Real-time prediction of hydraulic conditions in slope ground based on monitoring data of moisture contents

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ABSTRACT

Moisture content is the most important factor affecting the stability of slopes against heavy rainfall events. In most of risk management methods for slope disasters, the rainfall intensity is used as the dominant index to evaluate the probability of failure events in an area. However, each slope should have individual hydraulic characteristics, and its probability of failure should be different from other slopes even under the same rainfall conditions. Some slope may contain a lot of water quickly after starting of rainfall, while some slope may show quick drainage after it stopped to rain. Such individual properties of each slope can be evaluated by observing the time histories of moisture contents in the slope ground together with rainfall records. In this paper, an attempt to establish a mathematical model on drainage process in a slope ground is reported. There is a simple relationship between the current moisture contents and the drainage rate of moisture, although this relation is affected by the adjacent rainfall intensity. The drainage properties of a slope can be evaluated by watching the behaviors of moisture contents at rainfall events with relatively low intensity. And the model parameters obtained by such weak rainfall events can be used to estimate the drainage rate after heavy rainfall events with some correction of the parameters, by using real time monitoring system.

Keywords: rainfall induced slope failure, hydraulic properties, monitoring, early warning

1. INTRODUCTION

Monitoring and early warning is a cost-effective countermeasure to mitigate slope disasters. Most of warning systems are based on the rainfall intensity, accumulated rainfall, or their functions as parameters to evaluate the potential of slope disaster. However, these parameters on rainfall are measured at a representative point in each area, and all the slopes in the area are evaluated with these data uniformly. Therefore, such warning systems overestimate the risk of failure for relatively stable slopes, while they underestimate it for unstable slopes.

The stability of each slope depends on many factors, such as slope angle, soil types, density, surrounding topography, etc., even the same rainfall conditions are given. This paper describes an idea of simple method to concern the hydraulic properties of each respective slope when the potential risk of failure is evaluated. Figure 1 illustrates the basic concept of this method. The authors have developed a low-cost and simple monitoring system for slope with wireless sensor network, which easily provides real-time data of the moisture contents, tilting displacement, etc. of slope ground. With continuous monitoring, the behaviors of moisture contents are monitored at usual (relatively weak) rainfall events. By comparing the history of moisture contents and rainfall, a mathematical model is determined with several parameters to formulate the relationships between rainfall and infiltration/drainage processes. At a heavy rainfall event, the behaviors of moisture contents in the slope ground in near future are predicted by using the model, based on the real-time data on the most recent rainfall history and moisture contents behaviors. By defining some critical value of moisture contents, the time for issuing and canceling warning can be decided based on the predicted moisture contents behaviors.

Fig. 1. Concept of real-time prediction of hydraulic condition of a slope based on monitored behaviors of moisture contents.

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Unlike the usual warning system mentioned above, this method determines the hydraulic properties of each slope respectively, and the risk of failure can be evaluated based on them. For example, if the parameters suggest that the moisture contents raise up quickly after beginning of rainfall in a slope, the warning will be issued earlier.

Figure 2 shows hydraulic behaviors measured in a model slope under artificial rainfall and drainage test. Excessive moisture content, \( W - W_0 \), is defined as Figure 2b). Then, this value shows linear behaviors with logarithmic scale with time in normal scale for the drainage stages after the rainfall, and the gradient of the drainage curve is constant (Figure 2c). This result suggests an idea to use this value of gradient as an index to evaluate the hydraulic property of this slope in drainage stage.

Herein, more detailed observations are made on model and real slope, and their drainage properties are mainly focused. Finally, some procedures are proposed to determine the parameters in real-time based on the monitored behaviors of moisture contents in the slope under rainfall events (Uchimura et al. 2010b).

In this paper, “moisture content” means “volumetric by the total volume of soil.

