On the prediction of slope saturated time considering unsaturated soils characteristics under rainfalls

Sur la prédiction du temps saturé de pente la considération a non saturé des caractéristiques de sols sous les chutes de pluie

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ABSTRACT

Many studies on slope stability have indicated that the slope stability decreases due to infiltration of rain water into a slope. In Korea, the fully saturated ground condition during rainy season, which is the worst, is used for the slope stability analysis where rainfall intensity, soil type and slope geometry are ignored. However, use of such a condition in rainy season would be conservative because most of the soil slopes is maintained at unsaturated condition. To evaluate slope stability properly, therefore, seepage analyses in an unsaturated soil need to be considered. Although, based on these results, slope stability analyses need to be performed by considering pore water pressure, many difficulties exist due to complicated processes. This paper suggests a simple method to predict saturated time of weathered granite soil slope in unsaturated ground condition on the basis of a result of seepage analyses in various conditions. If predicted saturated time exists within possible range (within 24 hours), we can understand that the fully saturation ground condition is appropriate for the slope stability analyses. To investigate the effects of soil-water characteristics, permeability at saturation, slope geometry, and rainfall intensity on saturated time of soil slope, the finite element analyses of transient water flow in unsaturated slopes are carried out. From the results, the chart for predicting saturation time of soil slope by considering soil-water characteristics, permeability at saturation, and slope height is presented. To verify the proposed chart, the prediction time is compared with laboratory model tests.

RÉSUMÉ

De nombreuses étude sur la stabilité de la pente ont indiqué que la stabilité de la pente diminue en raison de l'infiltration de l'eau de pluie dans une pente. En Coreé, la condition de terre complètement saturée pendent la saison pluvieuse, qui est le pire, est utilisée pour l'analyse de stabilité inclinée où l'intensité de chute de pluie, le type de sol et la géométrie inclinée sont ignorés. Cependant, l'utilisation d'une telle condition dans la saison pluvieuse serait conservatrice parce que la plupart des pentes de sol sont maintenues à la condition non saturée. Pour évaluer la stabilité inclinée correctement, donc, les analyses de suintement dans un sol non saturé doivent considérées. Bien que, basé sur ces résultats, les analyses de stabilité inclinées doivent être exécutées par la considération étudient soigneusement la pression d'eau, beaucoup de difficultés existent en raison des processus compliqués. Ce papier suggère une méthode simple de prédire le temps saturé de pente de sol de granite érodé dans la condition de terre non saturée sur la bse d'un résultat d'analyses de suintement dans les conditions différentes. Si prédit le temps saturé existe dans la gamme possible (au cours de 24 heures), nous pouvons comprendre que complètement la condition de terre de saturation est appropriée pour les analyses de stabilité inclinées. Pour examiner les effets de caractéristiques de sol-eau, la perméabilité à la saturation, la géométrie de la pente et la intensité de chute de pluie sur le temps saturé de pente de sol, les analyses d'élément finies sur l'écoulement transotoire d'eau dans les pentes non saturées sont réalisées. A partir de résultats, le graphique pour prédire le temps de saturation de pente de sol en considérant des caractéristiques d'eau de sol, la perméabilité à la saturationet à la hauteur inclinée est présentée. Pour vérifier le graphique proposé, le temps de prédiction est comparé avec des tests en laboratoire.

Keywords : slope stability, unsaturated soils, weathered granite soils, rainfalls

1 INTRODUCTION

This is an part of the fundamental study to present reasonable evaluation method for the slope stability of weathered granite soils, which take most part of surface soil in Korea. For this purpose, unsteady state seepage analyses with numerical program are performed varying with slope height and inclination, and soil-water characteristics. Based on these results, characteristics of the seepage behavior are observed with respect to slope variation and soil condition during rainfall. The chart for predicting slope saturated time is presented. In addition, to confirm the applicability of the chart, the results between numerical analysis and suggested chart for an arbitrary slope are compared.

2 SOIL-WATER CHARACTERISTIC CURVE

The soil-water characteristic curves (SWCC) for unsaturated soil are suggested by many researchers. Leong and Rahardjo (1997) have modified Fredlund and Xing model (1994) and suggested new SWCC model as shown in equation (1).

$$\theta = \theta_s \left\{ \frac{1}{\ln[e + (\psi / a)^n]} \right\}^m \quad (1)$$

where θ is volumetric water content, θ_s is volumetric water content at saturation, e is natural logarithm, ψ is suction, and a, n, m are parameters determining SWCC shape.

