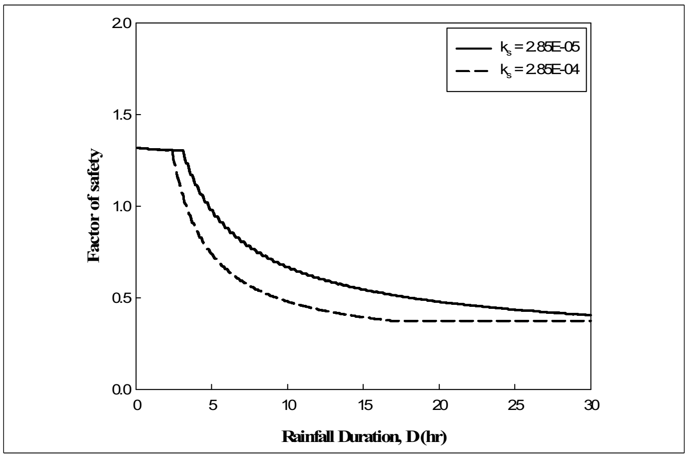


(a) (b)

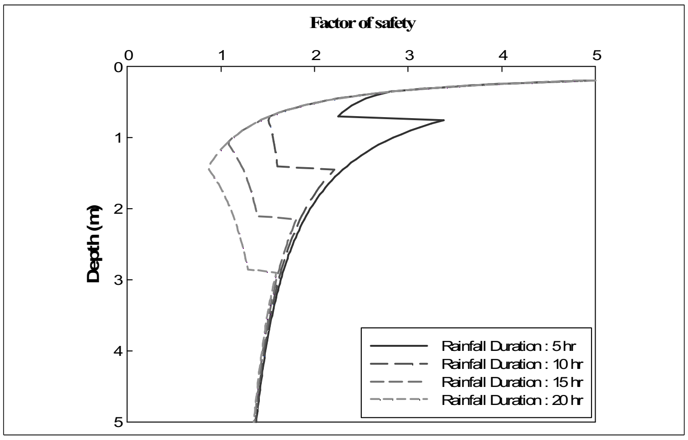
<Figure 5> Variation of safety factor with respect to rainfall intensity-duration (a) effect of rainfall Intensity; (b) effect of rainfall duration



<Figure 6> Variation of safety factor with respect to steep slope angle



<Figure 7> Variation of safety factor with respect to permeability



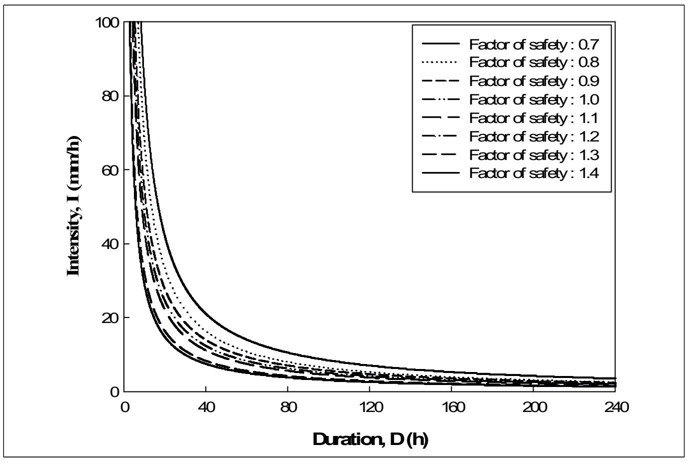
<Figure 8> Variation of safety factor with respect to infiltration depth

III. STEEP SLOPE FAILURE ESTIMATION CRITERIA

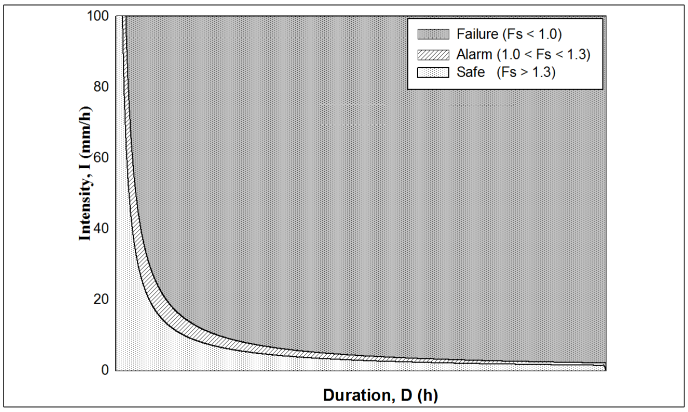
In this study, new analysis and estimation methods on steep slope failure are suggested so that these new methods reflect the changes of hydro- and mechanical- properties of foundations due to rainfall. To consider a realistic mechanism of steep slope failure, unsaturated characteristics (soil-water characteristic curve, unsaturated permeability curve, and shear strength of unsaturated soils), and rainfall infiltration characteristics of weathered soils from frequent steep slope failure regions in Chuncheon, are taken into account. In addition, an unsaturated infinite slope stability theory is implemented, reflecting the unsaturated behavior characteristics of the decrease of matric suction and the increase of self-weight, due to rainfall infiltration.

Stability analysis is performed using the unsaturated infinite slope stability theory (Equation 1), and the steep slope failure estimation criteria is suggested. The FS of unsaturated infinite slopes can be calculated for a given rainfall pattern (intensity and duration) (<Figure 9>).

The steep slope failure estimation criteria is developed based on the boundary criterion representing a safety level obtained from the safety factor calculations, considering rainfall intensity and duration. The following are the safety levels of slope failure: Safe: FS > 1.3, Alarm: 1.0 < FS < 1.3, Failure: FS < 1.0. These can be used to build the steep slope failure estimation criteria(<Figure 10>).



<Figure 9> Factor of Safety based on rainfall intensity and duration (slope angle=30°)



<Figure 10> Steep slope failure estimation criteria

IV. CONCLUSIONS

In this study, a new failure estimation model for steep slopes is suggested based on the dynamic risk analysis for a wide area, by integrating the factor of safety(FS) calculated from the unsaturated infinite slope stability analysis. The general equation to calculate the FS in an unsaturated infinite slope is derived, and three important factors affecting the expression are identified: infiltration model, shear strength model, and suction profile.

The unsaturated infinite steep slope infiltration considered stability analyses were conducted using the infiltration model and the shear strength model reflecting suction stresses. In the analyses, the suction profile, which is expressed in terms of positive pore water pressure within seepage profile exerted from precipitation, is adapted based on the results of infiltration model tests and the research by Rahardjo, *et. al.*(1995). The suggested failure evaluation model for steep slopes enables a steep slope risk assessment based on the major influential factors of steep slope failure, such as rainfall, topographic characteristic(slope angle), and unsaturated characteristics of slope.

Future studies are required for the improvement of the steep slope stability evaluation model proposed in this study. The improvement will offer the possibility of the real-time risk assessment of steep slopes, and the suggestion of real-time Management and Disaster Warning System of steep slopes.

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