International Journal of GEOMATE, June, 2016, Vol. 10, Issue 22, pp.2094-2100
Geotec., Const. Mat. & Env., ISSN: 2186-2982(Print), 2186-2990(Online), Japan

A METHOD TO JUDGE SLOPE FAILURES USING SOIL MOISTURE CHARACTERISTICS

Tetsuya Iida[1], Masamitsu Fujimoto[2], Nobuyuki Kumakura[3], Daisuke Takasaki[3], Nobutaka Hiraoka[4] and Ryoichi Fukagawa[2]

[1]Graduate School of Science and Engineering, Ritsumeikan University, Japan,
[2]College of Science and Engineering, Ritsumeikan University, Japan
[3]Community Solutions Division, Toshiba, Japan
[4]Research Organization of Science and Technology, Ritsumeikan University, Japan

ABSTRACT: Slope failures often occur in Japan, and they frequently result from an increase in the moisture content of the soil. Thus, it is important to consider soil water content. In this study, we carried out a series of laboratory experiments to evaluate changes in soil moisture during rainfall. In the experiments, we constructed a model slope in which we installed 10 soil moisture sensors. The results indicated that the volumetric water content in the slope increased with rainfall, and the increments in volumetric water content were affected by the intensity of the rainfall. Then, using the experimental results, we developed a technique for judging slope failure risk based on absolute values of volumetric water content and rainfall characteristics. Our proposed method will be useful in judging the risk of slope failure because the criteria for the method are based not only on the precipitation but also on the soil moisture in-situ.

Keywords: Slope Failures, Laboratory Experiments, Soil Moisture Sensors, Volume Water Contents, Rainfall

1. INTRODUCTION

In Japan, many slope failures have occurred with heavy rainfall. Several models for predicting slope failure in forested areas have been proposed since the 1980s. Most studies used an approach that combined a physical model to simulate rainfall infiltration processes with slope stability analysis [1]-[9]. With regard to the physical model, one of main factors in slope failure is an increase in the moisture content of the soil. Most of these studies analyzed slope failure based on pore water pressures in the soil. The soil water content may be a good indicator to gain predictive information regarding slope failure because the soil water content responds to rainfall events as well as to pore water pressure. Although measurements of soil water content have been conducted in situ [10], [11], the role of soil water content in slope failure processes is still not well understood.

Generally, soil water conditions are measured by a tensiometer for pore water pressure and soil moisture sensors for soil moisture. A measurement system using a tensiometer and soil moisture sensors normally receives electricity by cables, leading to high costs for installing a measuring system. Thus, there is a need to develop a wireless measurement system for determining the water content in soil. Although tensiometers require regular maintenance, with degassed water in the equipment, soil moisture sensors have no such requirement. Considering the operating costs of measurements on a hazardous slope, a measurement system for soil water content would have a good return as a warning system for impending slope failure. In this study, we evaluated changes in soil moisture during rainfall using laboratory experiments, and developed a technique for judging the risk of slope failure based on the experimental results.

2. METHOD

We carried out two laboratory experiments to assess changes in soil water content during rainfall. We conducted one using an artificial rain simulator (Daiki Rika Co., DIK-6000S) at Ritsumeikan University. Granite soil (Masa soil) was used to make a model slope. Measurement devices for pore water pressure and soil moisture content were a tensiometer (with hydraulic gauge; Nidec Copal Electronics Corp., PA-850-102V-NGF) and soil moisture sensors (Decagon Devices, S-SMx-M005), respectively.

We performed two experiments for different purposes. The experiment in Case 1 was designed to evaluate the relationship between pore water pressure and soil moisture content and the responses in slope failure. Case 2 was conducted to determine changes in soil moisture from the start of rainfall to after the rainfall ended.

