Physical Modelling in Geotechnics

Introduction to coupled analysis for slope stability considering rainfall

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ABSTRACT: Due to recent climate change, rainfall intensity from June to August in Korea is increasing. As a result, there are many cases in which the slope is failed. In this regard, it is necessary to analyze the slope stability considering the rainfall. Generally, Limit Equilibrium Method(LEM) is widely used in the existing slope stability analysis. However, the LEM provides a safety factor for shear strength, but does not consider displacement. In recent years, with the development of measurement technology, it has become possible to obtain real-time measurement data of slope. But the studies on the correlation between the measured displacement and the stability factor of the slope are still insufficient. Therefore, in order to analyze the slope stability using the displacement measured in real time with rainfall, the linkage between the seepage analysis using Seep/W and the slope stability analysis using FLAC which can consider displacement will be applied.

Keywords: Rainfall, Seepage Analysis, Seep/W, Slope Stability Analysis, FLAC.

1 INTRODUCTION

Korea has a climatic condition in which the average annual rainfall is concentrated between June and August. Most of the slope failure in the rainy season is caused by the infiltration of rainfall. In particular, the heavy rains that occurred around July and August, 2020, caused social losses, such as casualties due to landslides or slope collapse. This is known to be because the matric suction of the soil of the slope is reduced by rainfall (Fredlund, 1995).

Based on the above situation, slope stability analysis was carried out considering rainfall. Lim (2008) calculated the factor of safety of the slope over time by considering the wetting front and the groundwater level during rainfall. Kim et al. (2019) conducted a slope stability analysis by linking the results of seepage analysis between programs of different origins to the slope stability analysis. After performing the seepage analysis considering the rainfall that meets the various design criteria regardless of the program type, it was confirmed that numerical analysis can be performed by reflecting the rainfall conditions in the same way with the slope stability analysis.

There are Finite Element Method(FEM), Finite Difference Method(FDM), and Limit Equilibrium Method(LEM) to evaluate slope stability and the LEM is generally used as in the previous studies. In the LEM, the strength-displacement characteristic of soil is non-brittle, and the value of shear strength is the same even when the large displacements occurred. This assumption is necessary because LEM does not consider displacement. In the FEM and the FDM, the slope stability is evaluated using the Shear Strength Reduction Method (SSRM). This method can estimate the deformation, stress, and pore pressure of the ground (Kim, 1999). Therefore, the SSRM can consider displacement, while the LEM cannot consider it.

In addition, with the recent development of measurement technology, it has become possible to obtain real-time measurement data for slopes. However, since the slope stability using the LEM cannot reflect slope measurement data, it is difficult to examine real-time stability changes.

Therefore, in this study, the maximum daily rainfall for about 10 years in Cheorwon, Gangwon-do, which is exposed to the risk of landslides, is selected. The type of soil that forms the slope is assumed to be the medium sand. Using Seep/w, which is the seepage analysis program, and the FLAC, based on the FDM, analyzes the stability of the slope considering the infiltration of the slope with rainfall. And presents a coupled analysis method that can consider the displacement that can be compared with real-time measurement data.

2 COUPLED ANALYSIS

The pore pressure occurred by the rainfall is calculated through Seep/W, and this result is applied as the initial condition in the FLAC model. Next, the factor of safety of the slope is calculated through the SSRM in FLAC, and the results such as displacement and SSI (Shear Strain Increment) are reviewed. Through this process, the stability of the slope according to the rainfall intensity can be quantitatively reviewed. In Fig. 1., the process of the entire analysis is shown.

