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Real-time unsaturated slope reliability assessment considering variations in monitored matric suction

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Abstract. A reliability-based slope stability assessment method considering fluctuations in the monitored matric suction was proposed for real-time identification of slope risk. The assessment model was based on the limit equilibrium model for infinite slope failure. The first-order reliability method (FORM) was adopted to calculate the probability of slope failure, and results of the model were compared with Monte-Carlo Simulation (MCS) results to validate the accuracy and efficiency of the model. The analysis shows that a model based on Advanced First-Order Reliability Method (AFORM) generates results that are in relatively good agreement with those of the MCS, using a relatively small number of function calls. The contribution of random variables to the slope reliability index was also examined using sensitivity analysis. The results of sensitivity analysis indicate that the effective cohesion c' is a significant variable at low values of mean matric suction, whereas matric suction (u_a-u_w) is the most influential factor at high mean suction values. Finally, the reliability indices of an unsaturated model soil slope, which was monitored by a wireless matric suction measurement system, were illustrated as 2D images using the suggested probabilistic model.

Keywords: unsaturated soil slope; reliability analysis; real-time monitoring.

1. Introduction

During heavy rainy seasons, rainfall-induced slope failure is one of the most frequent natural hazards in many countries (Lumb 1962, Brand *et al.* 1984, Cho and Lee 2001, Tsaparas *et al.* 2002, Roy *et al.* 2009). Generally, such failures are related to rainfall infiltration and matric suction (Fredlund and Rahardjo 1993, Rahardjo *et al*. 2009). When rainfall infiltrates the soil slope, it decreases matric suction, which in turn triggers slope failure. For this reason, the concern for effective monitoring of unsaturated hydraulic properties such as matric suction and soil water content is increasing for economically sustainable maintenance. Thus, many studies have been performed to monitor matric suction and soil moisture content (Lim *et al*. 1996, Gasmo *et al.* 1999, Li *et al.* 2005, Zhan *et al*. 2006, Kim and Lee 2010). During the last decade, the rapid development of wireless sensor networks (WSN) for structural health monitoring (SHM) has also made it possible to obtain large amounts of scalable monitored data for large geotechnical structures (large cut slope, underground tunnel, and so on), which have been difficult to assess with conventional wire-connected monitoring

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systems because of poor working conditions and high maintenance costs (Glaser 2004, Li and Liu 2007, Wright 2010, Bennett *et al.* 2010). Despite these developments, the need for effective and reasonable inclusion of large amounts of monitored data in slope stability assessment and prediction is continuing to increase.

Soil has inherent variability due to its non-homogeneous and anisotropic material characteristics. In addition, because of the complex structures of soil, measurement errors are naturally involved in monitoring its properties. In a conventional deterministic analysis, the safety margin is used to consider the uncertainties in soil properties. However, this kind of safety margin is determined empirically and it cannot consider the amplitude of uncertainties (Christian 2004). To quantify the effects of numerous soil uncertainties on slope stability, many probabilistic approaches based on the limit equilibrium method have been presented to obtain a reliability index for a slope (Vanmarcke 1977, Li and Lumb 1987, Christian *et al.* 1994, Low and Tang 1997, El-Ramly *et al.* 2002, Babu and Singh, 2010). A few studies of probabilistic approaches to infer the uncertainties of unsaturated soil properties have also been reported (Chong *et al.* 2000, Rubio *et al.* 2004, Zhang *et al.* 2005, Phoon *et al.* 2010). However, approaches that yield a reliability index for a slope have been applied to steady-state slopes. Attempts at formulating reliability-based approaches considering temporal fluctuations in unsaturated soil slope data obtained by SHM systems have not been undertaken thus far.

