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Rail-Transport Operation Control under Rainfall for a Slope Monitoring System in Railroad Lines

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ABSTRACT

Recently various monitoring systems of a slope have been constructed along Korean railroad lines. Using these systems, we could secure safety of a train under rainfall condition. Rail-transport operation control (RTOC) under rainfall consist of 3 steps ; 'Warning', 'Speed reduction' and 'Train stop'. It is important to convert stability of a slope into rainfall index. Based on unsaturated soil mechanics, RTOC is suggested by slope stability analysis and it compare with the existing RTOC in KORAIL. It can help safety of a train to be secured and the regulation of monitoring systems to set up.

1. INTRODUCTION

Railroad is responsible for securing safe and stable transportation as a public transportation organization. In order to secure safe transportation from the disaster caused by such rainfalls, it is necessary to conduct thorough inspections of the dangerous sites and to perform counter-measures as well as appropriately implement the rail-transport operation control (RTOC). The RTOC currently in place domestically and internationally are mainly based on the experiential method or statistical analysis with the standards according to the correlation analysis of the rainfall, critical rainfall (Sugiyama et al., 1995) or effective rainfall (Suzuki et al., 1994), and disaster. These types of statistical analysis are effective only when a numerous data containing accurate information must be secured and it is difficult to apply statistical analysis to the region where only limited information is available. Moreover, since these methods are not based on engineering stability analysis, there is a potential for unpredictable disaster occurrence. And also various monitoring systems have been constructed along railroad lines. They monitored earth movement, pore water pressure, ground water level etc. as well as rainfall. Those systems should have their specification for warning sign.

In this study, rainfall infiltration and slope stability analysis are executed based on unsaturated soil mechanics concept. And method how to set up the RTOC is suggested for monitoring systems and rainfall warning system. Using this method, evaluation of slope stability and warning rainfall index are set up simultaneously.

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2. THEORETICAL BACK GROUND

Soil water characteristic curve (SWCC) is defined as matric suction with volumetric water contents. Researchers have been suggested their empirical method to evaluate SWCC. In this study, the prediction model (Fredlund and Xing, 1994) that can express the representative SWCC of all the unsaturated zone was used eq. (1).

$$S = \frac{\theta_w}{\theta_s} = \left[1 - \frac{\ln(1+\psi/h_r)}{\ln(1+10^6/h_r)}\right]\left[\left\{\frac{1}{\ln\{\exp(1)+(\psi/a)^n\}}\right\}^m\right] \tag{1}$$

where, S : degree of saturation, θ_w : volumetric water content, θ_s : saturated volumetric water content, ψ : soil suction, h_r : suction related to the volumetric residual water content, θ_r, a : suction related to the inflection point on the curve, n : soil parameter related to slope at the inflection point, m : soil parameter related to the residual water content.

By performing a direct shear test, the shear strength parameters (c', ϕ') were obtained and ϕ_b was obtained from the eq. (2) which was proposed by Fredlund et al. (1995).

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + \tan\phi' \int_0^{\psi} \left(\frac{S - S_r}{1 - S_r}\right) d(u_a - u_w) \tag{2}$$

where, τ : unsaturated shear strength, c' : effective cohesion, $(\sigma_n - u_a)$: net normal stress, ψ : soil suction, ϕ' : effective cohesion, S : degree of saturation, S_r : degree of saturation, $(u_a - u_w)$:matric suction, ϕ_b : angle of shearing resistance with respect to matric suction.