In Case 1, slope failure did not occur due to the development of gully erosion related to rainfall intensity (Photo 1). Based on these results, we do not discuss the dynamics of soil water contents for slope failure processes directly. Details of the model slope and experimental conditions for Case 1 are shown in Table 1 and Fig. 1. Details of the model slope and experimental conditions for Case 2 are shown in Table 2 and Fig. 2. We provided artificial rainfall to the model slope in the experiments to recreate natural conditions of soil moisture. The amount of rainfall per hour was changed twice in Case 1 in an attempt to provoke slope failure. In Case 1 we raised the groundwater level of the model slope by modifying the drainage conditions.

Photo 1 Model slope after experiment (Case 1)

Table 1 Experimental conditions (Case 1)

Moisture content	10%
Dry density	1.85g/cm^3 (basement layer) 1.60 g/cm^3 (soil layer)
Wet density	2.035 g/cm^3 (basement layer) 1.760 g/cm^3 (soil layer)
Drainage condition	discharged water (10 hrs)
	not discharged water (11 hrs)
Preliminary rainfall condition	25 mm/hr (2 hrs)
Rainfall condition	25 mm/hr (4.5 hrs)
	50 mm/hr (15.5 hrs)
	120 mm/hr (1 hr)
Measuring interval	1 min

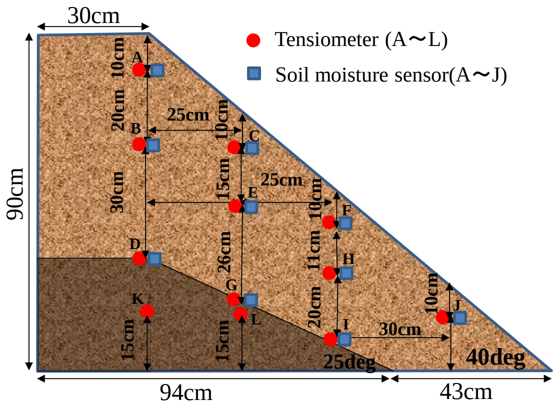

Fig.1 Schematic diagram of model slope (Case 1)

Table 2 Experimental conditions (Case 2)

Moisture content	10%
Dry density	1.60 g/cm^3
Wet density	1.76 g/cm^3
Preliminary rainfall condition	25 mm/hr (2 hrs)
Rainfall condition	15 mm/hr (14 hrs)
Measuring interval	10 mins

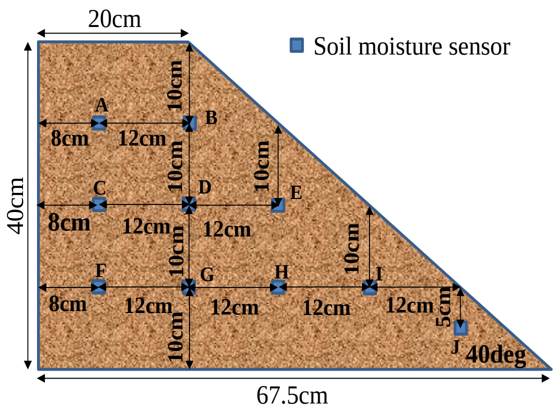

Fig.2 Schematic diagram of model slope (Case2)

3. RESULTS AND DISCUSSION

3.1 Relationship between the Pore Water Pressure and the Volumetric Water Content of the Soil

The results of the Case 1 experiment are shown in Fig. 3, which indicates the variation in accumulated rainfall, amount of rainfall per hour, pure water pressure, and volumetric water content. In Case 1, the values of the density of the soil layer whilst dry and the soil moisture content were

1.6g/cm^3 and 10% respectively. These values imply that the initial volumetric water content was 16%. The experimentally observed values of the volumetric water content varied considerably with the date that the soil moisture sensors were calibrated. Therefore, we reset the initial value of the volumetric water content before beginning the preliminary rainfall, which uniformed the water content of the soil to 16%. Fig. 4 shows the time series variation of the volumetric water content with an initial percentage 16%. The results of the experiments performed in Case 2 are shown in Fig. 5. This shows the time series variation in accumulated rainfall, volume of rainfall per hour, and volumetric water content.