In this paper, we present a reliability-based model for assessing slope stability for automatically monitored unsaturated matric suction. The assessment model was based on the limit equilibrium model for infinite unsaturated slope failure. The first-order reliability method was adopted to calculate slope reliability indices. To validate the accuracy and efficiency of the suggested model, the results were compared with those of a Monte-Carlo simulation (MCS) at matric suction values measurable with the monitoring system. The contribution of random variables to the slope reliability index was also examined by a sensitivity analysis. Finally, the reliability indices of an unsaturated model soil slope, which was monitored by a wireless matric suction monitoring system, were illustrated as 2D images using the suggested probabilistic model.

2. Reliability assessment model for unsaturated infinite slopes

2.1 Safety factor for unsaturated infinite slope

In many cases, most of a soil slope can be located above the ground water table. The slope above the ground water table should be in an unsaturated soil condition that develops matric suction ψ, which corresponds to the difference between pore air pressure u_a and negative pore water pressure u_w. The matric suction causes an increase in the shear strength of the soil. Thus, the matric suction term can be considered a stress state variable for the geotechnical analysis such as the stability of slopes and embankments, the bearing capacity of foundations, and lateral pressures exerted on earth-retaining structures. To account for the influence of matric suction on soil shear strength, Fredlund *et al*. (1978) suggested a modified Mohr-Coulomb shear strength criterion with two stress state parameters, as follows

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \tag{1}$$

where c' is the effective cohesion, σ_n is the normal stress, ϕ' is the effective friction angle, and ϕ^b is the angle defining the increase in shear strength by an increase in matric suction. Rainfall-induced slope failures usually occur at shallow failure surfaces that are parallel to the slope surface (Rahardjo *et al.* 1994). Using the unsaturated soil shear strength criterion given by Eq. (1) and the limit equilibrium model, the safety factor for an unsaturated soil slope along the depth z can be defined as

$$F_s = \frac{c' + \gamma z \cos^2\alpha \tan\phi' + (u_a - u_w)\tan\phi^b}{\gamma z \sin\alpha \cos\alpha} \tag{2}$$

where F_s is the safety factor of the slope, γ is the total unit weight of the soil, and α is the slope angle. Although ϕ^b shows non-linear behavior which decreases with increasing suction, it shows behavior similar to that of the effective friction angle ϕ' at low matric suction values (Fredlund *et al.* 1987). For simplicity, ϕ^b was assumed to be equal to the effective friction angle ϕ' in this study. Eq. (2) can then be rewritten as follows

$$F_s = \frac{c' + \{\gamma z \cos^2\alpha + (u_a - u_w)\}\tan\phi'}{\gamma z \sin\alpha \cos\alpha} \tag{3}$$

During rainfall, the safety factor of the slope expressed in Eq. (3) decreases as matric suction (u_a-u_w) is reduced. The safety factor for an unsaturated soil slope can thus be regarded as function of matric suction with time.

2.2. Reliability method

To apply the probabilistic approach to an unsaturated soil slope, the failure criterion of the slope should be identified via the limit state function $G(\mathbf{X})$. The limit state function defines safe and non-safe regions in the state space of random variable X. $G(\mathbf{X}) > 0$ indicates that a slope is stable, and $G(X) \leq 0$ means that it is not. The limit state function of an unsaturated infinite soil slope can be defined, using the safety factor indicated in Eq. (3), as follows

$$G(\mathbf{X}) = F_s - 1 \tag{4}$$

where $\mathbf{X}$ is a vector of random variables in the reliability analysis of an unsaturated slope. The probability of failure, P_f, can be defined as

$$P_f = P\{G(\mathbf{X}) \leq 0\} = \int_{G(X) \leq 0} f(\mathbf{X})dx \tag{5}$$

where $f(\mathbf{X})$ is the joint probability density function of the random variables. In practice, the calculation of Eq. (5) in reliability analysis is very difficult, because identification of the joint probability density function is hard and multiple integration over the failure domain is sometimes impossible.

The reliability index is a general approach for approximating P_f using means and standard deviations of the random variables. The reliability index β can be defined as

$$\beta = \frac{\mu_G}{\sigma_G} \tag{6}$$

where μ_G and σ_G are mean and standard deviation, respectively, of the limit state function $G(\mathbf{X})$. If random variables are assumed to be normally distributed, the probability of failure can be calculated by

$$P_f = \Phi(-\beta) \tag{7}$$

where Φ is the cumulative normal density function.