Parameter, a, corresponds to suction in inflection point, n, slope of the straight part in curve, and m, curve shape in high suction stage. Granite formed in Mesozic era in Korea takes

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most part of the bedrock, which are distributed in the form of sedimentary and residual soil by weathering. Weathered granite soils, the object of this study, corresponds to silty sand (SM) by unified soil classification system (USCS) and is nationwide in Korea whose country rocks are granite and granite gneiss. Lee et al. (2005) performed experimental tests for the unsaturated characteristics with weathered granite soils distributed in the areas of Seochang, Yeonki, Okcheon, Chochiwon etc., and presented soil-water characteristics using Fredlund and Xing's parameters. In this study, using a part of the results as shown in Table 1, seepage analyses are performed for the weathered granite soils.

Table 1. Soil-Water characteristics for weathered granite soils (Lee et al. 2005).

No.	θ_s	S	a	n	m	R^2
1	0.286	0.379	42.08	0.743	1.404	0.998
2	0.375	0.447	46.00	1.058	1.297	0.999
3	0.444	0.451	109.97	0.854	1.710	0.999
4	0.444	0.367	73.08	0.672	1.920	0.999
5	0.400	0.400	50.91	0.943	1.308	0.998
6	0.400	0.448	46.18	1.105	0.933	0.998
7	0.370	0.421	23.03	1.215	1.110	0.998
8	0.320	0.265	17.80	0.513	1.694	0.996

where S is degree of saturation and R^2 is coefficient of determination.

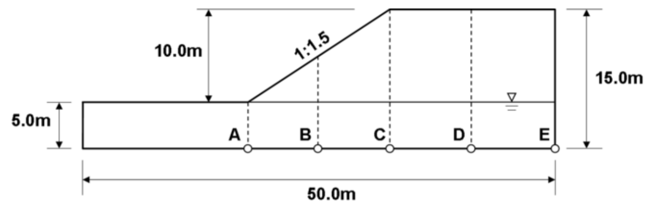
3 INFLUENTIAL FACTORS ON SLOPE SATURATION

3.1 *Effect of the rainfall intensity*

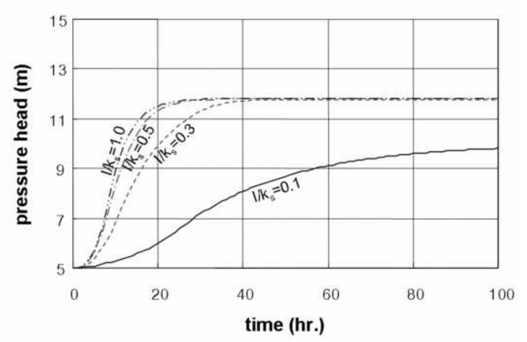
The seepage analyses are carried out in order to analyze the effects of rainfall intensity (Table 2) on slope saturation. From the results, in case that the ratio of the rainfall intensity to saturation permeability (I/k_s) is larger than 0.3, slope reach saturated state (when I/k_s= 0.3, 0.5) or near saturated state (when I/k_s= 0.9, 1.0). However, in case that I/k_s is less than 0.3, slope does not reach saturated state.

Table 2. Rainfall intensities applied to seepage analyses.

Items	analysis 1	analysis 2	analysis 3	analysis 4	analysis 5
I (mm/hr.)	36	108	180	324	360
k_s (m/sec.)	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}
I/k_s	0.1	0.3	0.5	0.9	1.0



(a) Geometric condition of the slope for the analyses

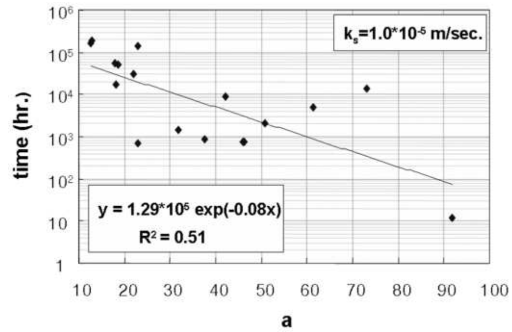


(b) Results of seepage analyses

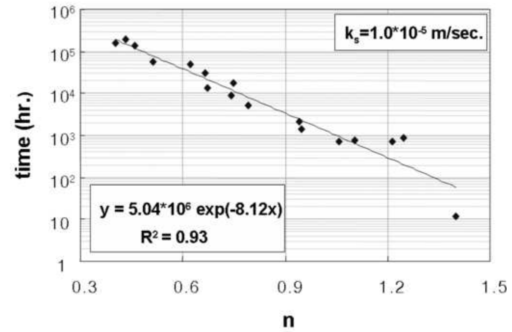
Figure 1. Effects of the rainfall intensities.