In Case 1, slope failure did not occur despite changes in rainfall intensity (Photo. 1), as the surface soil of the model slope in Case 1 was eroded. Most of the pore water pressure measurements in the slope increased with the rainfall. Increased pore water pressure occurred at a shallow measurement depth. Following the initial increase in pore water pressure, the values of pore water pressure became constant. Moreover, the pore water pressure of points at greater depths (D, G, and I) exceeded 0, indicating that saturation occurred at the bottom of the soil layer. The soil moisture in the slope increased due to the rainfall. Additionally, the soil water contents became constant after the increase during the rainfall, as did the pore water pressure. Moreover, the volumetric water content rose again before the end of the rainfall. The second increase in the volumetric water content may have been caused by rainfall directly on the soil moisture sensor because of the denudation of the model slope. Furthermore, the volumetric water content at the measurement points (D, G and I) where the pore water pressure exceeded 0 was higher than that at other measurement points (Fig. 4).

The relationship between pure water pressure and volumetric water content at D, G, and I is shown in Fig. 6. This figure shows the relationships between the cases with and without correction and modification of the initial values of the volumetric water content. From Fig. 6, we can see that there is a difference in the value of the volumetric water content between two cases. When the pore water pressure exceeded 0, the value of volumetric water content had a large range, especially at point D. The increase in the volumetric water content after saturation was due to a decrease in pore air in the soil under saturated conditions. This result also indicated that soil saturation cannot be detected by a specific value of the volumetric water content of the soil. Thus, the risk of slope failure with saturation should be judged using the range of the volumetric water content.