2.2.1 Mean Value First-Order Second-moment Method (MVFOSM)

The Mean Value First-Order Second-Moment Method (MVFOSM) calculates the mean and standard deviation of the limit state function using first-order terms in a Taylor series approximation (Cornell 1971). The mean value of the limit state function in Eq. (4) can be obtained by

$$\mu_G = G(\mu_X) = F_s(\mu_X) - 1 \tag{8}$$

where μ_X is mean value of random variables. The standard deviation of the limit state function can be obtained as follows

$$\sigma_G^2 = \sigma_{F_s}^2 = \sum_{i=1}^{n}\sum_{j=1}^{n}\left(\frac{\partial F_s}{\partial X_i}\right)\left(\frac{\partial F_s}{\partial X_j}\right)\sigma_{X_i}\sigma_{X_j}\rho_{X_i, X_j} \tag{9}$$

where σ_{Xi} is the standard deviation of random variable X_i, and $\rho_{Xi, Xj}$ is the correlation coefficient between random variables X_i and X_j. In most cases, the closed form solution of the partial derivatives in Eq. (9) is difficult or impossible to calculate. The partial derivatives were calculated by a numerical approach using the Corps of Engineers methodology for reliability analysis (U.S. Army 1993) as follows

$$\frac{\partial F_s}{\partial X_i} = \frac{F_s(\mu_{X_i} + m\sigma_{X_i}) - F_s(\mu_{X_i} - m\sigma_{X_i})}{2m\sigma_{X_i}} \tag{10}$$

If n is the number of random variables for slope reliability, $2n$+1 calculations of F_s are required to obtain the reliability index β in Eq. (6) using MVFOSM. The parameter m is the number of standard deviations to be deducted from the mean. When m takes a value greater than 1, the reliability index β is calculated to be constant (Hassan and Wolff 1999). Therefore, it is reasonable to adopt m=1 in this study.

2.2.2 Advanced First-Order Reliability Method (AFORM)

The Advanced First-Order Reliability Method (AFORM) is a complementary method to overcome a lack of invariance in MVFOSM. If the random variables are converted to standard normal form, the reliability index can be calculated as the minimum distance between the mean value points and the limit state surface (Hasofer and Lind 1974). The reliability index based on the AFORM can be regarded as the solution to the problem of finding the minimum for the following equation using optimization

$$\beta = \min_{\boldsymbol{Z} \in F} \sqrt{\boldsymbol{Z}^T \boldsymbol{R}^{-1} \boldsymbol{Z}} \tag{11}$$

where $\boldsymbol{R}$ is the correlation matrix of random variables and $\boldsymbol{Z}$ is a vector of the standard normalized random variables. The vector $\boldsymbol{Z}$ can be defined as follows

$$\boldsymbol{Z} = \frac{\mathbf{X} - \boldsymbol{\mu}}{\boldsymbol{\sigma}} \tag{12}$$

where $\boldsymbol{\mu}$ is a vector of the means of the random variables, and $\boldsymbol{\sigma}$ is a vector of the standard deviations of the random variables. The design point of the limit state surface $\boldsymbol{Z}^*$ can be defined as

$$\boldsymbol{Z}^* = \beta\boldsymbol{\alpha} \tag{13}$$

where α is a direction cosine vector at the design point.