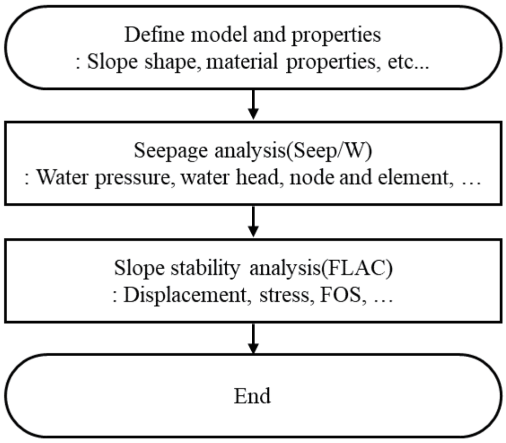


Fig. 1. Flowchart for Coupled Analysis

2.1 Seepage analysis

Seepage analysis should be preceded for the coupling between the seepage analysis affected by the rainfall and the slope stability analysis. After, the seepage analysis is performed, the pore pressure and total head of each node remain. Slope stability analysis is performed based on the results of the seepage analysis.

2.2 Slope stability analysis

The process of the SSRM is shown in Fig.2.. The SSRM introduce the trial factor of safety(F^{trial} in Eq.(1), Eq.(2)) to find the F^{LL} in Fig. 2. which is the value of factor of safety when the slope failure occurs. The F^{trial} increase until it is converged while the trial variables(c^{trial} in Eq.(1), ϕ^{trial} in Eq.(2)) are decreasing. The input variables(c n Eq.(1), ϕ in Eq.(2)) are fixed.

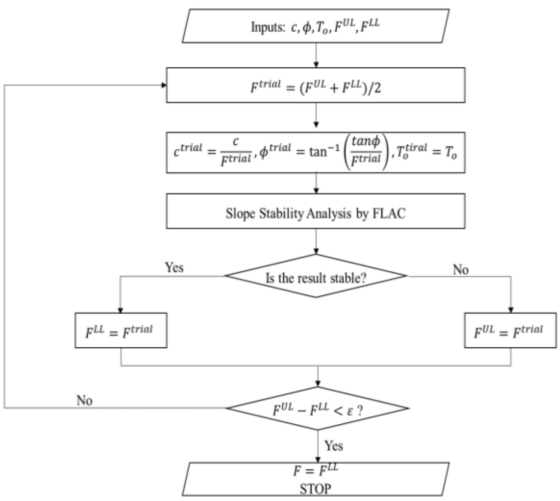


Fig. 2. Flowchart for Shear Strength Reduction Method Graph

$$c^{trial} = \frac{1}{F^{trial}} c \qquad \text{Eq.(1)}$$

$$\phi^{trial} = arctan(\frac{1}{F^{trial}} tan\phi) \qquad \text{Eq.(2)}$$

And the strength parameter is calculated by the Eq.(4), Eq.(5). The SSRM use the Mohr-Coulomb model and the Hoek-Brown model among various ground material models. In this study, the Mohr-Coulomb model was used because it can consider the strength parameter from the general ground survey.

$$\mathrm{u} = \gamma_w \cdot h \qquad \text{Eq.(3)}$$

$$s = c' + \sigma' \cdot tan\phi' \qquad \text{Eq.(4)}$$

$$s = c' + (\gamma_t \cdot a + \gamma_{sat} \cdot h - \gamma_w \cdot h) \cdot tan\phi' \qquad \text{Eq.(5)}$$

Among the result of Seepage analysis, the pore pressure u(Eq.(3)) is used. Since the hydraulic condition that can only be considered with the slope stability analysis is the hydrostatic condition, the pore pressure can be used in Eq.(5) (Kim et al., 2019)

3 NUMERICAL ANALYSIS

3.1 Result of the Seepage Analysis

It is assumed as the steady-state during the seepage analysis, because the result of steady-state analysis is higher than the transient analysis. The steady-state analysis is conservative considering the safety of slope. (Seo, 2014) The rainfall is considered as the boundary condition in Seep/W. The input rainfall is $4.44e - 6\,m^3/sec\,/m^2$ the condition of Cheorwon, Gangwon-do in Korea. It is from the most maximum rainfall of a day from 2012 to 2021 (10 years), and transferred to the rainfall in a second. And the bottom of the model's water head is zero since it is the starting line. The soil is assumed as medium sand. The input variables for the seepage analysis is in Fig. 3. and Fig. 4. And the saturated hydraulic conductivity is $0.0014 m/sec$. (Rulon and Freeze, 1985)