3.2 *Effect of soil-water characteristic*

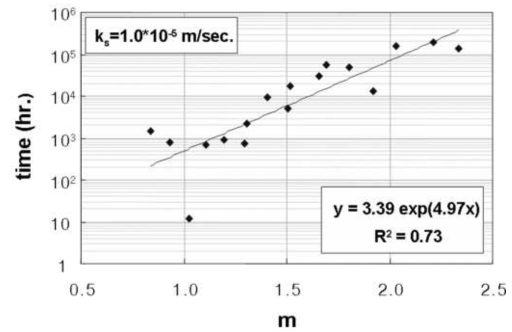
The SWCC proposed by Fredlund and Xing (1994), is defined by volumetric water content and parameters a, n and m at saturation. The seepage analyses, therefore, are carried out in order to analyze the effects of these factors and permeability at saturation on saturation of the slope. As results, in accordance with increment of saturation permeability and parameters, a and n, and decrement of coefficient m, slope saturated time decreases. As a result of regression analysis, parameter, n, shows the highest correlation with slope saturated time.



(a) Effect of parameter, a



(b) Effect of parameter, n

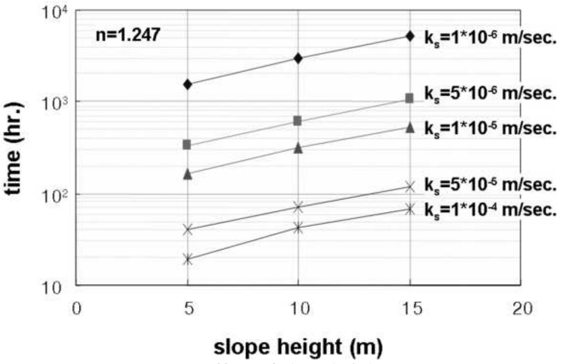


(c) Effect of parameter, m

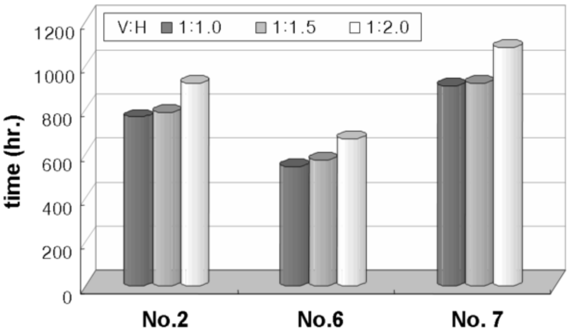
Figure 2. Effects of soil-water characteristics.

3.3 *Effect of the slope height and inclination*

The seepage analyses are also carried out to analyze the effects of the slope height and inclination on slope saturation when slope height is between 5m to 15m and inclination is between 1:1.0(V:H) and 1:2.0(V:H). As results, as slope height increases saturated time proportionally increases and as slope inclination is changed, it shows difference as well.



(a) Effect of slope height



(b) Effect of slope inclination

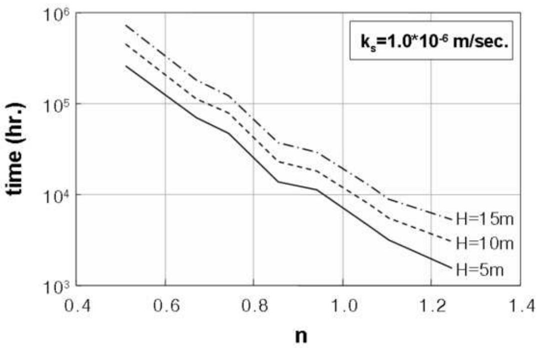
Figure 3. Effect of slope height and inclination.