2.3. Procedure for real-time unsaturated slope reliability assessment

The procedure for real-time unsaturated slope reliability assessment can be summarized as follows:

Step 1: Preliminary investigation of unsaturated slope properties

To identify the limit state function $G(\mathbf{X})$, six parameters such as the effective cohesion c', effective friction angle ϕ', matric suction $(u_a$-$u_w)$, unit weight γ, angle of slope α, and depth z must be determined. Among these parameters, the effective cohesion c' and effective friction angle ϕ' are usually considered steady-state random variables in general slope reliability analysis (Li and Lumb 1987, Hassan and Wolff 1999, Xu and Low 2006). For unsaturated slope reliability assessment, matric suction $(u_a$-$u_w)$ is added as a transient random variable to the general slope reliability problem. Thus, the mean and standard deviation of c' and ϕ', as well as deterministic values for γ, α, and z must be investigated in advance before monitoring.

Step 2: Estimating the mean and standard deviation of the monitored matric suction

Among the soil parameters comprising F_s in Eq. (3), matric suction $(u_a$-$u_w)$ can be a transient parameter, which varies with time and rainfall events. The probabilistic analysis requires the mean and standard deviation of monitored data. In this study, the sensor reading of matric suction is assumed to be the mean value. Such approaches that assume the sensor reading as the mean were introduced by structural reliability studies for smart health-monitoring applications (Frangopol *et al.* 2008, Catbas *et al.* 2008). The standard deviation of the monitored data can be determined by various methods such as Bayesian updating techniques, soft computing methods, experimental or literature value, and so on. In this study, linear interpolation of standard deviation using experimental data was used to estimate the standard deviation of the monitored matric suction.

Step 3: Evaluating real-time unsaturated slope reliability

Based on the deterministic parameters (γ, α, and z) and steady random variables (c' and ϕ'), the real-time unsaturated slope reliability can be estimated with the suggested reliability assessment model in Eqs. (6) and (11) using the monitored matric suction $(u_a$-$u_w)$. The calculated reliability is plotted as a filled contour image with time and depth using the interpolating and contour functions in MATLAB, which allow easy and eidetic decision-making for the user.

3. Model validation

To validate the applicability of the proposed model, the model was compared to the results of MCS in the range of field-measureable matric suction values. MCS is an iterative simulation technique used to evaluate the functions of random variables. It is also known to give a relatively accurate value for the probability of failure. For reliability analysis, computer simulations were performed in MATLAB code. On 1,000,000 trials, random numbers were generated for MCS by Latin hypercube sampling. The effective cohesion c', effective friction angle ϕ', and matric suction $(u_a$-$u_w)$ were considered random variables, while the unit weight γ, angle of slope α, and depth z were considered deterministic. All random variables were assumed to be normally distributed. The basic statistics of these random variables are summarized in Table 1. In particular, the coefficient of variation (COV) of matric suction was determined by mean values and standard deviations of 6 soil samples for corresponding degree of saturation levels. The experimental data of soil water characteristic curve (SWCC) for COVs, which is classified as loamy sand, are shown in Fig. 1. The COVs of the matric suction are plotted as a function of the mean matric suction in Fig. 2.

Table 1 Mean and COV of random variables for validation problem

Parameters	Mean	COV (%)	Distribution	Source
Effective cohesion c' (kPa)	12.0	40.0	Normal	Fredlund and Dahlman (1971)
Effective friction angle ϕ' (°)	20.0	10.0	Normal	Phoon and Kulhawy (1999)
Matric suction (u_a-u_w) (kPa)	0 ~ 100.0	10.0 ~ 50.0	Normal	
Unit weight γ (kN/m^3)	18.816	-	Deterministic	
Angle of slope α (°)	45.0	-	Deterministic	
Depth z (m)	0.45	-	Deterministic	

