論 文 の 内 容 の 要 旨

論 文 題 目 :
Real-time Prediction of Rain-induced Embankment Failure by Minimum Measurements with Back-analysis for SWCC Parameters
(最少の計測情報と土壌水分特性の逆解析による盛土の降雨崩壊のリアルタイム予測)

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Embankments are geo-structures that are mostly used to support infrastructures such as rails and roads. Therefore failures of embankments are result not only in loss of human lives but also affected the economic activities of a region. Rainfall has been identified as one of major causes to make embankments unstable and lead to subsequent failures. In fact, rain-induced embankment failures are categorized under the rain-induced landslides, the existing warning systems can not be implemented to minimize the risk successfully and economically. Therefore, in this study, a method for real-time prediction of rain-induced embankment was proposed. The method involves real-time calculation of embankment instability using numerically calculated pore-water pressures and unsaturated shear strength properties. It is necessary to have in-situ real-time pore-water pressure (or water content) measurement and rainfall data for numerical seepage analysis, in addition to laboratory-measured soil properties such as the soil-water characteristic curve (SWCC) and the hydraulic conductivity functions.

The proposed method was validated by employing to predict the failure of conducted model test. The necessary soil parameters for the analyses were obtained in the laboratory. The calculated FOS (factor of safety) was compared with the measured displacement in the model. The results suggested that the failure of the model test could be well-predicted by the proposed method. Finally, a procedure to back-calculate the SWCC from in-situ measured pore-water pressures and the results of the numerical seepage was formulated. The proposed procedure was used to back-calculate the SWCC of soil used in the model test.

As a part of this study, the SWCCs and saturated/unsaturated permeability functions of test materials for different dry densities were obtained using the laboratory-designed Tempe pressure cell and permeability apparatus. Based on the available results, following conclusions were made:

- As the initial dry density of silty soil increases, the air entry value of the soil is higher and specimens de-saturate at a slower rate than the low-density specimens. Further, the high-density specimens have higher water contents than the low-density specimens at matric suctions beyond their air entry values. In addition, the hysteresis associated with drying and wetting becomes smaller, as density increases.
- The SWCCs of the materials are affected by their particle distributions. Finer material has higher capacity of water retention than the coarser materials. It can be concluded that as the amount of fines in a material increases, the rate of de-saturation decreases. In addition, the specimens with high fines content have higher water content than the specimens with low fines content at the same matric suction.
- The laboratory-designed permeability cell can be used to measure unsaturated permeability coefficient for low suction range (0 ~ 8 kPa) in drying.
- The method proposed by Fredlund (1994) and Green and Corey (1971) can predict the laboratory measured unsaturated permeability function reasonably well using the given SWCC and the saturated permeability coefficient.

The shear behavior of unsaturated silty soil for low suction range (0 ~50 kPa) was investigated by using the modified triaxial apparatus and the modified direct shear apparatus. Aiming to obtain unsaturated shear strength parameters for stability analysis using SLOPE/W (Geostudio, 2004), a series of shear tests was conducted on Edosaki and Isumi embankment soils under various combinations of net stress (confining or normal) and suction. The suction was achieved by either wetting or drying in order to investigate the effect of wetting-drying (the hysteresis of SWCC) on the shear behavior of unsaturated soils. Some tests were conducted on samples with different initial dry densities as well. The main conclusions of the investigation on unsaturated shear strength parameters are as follows:

- The shear resistance and the initial shear stiffness increase with the increase in the net stress (net confining or net normal). The volume change of the specimen becomes more contractive as the net stress increases.
- It was observed that soil subjected to a higher value of suction exhibits a stiffer response and higher stress-strain curve as compared to those of lower value of suction. Further, soil having a higher suction shows less compressive behavior.
- The internal friction angle of tested materials is independent of suction and wetting-drying hysteresis of SWCC. It is apparent that the increase in the density may result in increase in the friction angle.
- The remarkable non-linearity in the relation between the apparent cohesion and the suction was observed in the test results. The test data indicated that the apparent cohesion increases generally at a decreasing rate with the increase of suction.
- Soil under wetting exhibited higher apparent cohesion than soil under drying at the same suction.