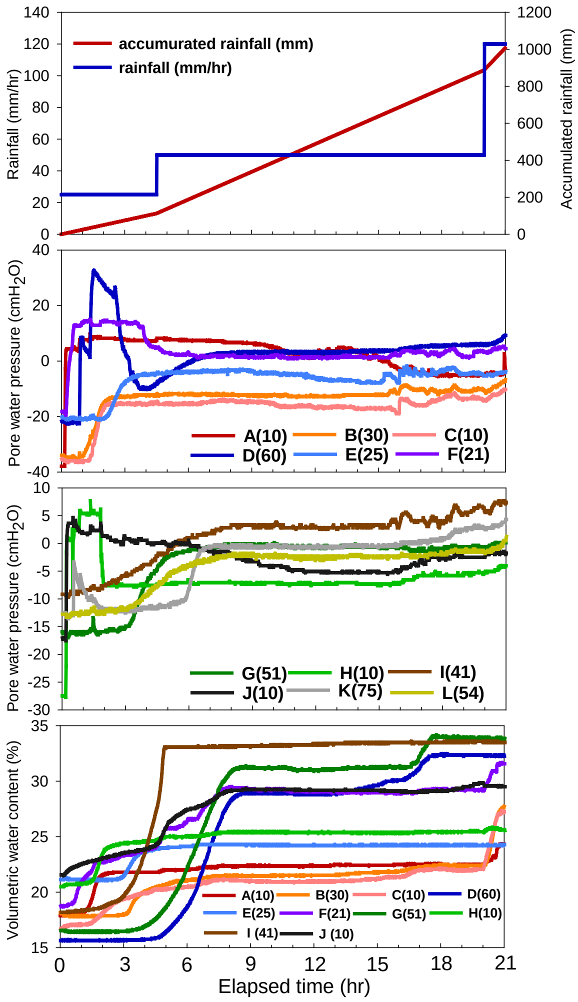

Fig.3 Time series variation in pore water pressure and volumetric water content

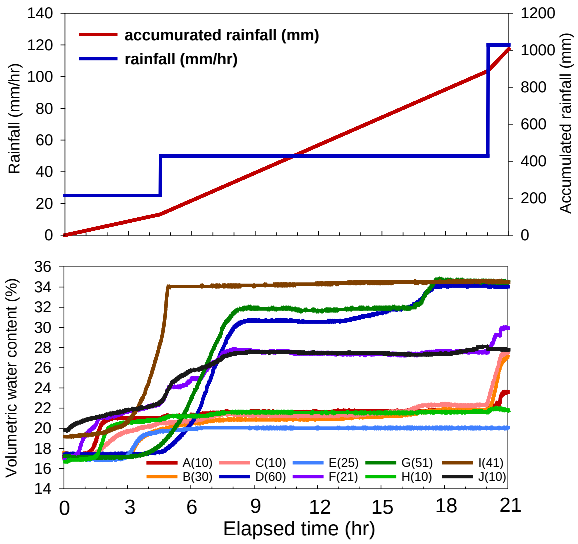

Fig.4 Time series variation in volumetric water content, initially at 16%

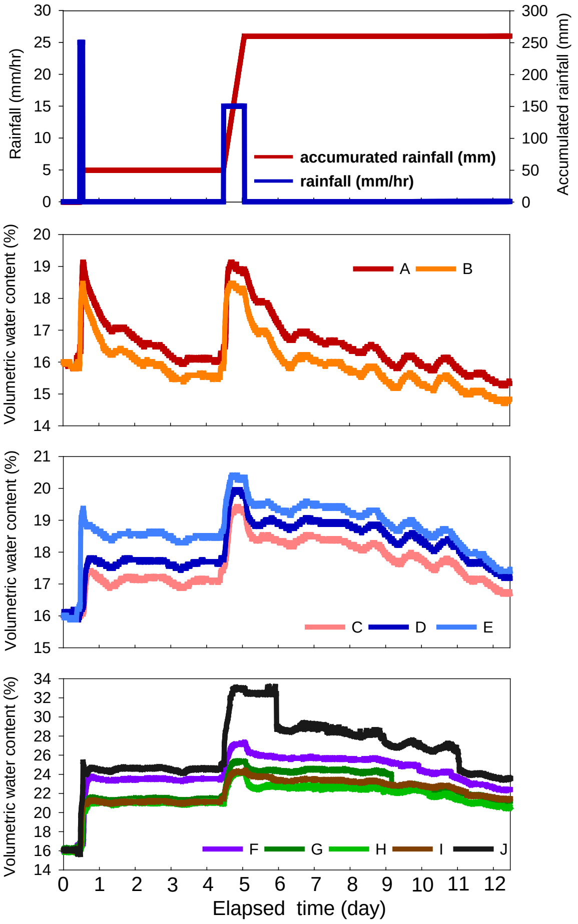

Fig.5 Time series variation in volumetric water content, initially at 16%

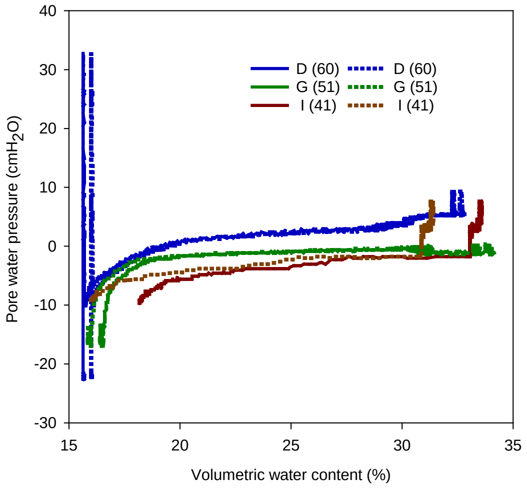

Fig.6 Relationship between pore water pressure and volumetric water content. The solid line shows the case with no correction to of the initial value and the broken line shows the case with an initial volumetric water content of 16%.

3.2 Responses of the Volumetric Water Content at Different Measurement Depths

In Case 2, the volumetric water content in the slope rose with the initial rainfall, after which, the volumetric water content at shallow depth points (A, B) decreased due to 4 dry days between the preliminary rainfall and the subsequent rainfall. The volumetric water content of other points did not decrease, largely because of drainage conditions of the model slope. The volumetric water content measurements, which declined after the preliminary rainfall ended, then rose again with further rainfall. The range of increase in the volumetric water content differed between the preliminary and subsequent rainfall. One cause of these differences was the differing rainfall intensity between the preliminary and subsequent rainfall.