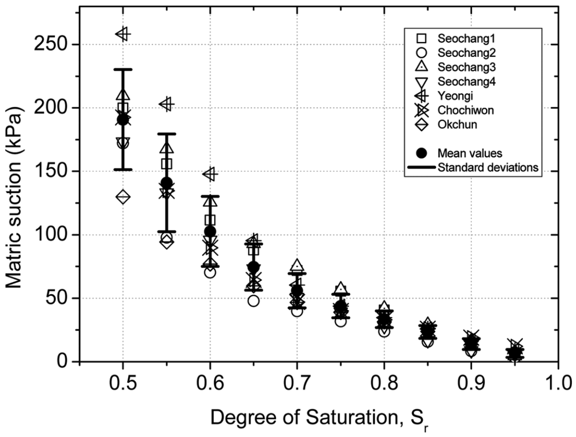

Fig. 1 Experimental SWCC for weathered granite soils at 4 sites in Korea

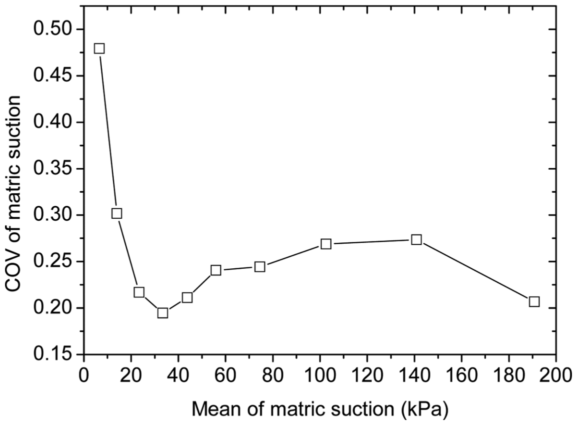

Fig. 2 COV of matric suction as a function of the mean matric suction

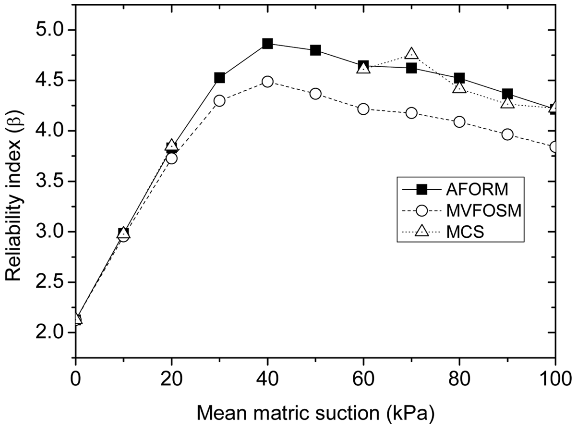

Fig. 3 Comparison of the proposed reliability assessment method with MCS

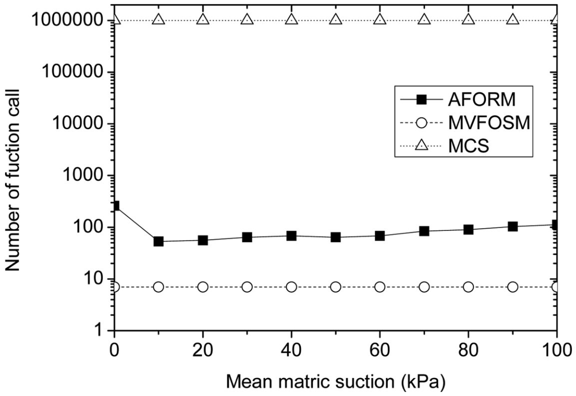

Fig. 4 Comparison of the number of function calls for each reliability assessment method

Fig. 3 shows analysis results of the proposed model to validate the accuracy of real-time assessment. When the mean matric suction values became larger, the reliability index increased. The reliability index was similar for MVFOSM and AFROM at lower values of mean matric suction. At high values of mean suction, MVFOSM gives lower reliability indices than those of AFORM. Although MCS failed to calculate reliability indices between 30 to 50 kPa despite the large number of trials, the results of the reliability assessment model based on AFORM were in good agreement with the MCS results throughout most of the range.