2 ESTABLISHING MODIFIED TANK MODEL BASED ON 1D COLUMN TEST RESULTS

Tank model is a simple tool to describe the behaviors of water distribution in a ground or a hydrological area. It has contributed to development of hydrology, and now, the idea is also used for “Soil Water Index (SWI)” proposed by Japan Meteorological Agent (Ishihara and Kobatake, 1979). Figure 3 shows the basic concept of the original tank model. At a time \( t \), an amount of water is pooled in a tank with a water height of \( h(t) \). The value of \( h(t) \) virtually represents the moisture content measured in a slope ground in this paper. If a rainfall intensity \( R(t) \) is given, \( h(t) \) increases with a rate of \( R(t) \). Besides, \( h(t) \) also intends to decreases always with a rate of \( q(t) \). There is a minimum value of \( h(t) \) in the tank, which is noted as base moisture contents, \( H \). \( H \) can be considered as the ultimate value of moisture contents if the drainage continues for a long time without rainfall. The difference \( h(t) - H \) corresponds to the excessive moisture contents. In the original tank model, \( q(t) \) is defined as a proportional function of \( h(t) - H \). The mathematical formulae for this model can be described as Equation (1) and (2). As the drainage stage after rainfall is the main target of this paper, \( R(t) \) is always 0.

\[
q(t) = \alpha(h(t) - H) \quad (1)
\]
\[
\frac{dh(t)}{dt} = R(t) - q(t) \quad (2)
\]

In order to validate the original tank model, a series of 1D column tests were conducted (Figure 4). A uniform model ground (Toyoura sand, \( D_r = 70\% \), \( \varepsilon_{\text{max}} = 0.975 \), \( \varepsilon_{\text{min}} = 0.614 \), \( D_{50} = 0.17 \) mm, \( U_c = 1.70 \)) is constructed in an acrylic pipe (diameter = 140 mm, height = 1250 mm). The bottom of column is open to a constant water head to simulate constant underground level. Moisture content sensors are installed at several heights on the side of column. Before the main test, a lot of water is given on the top of column so that the ground is nearly saturated, and then it was drained by gravity until the moisture contents become constant. As a result, a stable distribution of moisture content is obtained as Figure 5. In this stage, the weight of water is balanced with suction, and this is considered to be similar to the natural water distribution in the ground,
and the moisture content is H in the model at each height. Then water drops are given on the top of column as a rainfall event. One hour rainfall with constant intensity (15, 31, 46, 62, 78, and 90 mm/h for respective test cases) was given, and then, the drainage stages were observed.

Figure 4. One dimensional column test.

Figure 5. Stable distribution of moisture contents.

Figure 6 shows the behaviors of excessive moisture contents at a depth of 10cm calculated from the test results with rainfall of 31, 62, and 93 mm/h, plotted in log scale versus the time in normal scale. According to the model formulae (1) and (2), the h(t) should be an exponential function of time if R(t) = 0, and it should plotted linearly in log scale. However, Figure 6 shows non-linear plots, especially in cases with heavy rainfall.

To investigate more details, the drainage rate q(t) is plotted against h(t) – H in Figure 7. According to Formula (1), the ratio between q(t) and h(t) – H is α. If α is a constant, this relationship should be linear. But, q(t) increases with h(t) – H more than proportional. And, q(t) is higher after heavier rainfall events, even if they are compared at the same value of h(t) – H.

Figure 7. Relations between q(t) and h(t) – H.

These two trends cannot be explained with the original tank model, but qualitatively reasonable. It is well known that the permeability coefficient of unsaturated soil increases with higher saturation ratio (Buckingham, 1907, for example). Therefore, with higher values of h(t) – H, or after heavier rainfall events, the saturation ratio in the surrounding area are higher, resulting in quicker drainage.

Thus, the tank model has to be modified. The original model assumes linear relationships between q(t) and h(t) – H. But, the test results suggest us to use a non-linear function for Formula (1). In Figure 8, a set of plots with one of the rainfall intensity values is chosen. It seems that a function \( y = \alpha x^\beta \) fits well to these plots. Therefore, we decided to use a modified Formula (3) in place of Formula (1):

\[
q(t) = \alpha (h(t) - H)^\beta
\]

Figure 8. Fitting a function to q(t) and h(t) – H.