3.3 Method for Judging the Risk of Slope Failure

We developed a technique for judging the risk of slope failure based on the experimental results. In this study, we judged the risk for the whole slope after judging the risk based on individual soil moisture sensors. First, the risk based on individual soil moisture sensors was judged, and we then judged the risk for the whole slope using a summary of the risk values of individual soil moisture sensors.

We first tried to judge the risk of slope failure at each measurement point using an absolute value of volumetric water content. A reference value needed to be determined for an absolute value of volumetric water content. The judgment values of volumetric water contents were calculated using Eqs. (1) and (2):

$$w = \left(\frac{\rho_w}{\rho_d} - \frac{\rho_w}{\rho_s}\right) S_r \qquad (1)$$

$$\theta = w\rho_d \qquad (2)$$

where w is the moisture content (%), ρ_w is the water density (g/cm^3), ρ_d is the dry density (g/cm^3), ρ_s is the soil particle density (g/cm^3), S_r is the degree of saturation (%), and θ is the volumetric water content (%).

The dry density of the soil and the soil particle density were measured in laboratory experiments using in-situ soil samples. From the results, we determined the boundary values of volumetric water content with different degrees of saturation. Two proposed values of S_s and S_a of the degree of saturation were used in our judgment method. The volumetric water contents corresponding to the saturation degree were calculated using the equations above. The meanings of S_s and S_a are as follows: When the degree of saturation was under S_s percent (%), we assumed that the soil moisture sensor at the measurement point was in a safe state. We assumed that soil moisture was in alert status when the measured value of the degree of saturation was $>S_s$ (%). When the value of the degree of saturation is $>S_a$ (%), we assumed that the soil moisture condition was in evacuation status.

To judge the risk over whole of slope, we scored individual soil moisture sensors. We gave 1 point where the soil moisture sensor was in a safe state; 2 points if the soil moisture sensor was in alert status; and 3 points if the soil moisture sensor was in evacuation status. We judged the state (safe, alert, or evacuation) based on thresholds for the summed totals of the individual measurement points.

3.4 Application of the Method for Judging the Risk of Slope Failure

Here, we show examples of the judgment method. We determined that the values of S_s and S_a for the degree of saturation were 50% and 70%, respectively. The volumetric water content corresponding to those saturation degrees was 19.2% and 26.9%, respectively. We judged a safe state when the sum of the 10 soil moisture sensor scores was less than 15 points, alert status was 16-20 points, and evacuation status was considered to be a total score of 21 or more points. The judgment results for Cases 1 and 2 are shown in Figs. 7 and 8, respectively. In this study, we judged the potential for slope failure based on two indices of soil moisture and the characteristics of the precipitation, which were used as an index of the effective rainfall. Effective rainfall is an indicator that facilitates the evaluation of residual effect of previous precipitation on soil moisture in the ground. We calculated the effective rainfall using Eqs. (3) and (4):

$$R_G = R_0 + a^1 R_1 + a^2 R_2 + \cdot\cdot\cdot\cdot\cdot a^n R_n \quad (3)$$

$$a = (0.5)^{1/T} \quad (4)$$

where R_G is the effective rainfall (mm), R_n is the rainfall before n minutes (mm/10min), a is a reduction factor ($0 < a < 1$), and T is the half-period. The x-axes of Figs. 7 and 8 are the effective rainfall that had a half-period of 72 h, and the y-axes are the effective rainfall where the half-period was 1.5 h.

In Case 1, the condition of the slope was judged safe before and just after the preliminary rainfall, At 2 h and 10 min after the beginning of the preliminary rainfall, the judgment changed to alert status, which continued after the end of the preliminary rainfall. Then, at 3 h and 10 min after the end of the preliminary rainfall, the judgment returned to a safe state. With regard to the later rainfall, after the preliminary rainfall, at 2 h and 30 min from the beginning of rainfall, the judgment changed to alert. Due to the continuing heavy rainfall, at 5 h and 30 min from the beginning of the rainfall, the judgment was shifted to evacuation status.

