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A probabilistic smart system to monitor unsaturated slope instability induced by rainfall infiltration

Seungrae Lee, Jungchan Choi, Yunki Kim
Department of Civil and Environmental Engineering, KAIST, Daejeon, 305-701, KOREA

ABSTRACT: In Korea, slope failures are one of the most frequent natural hazards in heavy rainy season. Accordingly, the necessity of reasonable maintenance system for monitoring the slope is impending. It is well known that soil slope failures induced by rainfall infiltration are triggered by reduced unsaturated shear strength which is the result of matric suction reduction by the infiltration. Thus the consideration of unsaturated soil condition in the smart maintenance system for the soil slope structure is fundamental. Besides, the soil properties involved in a soil slope analysis imply many uncertainties. In addition, the consideration of spatial variability of soil properties results in more reasonable solutions to the slope stability analysis. In this paper, for developing more reasonable and quantitative slope maintenance system, statistical analysis scheme is combined with web based real-time data. A reliability analysis method is used for practical and simple application to the slope stability assessment method, considering unsaturated soil properties and shallow failure condition. The system reliability is checked by applying it to a real site.

1 INTRODUCTION

Generally, soil slope failure induced by rainfall infiltration is triggered by reduced unsaturated shear strength which is the result of matric suction reduction by the infiltration. Thus the consideration of unsaturated soil condition in analyzing the rainfall induced instability of soil slope gives rise to more reasonable results. To consider the unsaturated soil condition, Fredlund et al.(1978) introduced a shear strength criterion using a linear relationship with the matric suction.

Besides, the soil properties involved in a soil slope analysis imply many uncertainties. To take into account the uncertainties, many researchers used reliability index based on deterministic critical slip surface (Cornell 1971; Bergado and Anderson 1985). However, the slip surface associated with the minimum reliability index does not locate the critical deterministic slip surface (Li and Lumb 1987). Hence, extensive studies have been performed on the critical probabilistic slip surface which had minimum reliability index (Bhattacharya et al. 2003).

Most of researches in the subject of monitor the slope focused on the deformation of the slope. Recently new and smart monitoring systems have been developed using GPS or FBG sensors. However, monitoring of the deformation arises the difficulty to predict the slope failure and to figure out the cause of the failure. To overcome the limitation involved in monitoring the deformation, some important factors related with unsaturated soils were newly introduced in the monitoring of slopes. A number of field experiments have been conducted to study the effects of rainfall infiltration on the slope stability. Ng et al. (2003) performed the measurements of matric suction, water content and movement of surface for an unsaturated expansive soil slope of a typical clay with medium plasticity in Zaoyang for the South-to-North Water Transfer Project. Li et al. (2005) also constructed a full-scale field experiment site in a saprolite slope in Hong Kong to reveal the surface infiltration process.

In this paper, a real-time probabilistic slope stability method considering unsaturated soil properties and shallow failure condition based on the critical probabilistic slip surface is suggested.

important unsaturated soil factors were monitored in the slope beside the highway road during the rainy season in order to apply the method to a real site.

2 PROBABILISTIC ASSESSMENT OF UNSATURATED SLOPE INSTABILITY

2.1 Concept of Unsaturated Slope Stability

The unsaturated slope stability analysis can be conducted using the Limit Equilibrium Method with the modified Mohr-Coulomb shear strength criterion, which includes the matric suction term. However, the variation of pore water pressure distribution with time as well as the initial matric suction must also be considered to include the effect of the rainfall conditions. The slope failure pattern must also include the possibility of the surface failure as well as the deep circular failure as the slope failure type can be affected mainly by both the soil characteristics and the rainfall conditions.

The equation (1) is applicable to a slope with consideration of the matric suction and stress state (Figure 1).