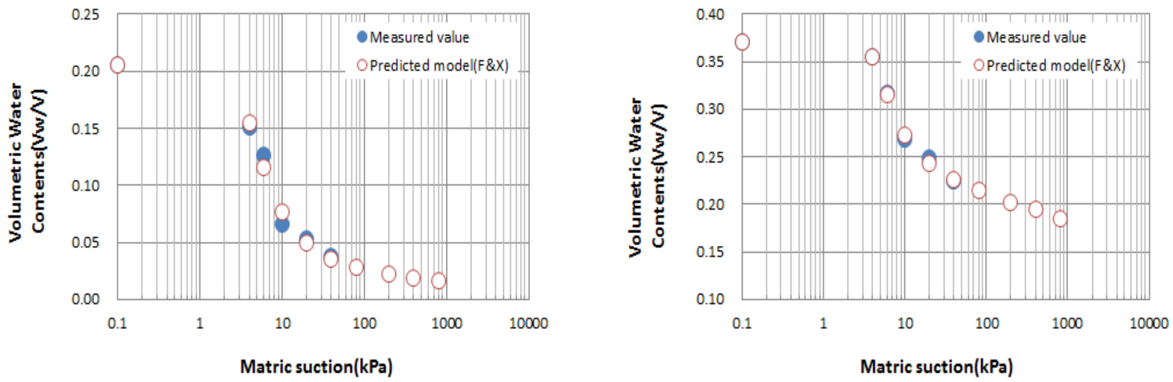

Fig. 1 SWCC for site A and B

The unsaturated hydraulic conductivity of the suction is obtained by eq. (3). This equation is proposed by Fredlund et al. (1994). It can be predicted that the hydraulic conductivity will be significantly reduced as the soil becomes unsaturated after Air-entry value (AEV).

$$k_r(\psi) = \sum_{i=j}^{N} \frac{\theta(e^{y_i}) - \theta(\psi)}{e^{y_i}} \theta'(e^{y_i}) dy \Big/ \sum_{i=1}^{N} \frac{\theta(e^{y_i}) - \theta(\psi)}{e^{y_i}} \theta'(e^{y_i}) dy \tag{3}$$

where, $k_r(\psi)$: relative permeability at suction, ψ, $\theta(\psi)$: volumetric water content at suction, ψ eq. (1), y_i : a dummy variable of integration representing the logarithm of suction, e : 2.718, N : ln(1,000,000)≅ 13.8

SWCCs were obtained by experimental study (Fig. 1) and they will use input data for numerical analysis to evaluate hydraulic conductivity and strength properties of unsaturated condition of each ground.

3. NUMERICAL ANALYSIS

According to the Korean Standard(KS spec.), the soil property tests such as grain-size distribution, specific gravity, hydraulic conductivity, and compaction were conducted to be shown in Table 1.

Table 1 Soil properties of each site

Site	γ_t (tf/m^3)	k_s ($cm/\sec$)	G_s	Friction angle (deg.)	Cohesion (tf/m^2)
A	1.917	1.79×10-3	2.668	29.7	6.5
B	1.9	1.64×10-3	2.660	31.5	7.1

For the ease of the analysis, it was assumed that the ground was structured with homogeneous soil and hydraulic conductivity of the ground was the same in both horizontal and vertical directions.

SEEP/W was used for the rainfall infiltration analysis for the rainfall that infiltrates inside the slope. A steady state analysis was performed under the initial condition of unsaturated infiltration analysis by introducing the ground water level. Transient state analysis of infiltration considering rainfall intensity and duration was conducted by applying the soil water characteristics and hydraulic conductivity of weathered granite soil to the slope. SLOPE/W was used to analyze the stability of railway slopes by rainfall infiltration. It makes the analysis possible by directly importing the results of the rainfall infiltration and allows the inclusion of the unsaturated shear strength function. And the design specification for slope stability analysis under rainfall was used by Ministry of Land and Transportation (2011).

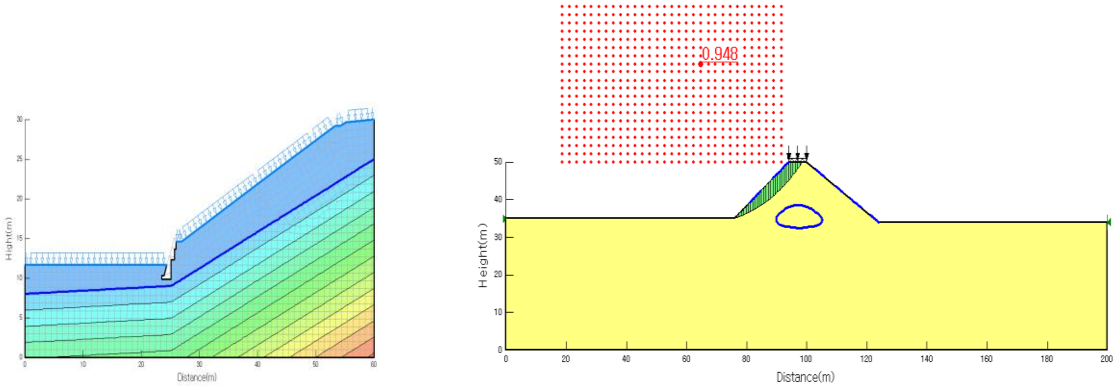

Fig. 2 an example of results of infiltration and slope stability analysis

4. THE RESULTS OF NUMERICAL ANALYSIS

4.1 The results

Variations in the safety factor (SF) of railroad slopes with hourly rainfall, rainfall duration and cumulative rainfall are shown in Figure 3~8. All results of the analysis show that the SF is decreased as the hourly rainfall, rainfall duration, and cumulative rainfall are increased.