4 PREDICTION OF SLOPE SATURATED TIME

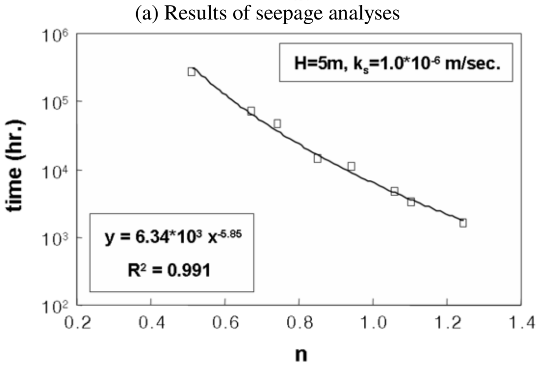
4.1 *Relationship between parameters*

Performing regression analyses with parameter *n*, which shows highest correlation with saturated time, slope height, and saturation permeability at the condition of 1:1.5(V:H) of slope inclination, following equation can be derived.

$$time = a \cdot n^{b} \tag{2}$$



(a) Results of seepage analyses



(b) Regression analyses using seepage analyses results

Figure 4. Seepage and regression analyses.

where *time* is the time required to saturate slope during rainfall, *n* is a parameter for SWCC, *a* and *b* are parameters.

Parameters, *a* and *b*, in equation (2) are varied with permeability at saturation and slope height. After evaluating slope saturated time during rainfall by seepage analyses changing with permeability at saturation and slope height, results of regression analyses using equation (2) can be summarized in Table 3.

Table 3. Regression analyses using seepage analyses results.

Slope height *H* (m)	Perm. at sat. k_s (m/sec.)	Parameter, *a*	Parameter, *b*
5	$1*10^{-6}$	$6.34*10^{3}$	-5.85
5	$5*10^{-6}$	$1.28*10^{3}$	-5.82
5	$1*10^{-5}$	$6.49*10^{2}$	-5.78
5	$5*10^{-5}$	$1.40*10^{2}$	-5.62
10	$1*10^{-6}$	$1.11*10^{4}$	-5.76
10	$1*10^{-5}$	$1.13*10^{3}$	-5.70
15	$1*10^{-6}$	$1.78*10^{4}$	-5.73
15	$1*10^{-5}$	$1.80*10^{3}$	-5.71

Based on regression analyses in Table 3, parameters, *a* and *b* can be correlated with slope height and permeability at saturation, respectively, as follows:

$$a = A \cdot k_s^{\,B} \tag{3}$$

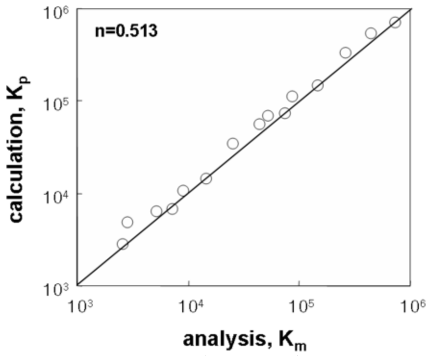
$$b = C \cdot k_s - D \tag{4}$$

where $A = 0.0024H^{0.845}$, $B = 0.9866H^{-0.00691}$, $C = 7300H^{-0.351}$, $D = 6H^{-0.0175}$, k_s (m/sec.) is permeability at saturation, and *H* (m) is slope height.

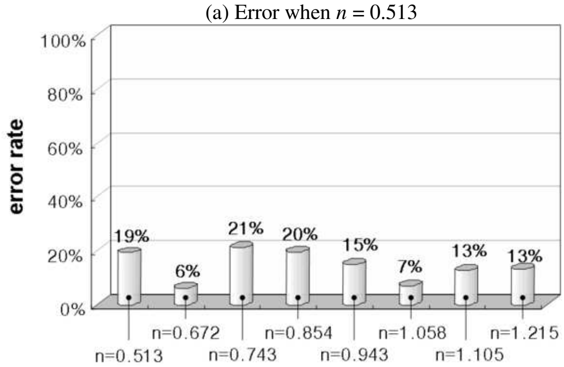
4.2 *Error rate of the proposed equation*

To confirm the applicability of the proposed equation, saturated time between proposed equation and numerical analysis are compared. As a result, average interface error rate (AIER), which is expressed as equation (5), is about 14%.

$$AIER(\%) = \frac{1}{N}\sum^{N}\frac{\left|K_m - K_p\right|}{K_m}\times 100(\%) \tag{5}$$



(a) Error when *n* = 0.513



(b) Error rate with respect to *n*

Figure 5. Comparison between numerical analysis and proposed equation.

where N is the number of predicted data, K_m, calculated values from numerical analysis, K_p, calculated values from proposed equation.