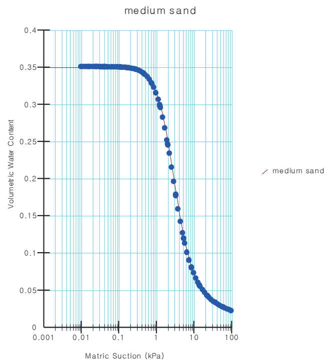


Fig. 3. Soil Water Characteristic Curve in Seep/W

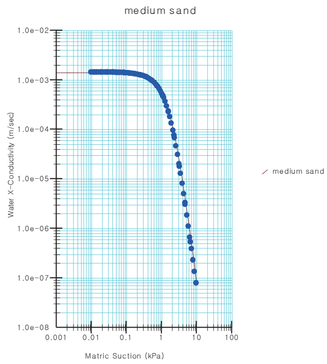


Fig. 4. Hydraulic Conductivity Curve in Seep/W

As a result of seepage analysis, results such as pore pressure and water total head can be obtained for each node. According to the Fig. 5. the pore pressure is presented at each node in the slope, so that infiltration has occurred

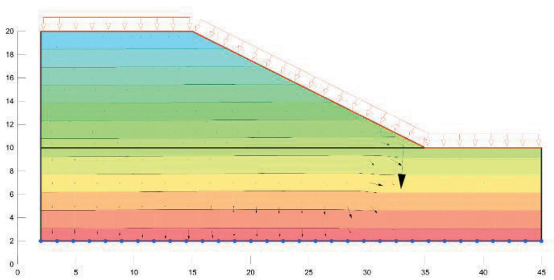


Fig. 5. Model and Result of the Seepage Analysis in Seep/W

3.2 Result of the Slope Stability Analysis

Similar to the model in Seep/W, after entering the soil parameters of medium sand, the model shown in Table. 1. is built. Then, the slope stability analysis was conducted without rainfall and with rainfall. The factors of safety of each cases are shown in the Table. 2. and the results of the analysis are shown in Table. 4.

The factor of safety before the rainfall is appeared to be 1.93, the failure shape of the slope is circular. After the rainfall the factor of safety is 1.79. The displacements increased in both x-axis and y-axis directions after the rainfall. It is because that the effective stress of soil is decreased because of the pore pressure

Table 1. Soil parameters in FLAC

<table>
<tr><td>Unit Weight</td><td colspan="2">Friction Angle</td><td>Cohesion</td></tr>
<tr><td>1845 kg/m^3</td><td colspan="2">29°</td><td>11e3 kg/m^2</td></tr>
<tr><td colspan="2">Bulk Modulus</td><td colspan="2">Shear Modulus</td></tr>
<tr><td colspan="2">24.44e6 kg/m^2</td><td colspan="2">8.15e6 kg/m^2</td></tr>
</table>

Table 2. Factor of Safety

Case	**FOS**
Without Considering Seepage Analysis	1.93
Considering Seepage Analysis	1.79

3.3 Introduction of Method of Utilizing the Result

Based on the results of Seep/W and FLAC, the displacements were calculated back in the not stable cases to utilize the real-time measurement data. After dividing the *c, ϕ* by the factor of safety, the *c, ϕ* when the factor of safety is 1.00 are calculated. The displacements at this moment in Table 5. can be obtained like the values in Table. 3.. If the factors above are accumulated as a database and compare it with the real-time measurement data, the safety of the slope in the field can be checked

Table 3. Soil Parameters in Each FOS

<table>
<tr><td rowspan="2">FOS
1.79</td><td>Friction angle</td><td>Cohesion</td></tr>
<tr><td>29°</td><td>11e3 kg/m^2</td></tr>
<tr><td rowspan="2">FOS
1.00</td><td>Friction angle</td><td>Cohesion</td></tr>
<tr><td>16.2°</td><td>6.15e3 kg/m^2</td></tr>
</table>

4 CONCLUSIONS

The factor of safety decreased from 1.93 to 1.79 after the rainfall. Because of the infiltration of rainfall to the slope, the pore pressure increased and this affected the decrease of safety of slope.