In real-time slope stability assessment, efficiency, i.e., how fast we calculate stability, is as important as accuracy. Thus, we compared the number of function calls in each method to verify their efficiency. Fig. 4. shows the number of function calls for each model during the analysis. For MVFOSM, $2n$+1 calculations of F_s are required to obtain the reliability index, one for the mean of the limit state function and $2n$ for the standard deviation of the limit state function. When c', ϕ', and (u_a-u_w) are considered random variables, the number of function calls for MVFOSM can be seven. For AFORM, the number of function calls was around 100. The number of function calls for AFORM may be determined by the tolerance for their optimization function in MATLAB. However, compared to the results with MCS, which requires a large number of trials and more than 1,000,000 times trials, the AFORM approach gives reasonable results with a relatively small number of trials for real-time stability assessment.

4. Sensitivity analysis

To identify the contribution of each random variable to the unsaturated slope reliability, sensitivity analyses using the direction cosine vector $\boldsymbol{\alpha}$ in Eq. (13) were performed. The sensitivity of the standard deviation for each random variable can be indicated as follows (Hohenbichler and Rackwitz 1986)

$$\frac{\partial \beta}{\partial \sigma_{X_i}} \approx -\beta \alpha_{X_i}^2 \tag{14}$$

The sensitivity of the standard deviation for each random variable (effective cohesion c', effective friction angle ϕ', and matric suction (u_a-u_w)) to the field-measurable values of mean matric suction is shown in Fig. 5. The effective cohesion c' is the most influential random variable at lower values of mean matric suction. However, the influence of matric suction becomes more important at high values of mean matric suction. The influence of the effective friction angle ϕ' is relatively small for all matric suction values. The results indicate that consideration of fluctuations in matric suction is important in unsaturated slope reliability assessment. In addition, the results help explain why the results of MVFOSM in

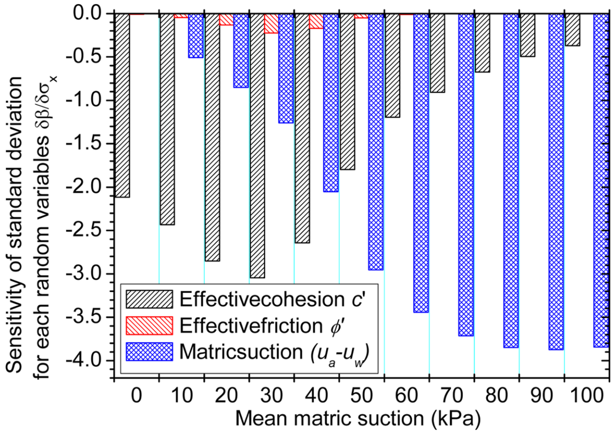

Fig. 5 Sensitivity of the standard deviation of each random variable

Fig. 3 are lower at high values of mean matric suction. The reason is that the large influence of the matric suction term at high matric suction values triggered nonlinearity of the limit state function in Eqs. (3) and (4), causing a lack of invariance in MVFOSM. This means that AFORM can be a more suitable method than MVFOSM for unsaturated slope stability assessment.

5. Field application

5.1 Model slope and monitoring system

The suggested method was applied to a model slope built in a test bed. The height and angle of the model slope were 2.0 m and 45º, respectively. The soil at the monitoring site was classified as loamy sand; the soil properties of the model slope are summarized in Table 1. Two types of sensors and a wireless data acquisition module were used for the monitoring system: a tensiometer for matric suction, a tipping-bucket rain gage for rainfall amount, and a V-Link for the wireless data acquisition module.

A jet-fill tensiometer from Soilmoisture Equipment Corporation and a pressure transducer (model: GT3-15) from ICT International Pty Ltd were used for monitoring matric suction. The jet-fill tensiometer consisted of a water-filled plastic tube, a high air entry ceramic tip, and a pressure transducer. When the tensiometer was inserted into the soil with filled water, the water moved through the ceramic tip until equilibrium was reached between the forces inside and outside of the tensiometer. When the water movement stopped, the soil matric suction could be measured with the pressure transducer. The capacity of the tensiometer was 100 kPa. The tensiometers were installed at 0.3, 0.45, 0.6 and 0.9 m depths.

A tipping-bucket rain gage (model: TE525WS) from Campbell Scientific, INC. was used for monitoring rainfall amount. The resolution of the rain gage was 0.254 mm.