4.3 *Chart for predicting saturated time*

Simply using slope geometric condition, soil-water characteristic, and permeability at saturation obtained from the proposed equation, chart can be introduced for predicting slope saturated time without seepage analysis. The condition for making chart is that rainfall intensity is larger than permeability at saturation (Figure 6). For the simplicity, the ratio of permeability at saturation to slope height is used.

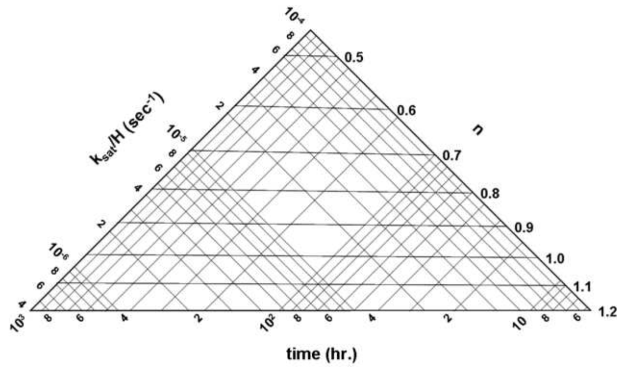
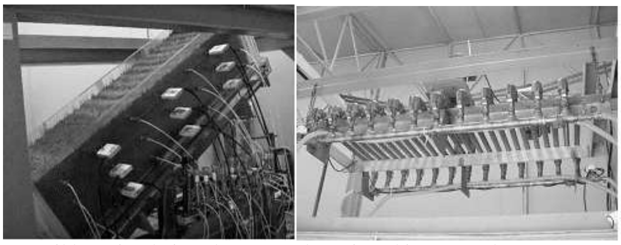


Figure 6. Chart for predicting slope saturated time.

4.4 *Verification of saturated time prediction*

Experimental apparatus (Lee 2006 and Han 2006) as shown in Figure 7 consists of acrylic soil box simulating slope(length: 1400mm, height: 300mm, width: 400mm), rainmaking control system with 273 pieces of rainfall pin (width: 360mm, length: 1300mm), vibrated tamping system, slope control system, tensiometer for measuring pore-water pressure, TDR for measuring volumetric water content. Slope inside soil box is filled with weathered granite soils with 300m in height.



(a) Soil box simulating slope (b) Rainmaking control system
Figure 7. Experimental set up.

Considering the unsaturated soil characteristic and soil box, k_s/H can be calculated as $(9.81\times10^{-4})/30 = 3.27\times10^{-5}$(sec.$^{-1}$). With n = 1.12 (dry side), slope saturated time can be predicted from the suggested chart as shown in Figure 8. As a result, it is estimated that slope saturated time is 21 hours. This shows good agreement with experimental test results because time to take steady state during rainfall from dry state is 24 hours after end of rainfall.

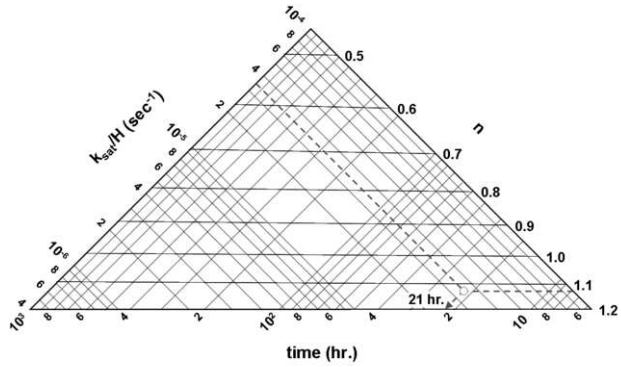


Figure 8. Chart for predicting slope saturated time (Park 2005).

5 CONCLUSIONS

In this study, it is shown that when the ratio of rainfall intensity and permeability at saturation ($=I/k_s$) is greater than 0.3, soil slopes can be saturated. As the permeability on the saturated state, a- and n-values of soil-water characteristics parameters presented by Fredlund & Xing (1994) increases, slope saturated time decreases. Also, as m-value of soil-water characteristics parameters decreases, slope saturated time decreases. It can be also concluded that the height of the slope, permeability at saturation and n-values of soil-water characteristics parameters are main parameters as a result of seepage analyses in various conditions. On the basis of these results, a prediction chart for the slope saturated time is presented. To verify the proposed chart, the prediction time is compared with that of laboratory tests where the duration until the steady state is measured. It appears to be similar as the slope saturated time is supposed to be 21 hours from the chart and 24 hours from the laboratory tests, respectively.

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