A series of embankment model tests subjected to rainfall was conducted in order to examine the effects of rainfall intensity, dry density of the slope, drainage condition at the slope bottom, and slope inclination on the failure of rainfall-induced embankment slope failures. Following conclusions can be drawn from the observed results.

- Rain-induced failures of most slopes initiate near the toe upon full saturation of the lower part of the slope.
- The slope failure induced by the high intensity rainfall is shallow and occurred at relatively short time after the start of rainfall as compared with the one induced by low intensity rainfall. Heavy slope surface erosion is involved in the failure induced by high intensity rainfall.
- Denser slopes are more stable against rain-induced failures due to low permeability and high shear strength.
- Improvement of the drainage condition beneath the toe of the slope is an effective countermeasure against rain-induced slope failures.
- Slopes become more vulnerable to sudden collapse with the increase in their inclinations.

Parametric analyses were conducted to examine the effects of different input parameters such as SWCC, saturated permeability coefficient, initial pore-water pressure, and rainfall intensity on the numerical seepage and stability analyses. The results suggest that the effects of SWCCs (drying and wetting) and the initial pore-water pressure on the numerical seepage and stability analyses are not significant especially when the pore-water pressure increases greater than -3 kPa. However, there is a significant effect for low pore-water pressure values (at the beginning of rainfall). The effect of the saturated permeability on the stability analysis is significant. If the saturated permeability is smaller than the rainfall intensity, surface area of the slope becomes unstable within relatively short time of rainfall. Further, an increase in saturated permeability (much greater than the rainfall intensity) may increase the stability of the slope due to the improvement of drainage. With the increase in the rainfall intensity, the time required for the embankment to become unstable is shorter.

In the comparison of measured and simulated pore-water pressure time histories, it can be seen that the results agree well for high pore-water pressure (greater than -3 kPa). There is a significant difference between measured and simulated values for low pore-water pressure (at the start of rainfall). As the slopes become unstable due to high pore-water pressure, reasonably good agreement between the start of slope deformation and the drop of the FOS below unity could be observed. This result suggests that the proposed strategy may be used to predict the instability of rain-induced embankment failure.

In-situ water content measurement was conducted in a slope of Isumi-railway embankment at Otaki in Chiba. As explained in this chapter, the selected slope of the embankment was instrumented with 11 ECHO water content sensors. Further, a rain gauge was set on the slope to measure rainfall in the site and a thermometer was installed at about 30 cm below the surface of the slope to monitor the soil temperature. Data logging was done using HOBO weather station data logger which operates with batteries. Although the complete setup was on the site for more than 4 months, it was able to conduct data logging only for 1 month due to some technical problems.

During the time in which data was recorded successfully, the embankment slope did not experience any significant rainfall. However, clear responses were observed from some of the installed water content sensors during the recorded rainfall.

In order to examine the applicability of the proposed method of prediction of rain-induced embankment instability, numerical seepage analysis and the stability analysis were conducted for a certain period of recorded rainfall. Transient seepage analysis was performed assuming uniform material properties in the embankment even though the measured dry density varied with the height of the embankment. The results (pore-water pressures) of the seepage analysis and the laboratory measured shear strength parameters were used to assess the instability of the embankment.

When the measured and simulated water content time histories are compared, reasonably good agreements can be observed in the region with high-initial water content. However, there is a significant difference between the measured and simulated water content values in the region with low water content (near surface area).

The change in the stability of the embankment slope during the considered time frame is consistent with the rainfall and the water content measurements in the slope. The slope is well stable for the particular rainfall and FOS which was about 3.7 at the beginning of the rainfall event decreased by 0.35 at the end of the rainfall event.