A V-Link from MicroStrain Inc. was used for wireless data transmission and acquisition. The V-Link consisted of the A/D converter, Flash memory, and RF transceiver. The A/D converter had 12 bit resolution and converted analog data received by the sensors into digital data. The flash memory kept the data received by the sensors. The RF transceiver, which wirelessly transmitted data, had 4 different channels for pressure transducers. Thus, 3 or 4 tensiometers were installed at one node. The

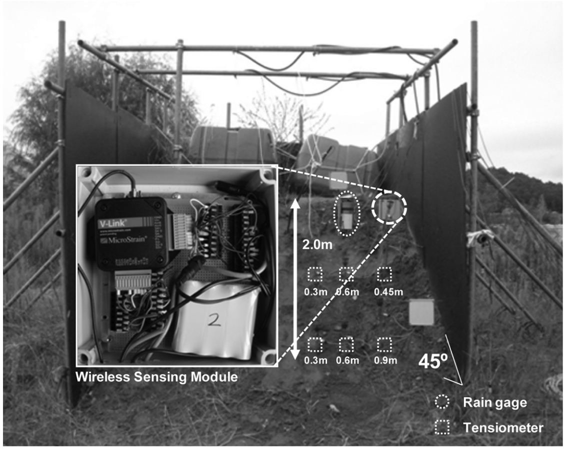

Fig. 6 Model slope and monitoring system

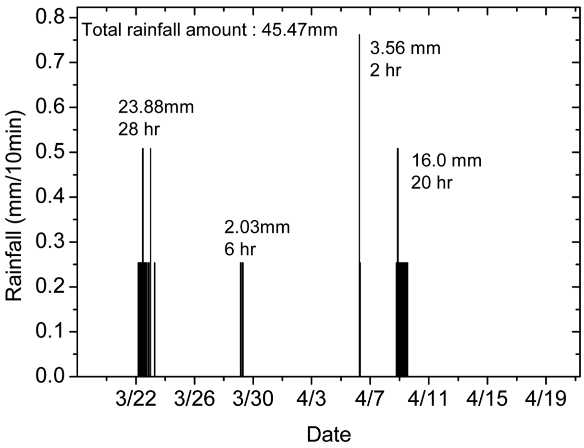

Fig. 7 Rainfall amount during monitoring

data received in the wireless module were transmitted to the gateway, and the data were interpreted using the suggested model for slope stability assessment.

5.2 Measured data

Monitoring was performed for about 1 month, from the 18th of March to the 21st of April in 2008. The data were statically measured every 10 min. The measured amount of rainfall is shown in Fig. 7. During monitoring, the total amount of rainfall was 45.47 mm. The biggest rainfall occurred on March 22nd, during which 23.88 mm of rainfall was recorded in 28 h. Fluctuations in the matric suction were measured with the tensiometers in the model slope, and the measured values were interpreted by a 2D image plot using interpolation and extrapolation techniques in MATLAB code. The measured matric suction during the monitoring period are shown in Fig. 8. The matric suction dropped suddenly after rainfall began. Positive pore water pressure developed as a result of the rainfall infiltration at the surface of slope. After rainfall stopped, the soil water became desiccated at