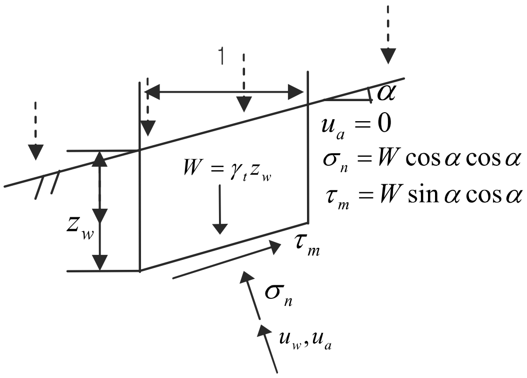


Fig.1 Infinite slope stability

$$FOS = \frac{c' + (u_a - u_w)tan\Phi^b + \gamma z cos^2\alpha tan\Phi'}{\gamma z sin\alpha cos\alpha} \quad \textbf{(1)}$$

where, z_w = depth of infinite slope; α = angle of slope; c' = cohesion; Φ' = frictional angle; ϕ^b = soil property related with the matric suction; $(u_a - u_w)$ = matric suction; γ = unit weight.

2.2 PROBABILISTIC ASSESSMENT OF UNSATURATED SOIL SLOPE

To perform the probabilistic analysis of a slope, the failure state of the slope should be identified via the performance function, $G(X)$, where X is the vector of input soil parameters. The performance function defines safe and non-safe regions of the slope such that can be described mathematically by $G(X) > 0$ for the safe region, and $G(X) < 0$ for the non-safe region, while the limit state surface is described by $G(X) = 0$.

Then, the probability of failure can be defined as:

$$P_f = P(G(X) < 0) = \iint_{G(X)<0} f(X)dx \quad \textbf{(2)}$$

Where $f(X)$ = joint probability density function of the basic variable vector X.

The performance function, $G(X)$, can be defined as $G(X) = f_s(X) - 1$ for stability problems, in which $f_s(X)$ is a function of the factor of safety. Therefore the performance function of an unsaturated soil slope can be defined as;

$$G(X) = \frac{c' + (u_a - u_w)tan\Phi^b + \gamma z cos^2\alpha tan\Phi'}{\gamma z sin\alpha cos\alpha} - 1 \tag{3}$$

It is difficult to identify the joint density function, $f(X)$, and to perform the integration of $f(X)$ over the entire multidimensional failure domain, $G(X) \leq 0$. To overcome the difficulty, an approximate method which is called First-order reliability method based on the ellipsoid method (Low and Tang, 2004) is adopted. The reliability index β can be defined as;

$$\beta_{HL} = \min_{X \in F} \sqrt{\left(\frac{x_i - m_i}{\sigma_i}\right)^T (R)^{-1} \left(\frac{x_i - m_i}{\sigma_i}\right)} \tag{4}$$

Where (R)=correlation matrix; σ_i=standard deviation of random variable x_i; m_i= mean value of random variable x_i.
From the reliability index β, the corresponding probability of failure can be evaluated by

$$p_f \approx 1 - \Phi(\beta) \tag{5}$$

Where Φ = cumulative distribution function (CDF) of the normal variable.

The U.S. Army Corps of Engineers(1997) suggested the expected levels of performance based on the reliability index as shown in Table 1. Wolff(1996) suggested that a reliability index of 3 for routine slopes and 4 for critical slopes should be acceptable.

Table 1. Expected levels of performance in terms of p_f and reliability index.

Expected performance level	Reliability index (β)	Probability of failure(p_f)
High	5.0	0.0000003
Good	4.0	0.00003
Above average	3.0	0.001
Below average	2.5	0.006
Poor	2.0	0.023
Unsatisfactory	1.5	0.07
Hazardous	1.0	0.16

3 SMART MONITORING SYSTEM

3.1 SMART SENSORS AND DATA STORAGE SYSTEM

The matric suction values in the slope are the most important factor for evaluating the rainfall-induced slope instability. Therefore an automatic and continuous monitoring system for the the matric suction values at certain depth in the slope is required to keep the slope stable and to alarm a possible danger of slope failure. We used the following instruments to measure the matric suction and rainfall condition, and the measured data were collected in a data logger operated using solar panels. The measured data are transmitted to the laboratory by wireless communication. Figure 2 represents a schematic diagram of the probabilistic smart monitoring system.

