Simulation of rainfall-induced Slope Failure using Distinct Element Analysis and Seepage Analysis

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Introduction

Rainfall has caused many landslides and slope failures in numerous areas throughout the world. Such rainfall-induced slope failures are common in Hokkaido, the northern island of Japan. The volcanic slopes found in Hokkaido have a strong potential to cause failure due to heavy rainfall and cyclic freeze-thaw action. It is important to accurately study the failure mechanism of slopes formed from these soils.

It is known that the change in matric suction in soils is crucial to the behavior of unsaturated slopes as it affects the shear strength of soils (Fredlund and Rahardjo 1993). Moreover, Kawamura et al (2009) reported that an impermeable layer inside the slope caused by freeze-thaw action is an important consideration when evaluating slope failures in cold regions. Therefore, it is indispensable to consider the effect of water distribution and water flow in the slope.

For numerical simulations of slope failure, discontinuous analysis and seepage analysis have been often utilized by many researchers. The Distinct Element Method (DEM) is a discontinuous numerical method developed and applied for analyzing rock mechanics proposed by Cundall (Cundall 1971). This is an effective method to analyze and simulate the dynamic mechanical behavior of granular soils as it can simulate the flow movement of soils in the case of slope failure. Seepage Analysis based on Finite Element Method (FEM) is an ideal method to simulate water movement and its distribution inside the slope.

The main objective of this study is to establish an analytical procedure to simulate rainfall-induced slope failures by combining the two different methods above described; discontinuous analysis, and seepage analysis. These analyses consider the hydro-mechanical properties of volcanic soils obtained from triaxial compression tests and permeability tests under saturated and unsaturated conditions. Seepage analysis is used to calculate the water distribution inside the slope; then this information is transformed into a numerical parameter that is input into the discontinuous model. The validity of this analytical procedure is examined by comparing experimental results of test models with the numerical simulation.

Seepage Analysis

Seepage analysis using the 3-D FEM software Hydrus was performed in order to establish the water distribution at the moment of slope failure. The program numerically solves the Richards equation for saturated-unsaturated water flow (Simunek et al 2006). The three-dimensional mesh and five sensors (sm) distributed throughout the model are shown in Fig.1-a.

Table1. Hydraulic Characteristics

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<tbody>
<tr>
<td>( \alpha )</td>
<td>0.034</td>
<td>1.900</td>
<td>0.199</td>
<td>0.485</td>
</tr>
<tr>
<td>( n )</td>
<td>1.450</td>
<td>4.464 x ( 10^{-6} ) m/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \theta_r )</td>
<td>10^{-6} m/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \theta_s )</td>
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The shape of the slope is similar to the test model conducted by Kawamura et al (2009). There is a frozen layer below the slope. The slope is formed from Kashiwabara volcanic soil, a typical volcanic soil in Hokkaido. The details of hydro-mechanical properties were already reported by Ishikawa et al (2009). The Van Genuchten model parameters of hydraulic characteristics are shown in Table 1. \( \theta_r \) and \( \theta_s \) denote the residual and saturated water contents, respectively, \( K \) is the saturated hydraulic conductivity, \( l \) is the tortuosity parameter and \( \alpha \) and \( n \) are shape parameters.
The soil water characteristic curve and the permeability-saturation relationship are shown in Fig.2. Rainfall intensities of 100 mm/hr were simulated. The initial water distribution was modeled according to the initial water content recorded on the sensors in the experimental results. The FEM simulation ran for 268 seconds, as this is the onset for slope failure in the test model.

The water distribution obtained through the seepage analysis (Fig. 1-b) was compared to the experimental results. The difference through time between each of the 5 sensor locations obtained by experiment and that calculated by the numerical simulation were evaluated. An average percentage error in relationship with the experimental model of 2.640% was obtained for the numerical simulation with 15% of surface runoff.

To properly simulate the saturated and unsaturated conditions the change in shear strength was related to the contact-bond parameter used in PFC-3D (Itasca 2003-b). The contact bond acts only at the contact point between two particles and can transmit force, having shear and tensile normal strength. However, the reformulation of contact bonds after breakage is not considered by the DEM mechanical model in this study. The unsaturated and saturated stress-strain relationship can be seen in Fig. 3.

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**Table 2.**

<table>
<thead>
<tr>
<th>Bond</th>
<th>Bond</th>
<th>Min.</th>
<th>Max.</th>
<th>$E_c$</th>
<th>$kn/ks$</th>
<th>$\phi$</th>
<th>$\mu$</th>
<th>$\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>31%</td>
<td>6 mm</td>
<td>8 mm</td>
<td>$4 \times 10^6$</td>
<td>1</td>
<td>43%</td>
<td>1.05</td>
<td>2.34</td>
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**Triaxial Test with DEM**

In this study, the analysis was carried out with PFC-3D software, which models the movement and interaction of spherical particles by DEM (Itasca 2003-b). In order to obtain suitable input parameters for the simulation of the slope failure, numerical triaxial tests were conducted that simulated the behavior of Kashiwabara volcanic soil (Ishikawa et al 2010). The DEM model is composed of a top and bottom wall separated by a vertical cylindrical wall and a particle assembly in which there is no discernible pattern in the arrangement of particles; the numerical triaxial conditions are similar to those found in the user’s guide (Itasca 2003-a). Real soil size ranges from 0.1 to 10 mm with a very high porosity of 80%; in this simulation the radii of the particles were between 6 mm and 8 mm and the porosity was 43%.
The numerical test models obtained in the triaxial simulation showed good agreement with the experimental results, with similar shear peak strength and stress-strain relationship. The stress-strain relationship is related to the ball-ball modulus (Ec) and the stiffness ratio (kn/ks); while the peak strength is related to a combination of the contact-bond force and the ball friction. The changes in saturation are simulated by modifying the contact bond force.

Simulations were also created and analyzed in the case of the whole slope being fully saturated. Slope failure patterns were investigated depending on the water distribution within the slope and other parameters. Fig. 4-b and Fig. 4-c shows an example of a typical slope shape after failure. In DEM simulation a slip line can be identified by velocity and displacement vectors (Fig. 4-d).

The results qualitatively correspond to the slope failure patterns obtained in the experimental tests (Fig. 4-e); analyzing the velocity and displacement vectors the shape and slip line were found to be similar. However the effects of water distribution inside the slope appear not to affect the failure pattern as expected. Further research should be conducted in the suitability of the contact-bond model for analyzing the saturation effect on slope failure flow.

Slope Failure Simulations with DEM

The dynamic behavior of volcanic soils during the slope failure was simulated using the DEM model. The shape of the slope is similar to the one used in the seepage analysis with the width being reduced to 100 mm due to numerical constraints. The particle-generation method used to obtain the desired porosity is the radius expansion method (Itasca 2003-a). The input parameters for the DEM slope model were obtained from the numerical triaxial test (Table 2). The contact-bond parameters which are dependent on the degree of saturation, were assigned to each layer in the slope (Fig. 4-a) depending on the degree of saturation previously obtained in the seepage analysis (Fig.1-b).
Conclusions

The following conclusions can be obtained:

- The results obtained in the triaxial simulation using the contact bond model showed good agreement with the experimental results, with similar shear peak strength and stress-strain relationship.
- The slope shape after failure is consistent with that previously obtained from experimental test models.
- Further research should be conducted in the suitability of the contact bond model for analyzing the saturation effect on slope failure flow.

From the above mentioned conclusions, it can be stated that the analytical procedure performed in this study, has the possibility to be applied for the prediction of flow movement in slope failure, though there is room for improvement.

References