In Case 2, the judgment of the condition of the slope before and immediately after the preliminary rainfall was that the slope was safe, as in Case 1. As the volume of rainfall increased, the judgment shifted to alert status. The judgment of risk levels necessitating an alert status continued after the end of the rainfall. The judgement reverted to the safe status 4 days, 1 h and 10 min after the end of the rainfall.

Although we judged the risk of slope failure, our method did not consider the measurement depth. However, it is vital to consider depth to accurately judge the risk of slope failure. When the measurement point at a deep depth was judged to be in evacuation status, the risk of slope failure was supposed to be very high. Thus, we weighted the score for evacuation status according to measurement depth. When the measuring point in the middle layer entered evacuation status, we gave it 4.5 points, and when the measurement point in the deep layer went to evacuation status, we gave it 6 points. Based on these changes in the scores of individual soil moisture sensors, we also revised the scores for the whole slope. We judged a safe state when the sum of the 10 soil moisture sensors was less than 15 points. Alert status was 16-24 points, and evacuation status was a score of 25 or more points.

In Case 1, the timing of the changes between safe and alert states were the same when using either weighted or unweighted judgments (Fig. 9). However the timing of evacuation status was delayed by 1 h and 20 min when weighted rather than unweighted judgments were used. Also, in Case 2, the times in safe and alert states were the same regardless of whether weighted or unweighted judgments were made. However, the method used to weight each measurement point may have a significant impact on the final judgment of the slope failure risk.

4. CONCLUSION

In this study, we carried out laboratory experiments to evaluate the relationship between pore water pressures and soil moisture conditions and assessed changes in soil moisture during and after simulated rainfall. The volumetric water content increased with the rainfall and showed a large range of values after reaching saturated conditions. Then, we developed a judgment method for slope failure risk based on absolute values of volumetric water content. soil moisture characteristics of the precipitation were used to judge the risk of slope failure. Although the result

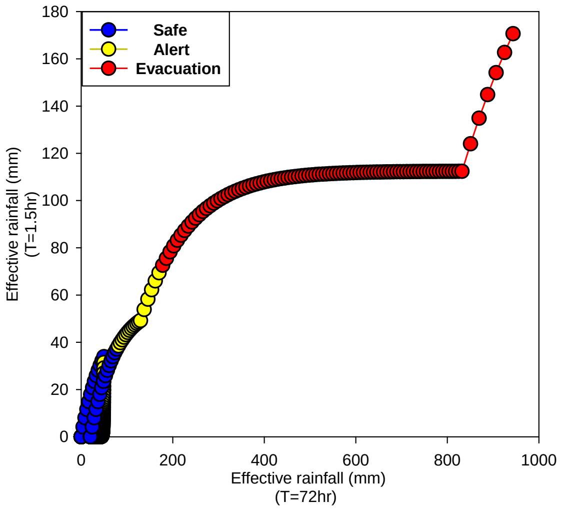

Fig.7 Result of judgment (Case 1)

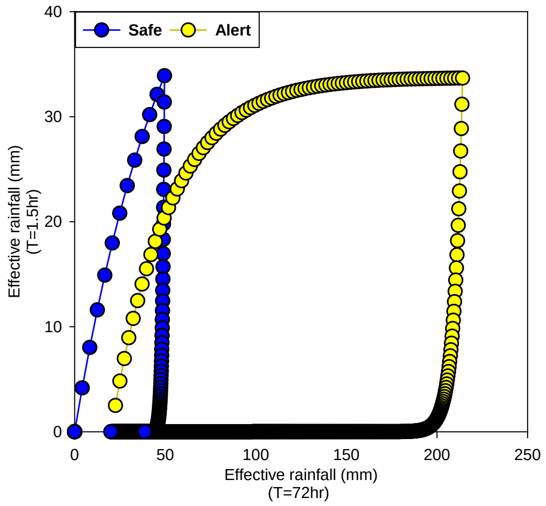

Fig.8 Result of judgment (Case 2)