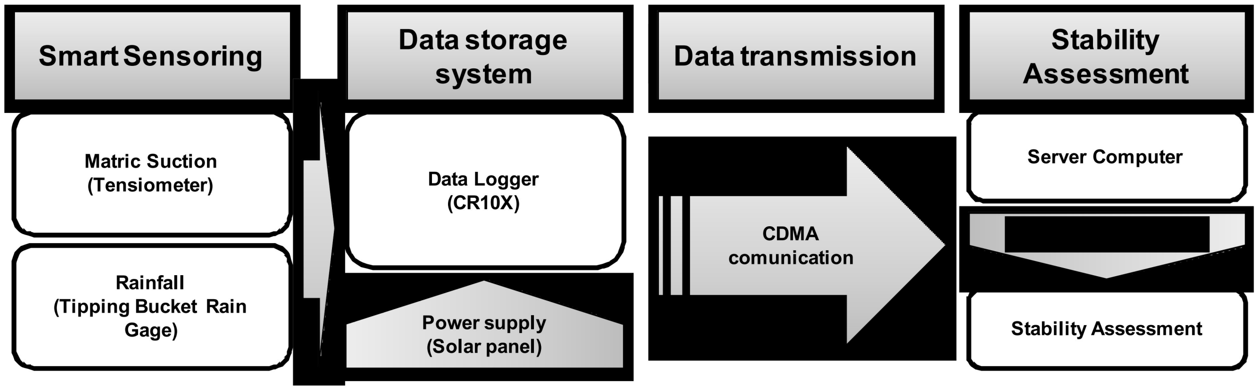


Fig.2 Schematic diagram of probabilistic smart monitoring system

3.2 MEASURED RESULTS

A compacted slope in a highway construction site from Daejeon to Dangjin city was selected to apply the smart monitoring system. To monitor the matric suction and rainfall, 4 tensiometers and 1 rain gage were installed in the field site. 4 tensiometers were installed at several depths of 15cm, 30cm, 45cm, 60cm from the surface.

Smart monitoring was performed for about 1 month from middle of September to middle of October, 2006. The measured rainfall amount is plotted in Figure 3. The peak rainfall intensity was 68mm/hr on 17^{th} of September and the maximum daily rainfall amount was 148mm at the same day.

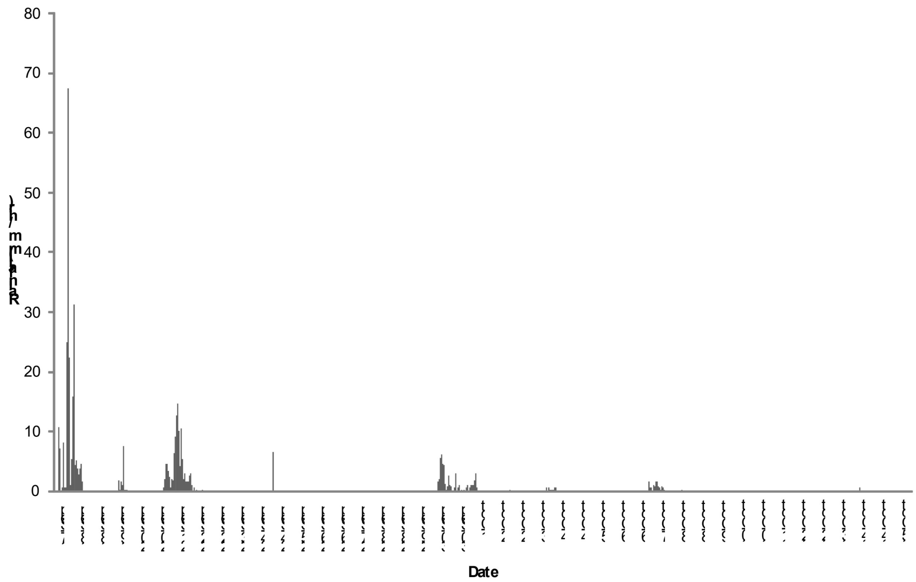


Fig.3 Measured rainfall amount during monitoring

The measured matric suction during the monitoring is shown in Figure 4. Matric suction values at 15cm depth represent very rapid variation because the water content increases easily due to the infiltration of rain in rainy period and decreases due to drainage to lower depth after the completion of rainfall and the evaporation to open air in hot and sunny period. This phenomenon occurs less sensitively as the depth increases. The sudden drop of matric suction happened immediately after the rainfall starts.