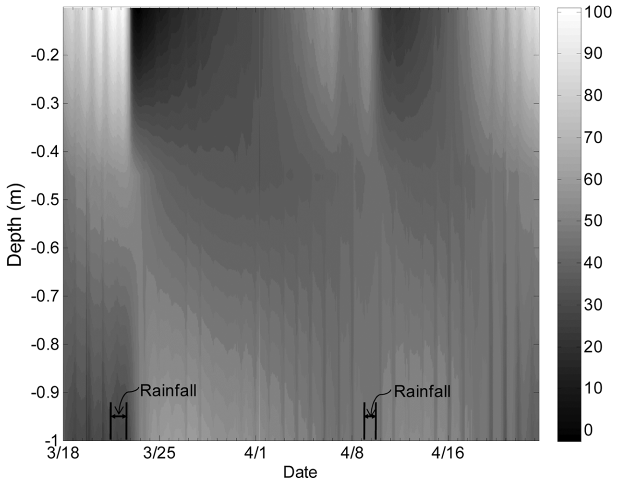

Fig. 8 Measured matric suction distribution during monitoring

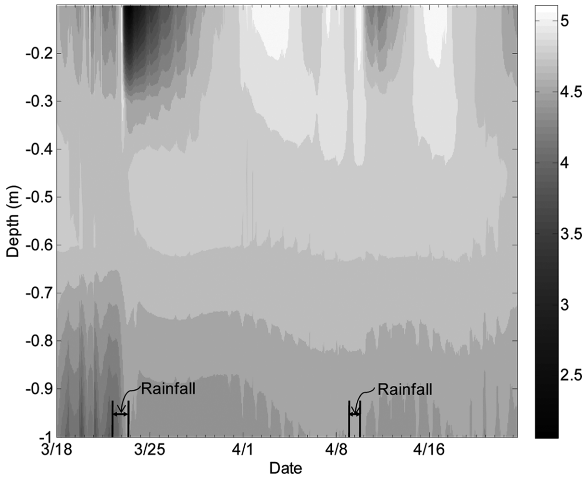

Fig. 9 Reliability index distribution during monitoring

the surface. However, some of the soil water infiltrated deeper areas. This result indicates that the deeper soil can have lower shear strength even after rainfall stops. The variation in matric suction at relatively greater depths was not as sensitive as that at the surface.

5.3 Reliability assessment

The slope reliability index considering the measured matric suction was evaluated with the proposed AFORM approach. The effective cohesion c', effective friction angle ϕ', and matric suction $(u_a\text{-}u_w)$ were considered random variables (Table 1). The measured matric suction was also used to calculate the COV (Fig. 2). The calculated reliability index during monitoring is shown in Fig. 9. The dark plots indicate a high probability of slope failure. The greater the depth, the lower the reliability index before rainfall begins. However, the reliability index at the surface decreased dramatically to 2.06 during rainfall. This corresponds to a 2% probability of failure. This is an unstable state if a reliability index of 3 or 4 is defined as the criterion for slope stability. Although this reduction also recovers quickly at the surface, it recovers at a slower rate at relatively greater depths. This can be explained if it is assumed that matric suction variation is the most significant factor to affect the reliability index, as previously discussed in the sensitivity analysis (Fig. 5). The change in the reliability index at the surface is larger than that at greater depths. According to this result, the control of rainfall infiltration into the slope would be the most effective way of increasing stability. The results of this analysis indicate that the probability of failure at every depth can be effectively quantified as a function of time by the proposed method.

6. Conclusions

A reliability-based slope assessment method considering the variation in monitored matric suction was proposed for identifying slope risk in real-time. The first-order reliability method (FORM) was adopted to calculate reliability indices of slope. To validate the accuracy and efficiency of the suggested model, the results were compared with those of a Monte-Carlo simulation (MCS) performed in the range of matric suction values measurable with the monitoring system. The analysis shows that the AFORM model generates results that are in good agreement with those of MCS with a relatively small number of function calls. The results of the sensitivity analysis also indicate that the effective cohesion c' is a significant variable at low matric suction values, whereas matric suction (u_a-u_w) is the most influential factor at high matric suction values. The importance of the friction angle ϕ' was estimated to be relatively low. Subsequently, the proposed method was applied to a model slope and the matric suction values were measured every 10 min for about 1 month. The model application results show that the reliability index at the surface changes considerably and becomes small during rainfall. The results also demonstrate that the reliability-based slope assessment method, which considers the monitored variation in matric suction, can quantify the slope risk and hence be an effective technique for slope monitoring and maintenance. The reliability-based slope stability criteria and statistical properties of the soil slope should be further studied for establishing practical reliability-based slope maintenance systems.

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