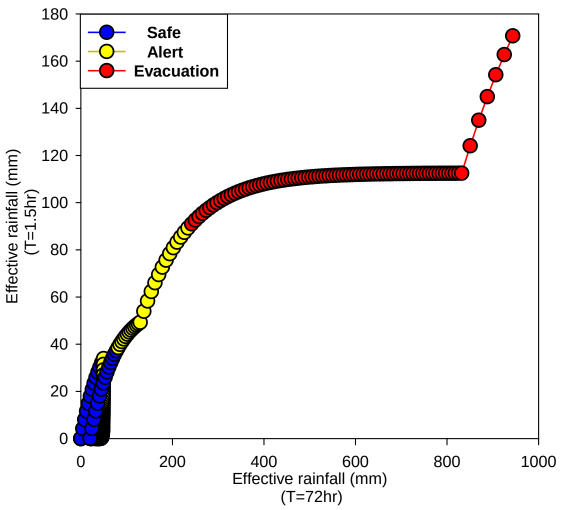

Fig.9 Result of weighted judgment (Case 1)

of the judgment differed with consideration of depth, our proposed method can judge the risk of slope failure in a comprehensive manner. We must examine its applicability to an actual slope in future studies.

5. REFERENCE

[1] Okimura T, Ichikawa R, “A prediction method for surface failures by movements of infiltrated water in surface soil layer”, Natural Disaster Science, Vol. 7, 1985, pp. 41-51.

[2] Hiramatsu S, Mizuyama T, Ishikawa M, “Study of a method for predicting hillside landslides by analysis of transient flow of water in saturated and unsaturated soils”, Journal of the Japan Society of Erosion Control Engineering , Vol. 43, 1990, pp. 5-15. (in Japanese with English abstract)

[3] Montgomery DR, Dietrich WE, “A physically based model for the topographic control on shallow landsliding”, Water Resources Research, Vol. 30, 1994, pp. 1153-1171.

[4] Wu W, Sidle RC, “A distributed slope stability model for steep forested basins”, Water Resources Research, Vol. 31, 1995, pp. 2097-2110.

[5] Pack RT, Tarboton DG, Goodwin CN, “The SINMAP approach to terrain stability mapping”, Proceeding of International Congress of the International Association for Engineering Geology and the Environment, 8, 1998, pp. 1157-1165.

[6] Khazai B, Sitar N, “Assessment of seismic slope stability using GIS modeling”, Geographic Information Sciences, Vol. 6, 2000, pp.121-128.

[7] Kosugi K, Mizuyama T, Fujita M, “Accuracy of a shallow-landslide prediction model to estimate groundwater table”, Journal of the Japan Society of Erosion Control Engineering, Vol. 55, 2002, pp. 21-32. (in Japanese with English abstract)

[8] Uchida T, Mori N, Tamura K, Terada H, Takiguchi S, Kamee K, “The role of data preparation on shallow landslide prediction”, Journal of the Japan Society of Erosion Control Engineering, Vol. 62, 2009, pp. 23-31. (in Japanese with English abstract)

[9] Fujimoto M, Kosugi K, Hayashi Y, Tani M, Mizuyama T, “The effect of resolution of elevation model data on shallow landslide analysis”, Journal of the Japan Society of Erosion Control Engineering”, Vol. 64, 2011, pp. 3-10. (in Japanese with English abstract)

[10] Kubota J, Fukusima Y, Suzuki M, “Observation and modeling of the runoff

process on a hillslope", Journal of Japanese Forest Society, Vol. 69, 1987, pp. 258-269. (in Japanese with English abstract)

[11] Kubota J, Fukushima Y, Suzuki M, "Observation and modeling of the runoff process on a hillslope (II)- Water budget and location of the groundwater table and its rising", Journal of Japanese Forest Society, Vol. 70, 1988, pp. 381-389. (in Japanese with English abstract)

International Journal of GEOMATE, June, 2016, Vol. 10, Issue 22, pp. 2094-2100.
MS No. 5367 received on June 30, 2015 and reviewed under GEOMATE publication policies.

Corresponding Author: Tetsuya Iida