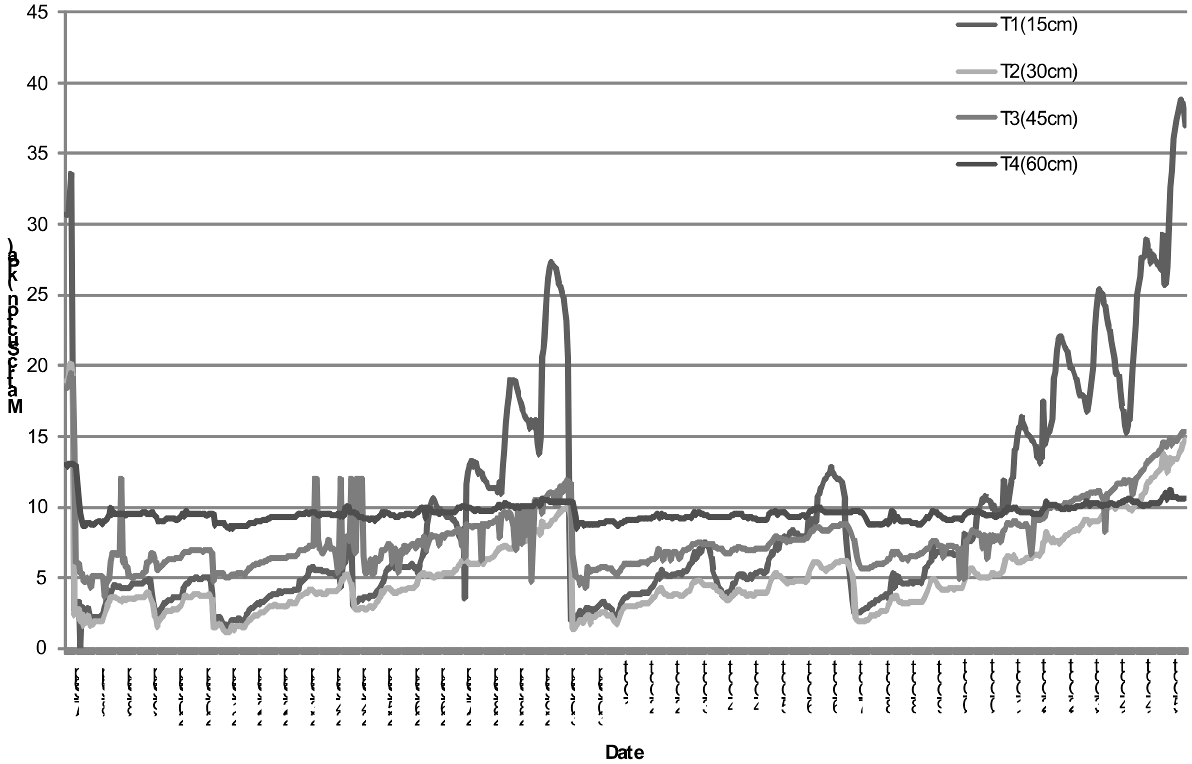


Fig.4 Measured matric suction during monitoring

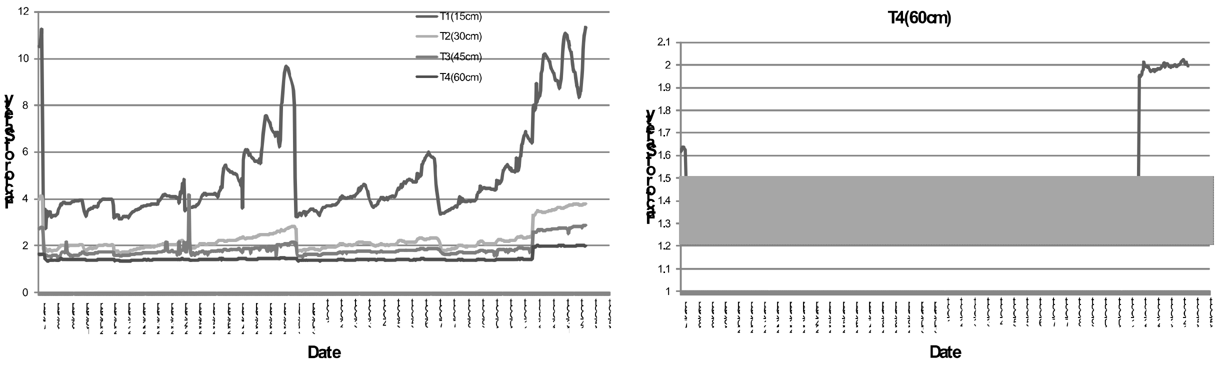
4 ANALYSIS RESULTS

To demonstrate the applicability of the suggested real-time stability assessment method, reliability analysis was performed using the measured data obtained from the site. For real-time assessment, the analysis program was developed with LabVIEW (National Instruments Corporation). The mean value and coefficient of variation of input data for the analysis are shown in Table 2.

Table 2. Soil parameters used in analysis.

Input parameter	Mean value	Coefficient of Variation (%)
Cohesion (c')	3.0 kPa	10
Frictional angle (ϕ')	20 °	10
Soil property related to the matric suction (ϕ^b)	18 °	10
Unit weight (γ)	17 kN/m^3	5
Matric suction $(u_a - u_w)$	Measured value	10
Angle of slope (β)	45 °	-
Depth (z)	0.15 ~ 0.6 m	-

Figure 5 shows the results of deterministic analysis at each time for each slope depth. The factor of safety(FS) values decreased as rainfall started. However, they recovered after rainfall stopped. The shallower the depth, they faster dropped. For real-time stability assessment, we could classify the criteria as FS>1.5: Stable zone, 1.2<FS<1.5: Suspicious zone, and FS<1.2; Unstable zone. As shown in Figure 5(b), some of FS values at 0.6m depth located suspicious zone.



(a) FS at each slope depth (b) FS at 60cm slope depth

Fig.5 Deterministic analysis results during monitoring

Figure 6 shows the results of probabilistic analysis for each slope depth. The pattern of reliability analysis results is similar to that of the deterministic results. It is confirmed that the reliability index has a tendency to decrease as the depth becomes deeper. The reliability index varies more near the surface rather than at the deeper depth during the rainy season. While the deterministic analysis results indicate that in most of period, the stability is critically involved in suspicious zone at 60 cm depth, the probabilistic analysis results present that the reliability index is more than 4.8, which is thought to be stable according to the criteria of real time stability assessment, refering to Table 1.