The coupled analysis between the Seep/W for seepage analysis, and the FLAC for slope stability analysis was available. And the conversion of model was possible.

Through this analysis process, the results about the displacements can be obtained and these can be compare with the real-time measurement in further research.

If the database about the displacements and the factor of safety according to the rainfall is built through this coupled analysis, the safety of the slope can be found directly in any rainfall.

Table 4. Result of Slope Stability Analysis

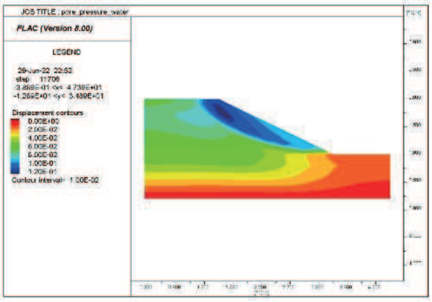
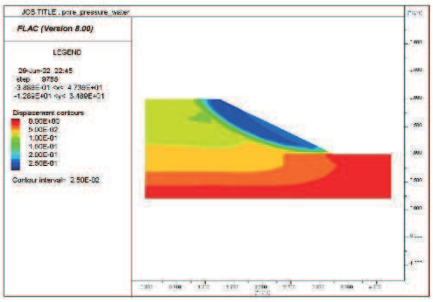
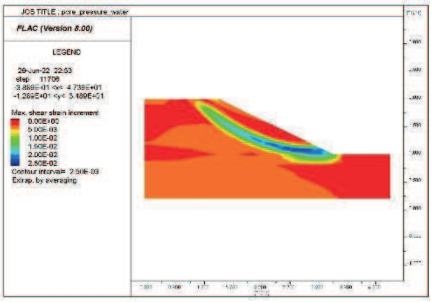
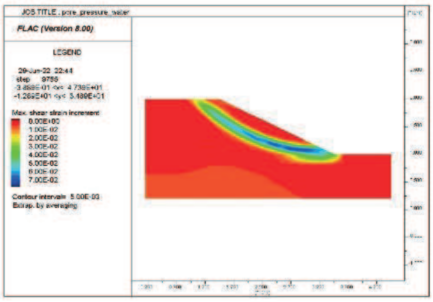
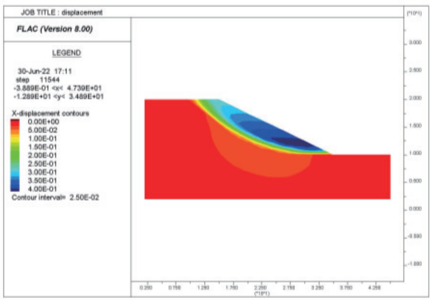
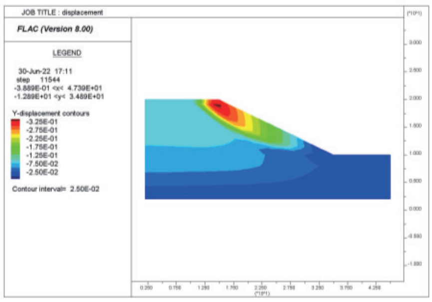
Displacement Without Rainfall	Displacement With Rainfall
	
SSI Without Rainfall	SSI With Rainfall
	

Table 5. Displacements in FOS = 1.00

Displacement x (FOS = 1.00)	Displacement y (FOS = 1.00)
	

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