As rainfall condition was applied, variation of the SF starts decrease. The SF decreases from initial 1.523 to final 0.941 for site A by rainfall infiltration of maximum 60mm/hr. After 10hours SF starts to vary and decreases for all rainfall condition. In case of site B, initial SF was calculated as 1.322. And it makes different condition with site A (Figure 3).

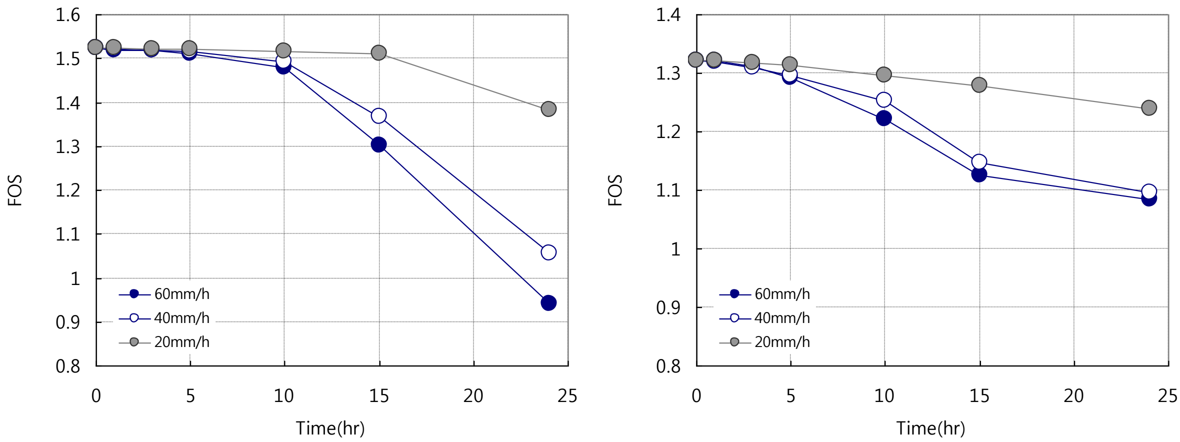

Fig. 3 Variation of the SF with rainfall duration time ; (A) and (B)

Though there is a little variation in initial stage, the SF with hourly rainfall greatly declined by increasing rainfall duration time. It means that the stability of a slope do not affected by surface infiltration rainfall but affected the variation of ground water level (Figure 4). In case of site A, the SF varies slightly with cumulative rainfall of 500mm but after that, greatly declined with increase of cumulative rainfall and hourly rainfall. Because initial SF is small, the SF decreases as cumulative rainfall increase in case of site B (Figure 5).

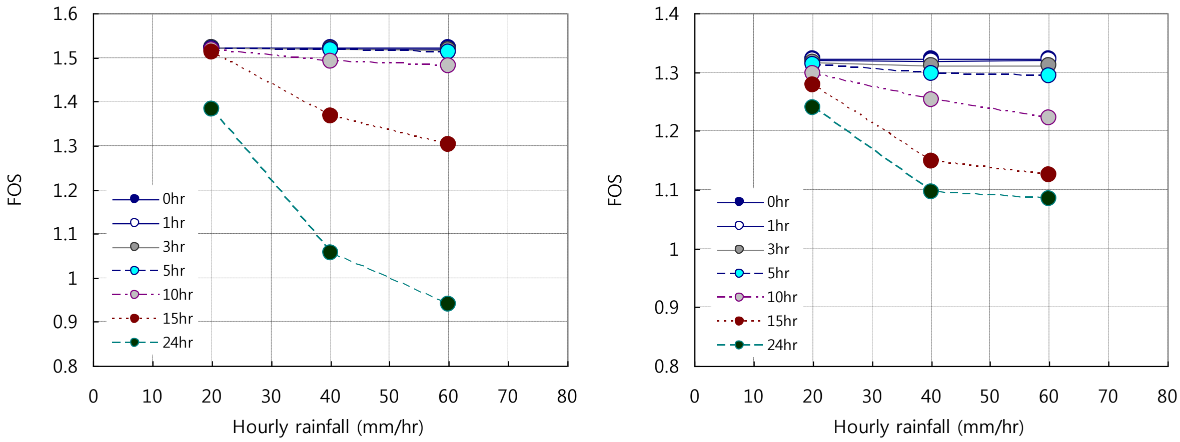

Fig. 4 Variation of the SF with hourly rainfall ; (A) and (B)