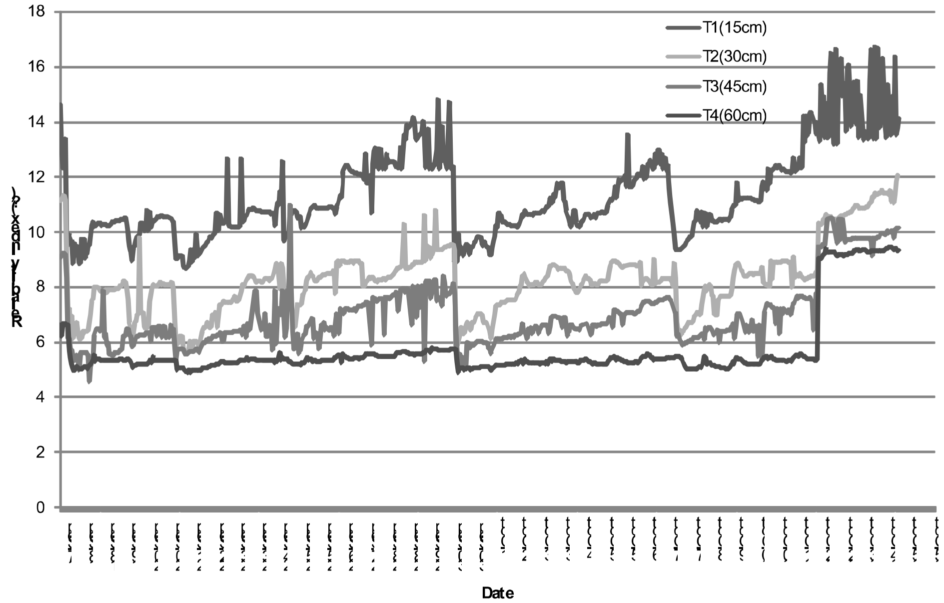


Fig.6 Probabilistic analysis results during monitoring

In order to investigate the influence of each soil property on the results of the reliability analysis, sensitivity analyse at 60cm depth were performed. The value $\frac{x_i^* - m_i}{\sigma_i}$ is used for the sensitivity approach, because this value indicates the variation from the mean value point to the design point of FORM ellipsoid method (Xu et al. 2006). As shown in Figure 7, uncertainty in cohesion is most important factor for this analysis. The soil properties ϕ^b and matric suction $(u_a - u_w)$ are more influenced by rainfall because of there variation which is shown as figure 7. According to the results of the sensitivity analysis, the reinforcement scheme to increase the cohesion and friction angle can be more effective and economical for the maintenance.

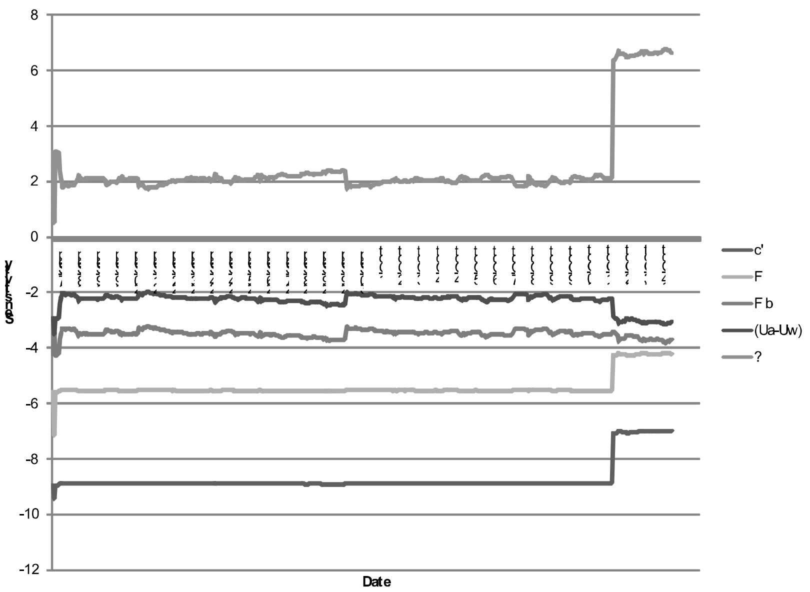


Fig.7 Sensitivity analysis results at 60cm depth

5 SUMMARY AND CONCLUSIONS

A probabilistic smart system to monitor unsaturated slope instability induced by rainfall infiltration is introduced and the applicability of this system is demonstrated. In order to perform the stability assessment, an analytical solution considering the infinite slope failure based on unsaturated soil mechanics was used. FORM is also used to calculate the reliability index β based on the ellipsoid method.

To measure unsaturated soil properties which affect the slope stability, matric suction values and rainfall amounts were measured by smart sensors. The measured data are collected in a data logger operated using solar panels. They are transmitted to the laboratory by CDMA wireless communication.

The system described in this study was applied to a slope in a highway construction site. According to the simulation results, matric suction values are in a range from 0 to 40 kPa and decrease during and right after the rainfall. Moreover, the effect of infiltration is greater in shallow depths. Based on the monitoring results and LabVIEW program analysis results, the variation is reduced as the depth increases.

While the conventional analysis results in the suspicious stability condition, considering the uncertainty of soil properties in the probabilistic analysis shows that the factor of safety of the slope is high enough. It might be concluded that the consideration of uncertain properties in the analysis gives more reliable results for the smart monitoring system.

Finally, the sensitivity analysis results show that the slope stability is affected by soil properties in the order of c', [illegible], ϕ^b, γ and $(u_a - u_w)$. Therefore, the methodology introduced in this study – real time sensitivity analysis and making decision for the priority of reinforcement in the soil properties according to the sensitivity analysis – may give a reasonable guideline for reliable and economical site maintenance and ground improvement.

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