Figure 9 is an attempt to fit the modified tank model to all the test results. It was found that the effect of rainfall intensity can be expressed by only changing the value of \( \alpha \). That is, by choosing one case of rainfall intensity, 62 mm/h for example, Formula (3) is fit to the plot, and the values of \( \alpha \) and \( \beta \) are determined. Then, the plot for other cases of rainfall intensity (15, 31, 46, 78, and 90 mm/h) can be reasonably fit by multiplying constants (2/5, 3/5, 4/5, 6/5, and 7/5, respectively) to \( \alpha \). The value of \( \beta \) is common for the drainage processes after weak and heavy rainfall events. This is convenient for the objectives of this paper shown in Figure 1b, because we can determine the value of \( \beta \) by monitoring the drainage behavior after usual weak
rainfall events, and when a heavy rainfall event happens, the model can be applied by changing the value of $\alpha$ only.

Figure 9. Fitting modified tank model to test results.

3 EARLY WARNING BASED ON THE HYDRAULIC MODEL

Now, the authors propose procedures to evaluate the drainage properties of a slope at weak rainfall events, and predict the drainage behaviors after a heavy rainfall event, as shown in Figure 10:

1. By monitoring the behaviors of moisture contents after usual rainfall events, the parameter $H$ and $\beta$ are determined. This value may be refined by experiencing many rainfall events for a long period;
2. At a heavy rainfall event, the beginning of drainage process is monitored in real-time for a short period.
3. We can determine $\alpha$ by plotting the drainage rate $h(t)$ and the excessive moisture contents $h(t) - H$.
4. The curve for relations between $h(t)$ and $h(t) - H$ is drawn.
5. The drainage behavior in near future is estimated.

Figure 10. Procedures of predicting moisture contents.

As the value of $\alpha$ depends on the rainfall intensity, it is difficult to estimate it for unexperienced heavy rainfall in advance. But, it can be determined by real-time monitoring of drainage behavior just after the heavy rainfall. Figure 11 shows an example of verification of this method on a test case with rainfall intensity of 62 mm/h. The values of $H$ and $\beta$ are determined at the lowest rainfall event (15 mm/h), and $\alpha$ is determined in the beginning of the drainage process. The model can predict the measured drainage process very well.

Figure 11. Verification of the proposed method.

4 CONCLUSIONS

An idea of simple method to make decisions of issuing and canceling warning, based on predicted drainage procedure in a slope ground after heavy rainfall, is proposed. The hydraulic (drainage) properties of a slope are evaluated at usual weak rainfall events, and a modified tank model is applied to the relationships between the rainfall history and moisture contents behaviors. Then, the model is extended to the case with heavy rainfall. The observed drainage rate is higher than proportional to the excessive moisture contents. Besides, it is also higher in drainage process after heavier rainfall events. Therefore, the model parameters have to be adjusted depending on the rainfall intensity, but it can be carried out by real-time monitoring of the beginning of drainage process.

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REFERENCES

1) Backingham, E. (1907): Studies on Movement of Soil Moisture, Bulletin 38. U.S. Department of Agriculture Bureau of Soils, Washington, D.C.
2) Ishihara, Y. and S. Kobatake (1979): Runoff Model for Flood Forecasting, Bull.D.P.R.I., Kyoto Univ., 29, 27-43
3) T. Uchimura, I. Towhata, Trinh Thi Lan Anh, J. Fukuda, C. J. B. Bautista, L. Wang, I. Seko, T. Uchida, A. Matsunaka, Y. Ito, Y. Onda, S. Iwagami, M. S. Kim, and N. Sakai (2010): Simple monitoring method for precaution of landslides watching tilting and water contents on slopes surface, Landslides, (Published online: 17 October 2009)
4) Uchimura, T., Tanaka, R., Suzuki, D., and Yamada, S. (2010): Evaluation of hydraulic properties of slope ground based on monitoring data of moisture contents, Proc. of the 4th Japan-Taiwan Joint Workshop on Geotechnical Hazards from Large Earthquakes and Heavy Rainfalls, Japan, pp. 85-90.