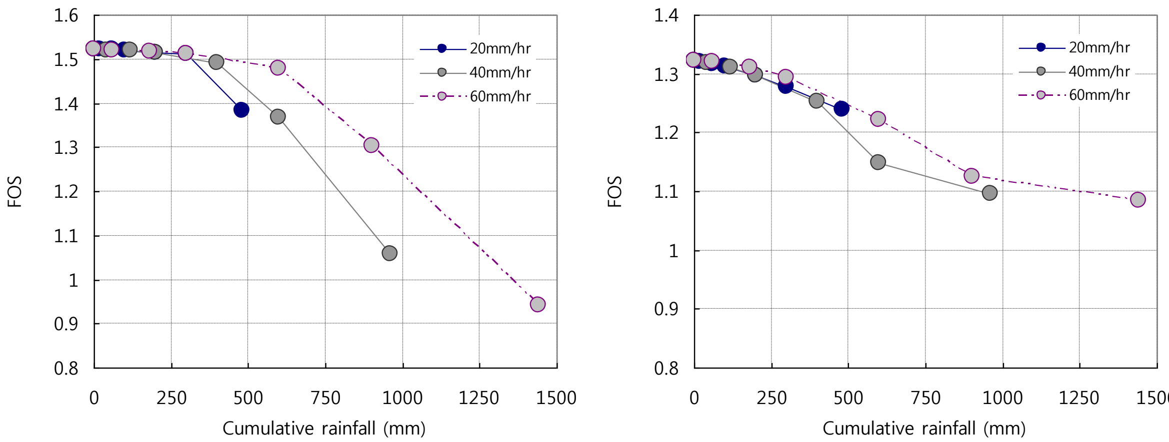

Fig. 5 Variation of the SF with cumulative rainfall ; (A) and (B)

4.2 Method to set up RTOC

When SF 1.3 is the standard specification, RTOC could set up by following steps. At first variation of SF must be calculated with hourly rainfall. Regression curve and equation is obtained from SF data. Then inverse calculation of hourly rainfall was executed applying SF 1.3 and regression equation. Finally calculate critical rainfall condition (hourly rainfall versus cumulative rainfall) related in rainfall duration time. This line divides stable and unstable region under rainfall. Additional signs such as ‘warning’, ‘speed reduce’ etc. were set up based on critical line from above steps applying 1/1.3, 1/1.5 for stable region. Figure 6 shows the comparison of this result with the current RTOC in KORAIL and critical rainfall in JR.

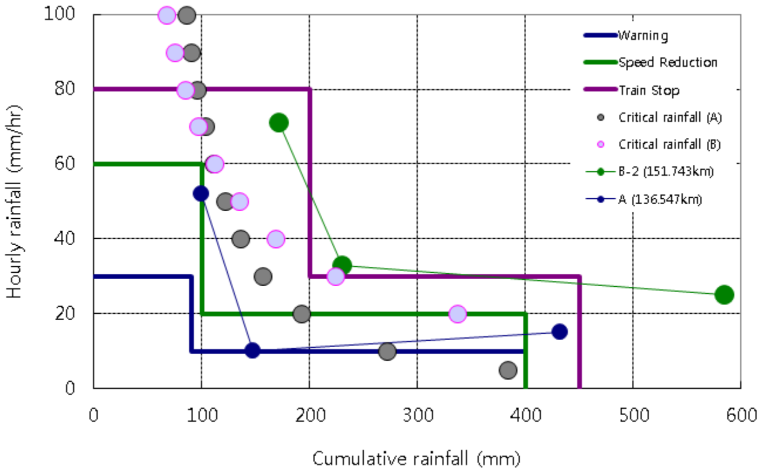

Fig. 6 The comparison of the RTOC

5. CONCLUSIONS

Railroad system has a responsibility to secure human and facilities from rainfall disaster. Safety of train running under rainfall condition must be retained by prediction of disaster such as RTOC. Current RTOCs are based on empirical and statistical method but, they have no engineering base. In this study RTOC having engineering base was suggested for modifying empirical method. Using this method RTOC of each railroad slope can easily set up for disaster mitigation. Furthermore specification for warning sign of slope monitoring systems also easily was made up. Using this method, evaluation of slope stability and warning rainfall index are set up simultaneously.

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