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MONITORING AND WARNING SYSTEM FOR SLOPE FAILURE DUE TO HEAVY RAINFALL

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Abstract

In this paper a monitoring and warning system for the slope failure due to heavy rainfall is introduced. This system is mainly composed of subsurface investigation, field measurement of rainfall, suction and temperature in unsaturated soil and the numerical simulation. The subsurface investigation is carried out to obtain the information on the soil profile and groundwater profile which is used in the numerical simulation as the initial and boundary conditions. The obtained data of rainfall, suction and temperature are acquired in the data logger and transferred to the laboratory and other organizations through the cellular phone. The Kitamura models for the soil water characteristic curve, unsaturated permeability coefficient and unsaturated seepage behavior of rainwater are applied to simulate the change in water content in unsaturated soil with time. Then the change in slope stability with time can be estimated on the real time. This information on the slope stability can be applied to the warning system.

INTRODUCTION

The green house effect has brought change in climate all over the world. In Japan, many slope failures due to rainfall have been frequently happened in the rainy season. A lot of lives, infrastructures and heritages have been lost due to slope disaster. Therefore, it is necessary to construct a slope disaster prevention system in order to predict the slope failure during heavy rainfall.

It is qualitatively said that the slope failures with rainfall are mainly caused by the increase in weight of soil mass, the decrease in suction of unsaturated soil with the increase in water content and the rise in groundwater level. So, it is important to measure the suction, rainfall, temperature etc., in order to predict the slope failure caused by heavy rainfall.

In this paper a monitoring and warning system for the slope failure due to heavy rainfall is introduced. A field monitoring system, which is used to measure the suction, rainfall, temperature, is described. And numerical simulations, which are applied to calculate the change in slope stability due to rainfall, are also explained.

MONITORING AND WARNING SYSTEM

Figure 1 shows the schema of the monitoring and warning system. First, a measuring point is determined by subsurface investigations. And then, the field measuring system (i.e. tensiometers, rain gage, thermometers and camera) are set up at that point. Using this monitoring system, the suction (negative pore water pressure), rainfall, temperature and photograph in the field can be obtained; these data are then transmitted to our laboratory through the cellular phone. On the other hand, in the laboratory, the slope stability with respect to rainfall time is quantitatively estimated based on the field measuring data and numerical simulations (i.e. slope stability analysis and 2-D unsaturated saturated seepage analysis). Finally, the warning is given according to the degree of risk obtained in our analysis.

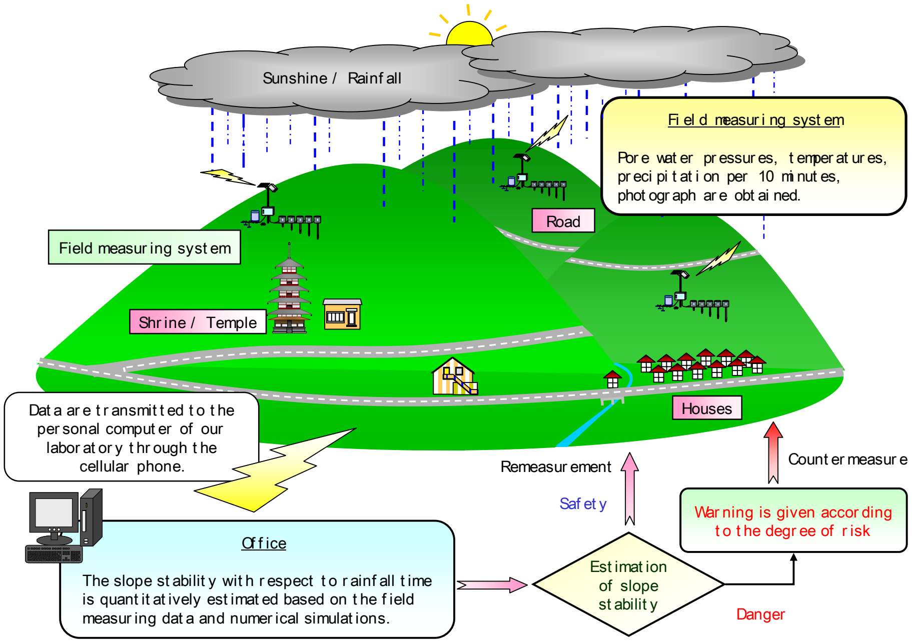


Figure 1. Scheme of monitoring and warning system

Figure 2 shows a research strategy of the prevention system of slope failures due to heavy rainfall proposed by Kitamura et al. [1]. The strategy is mainly composed of five items as shown in Fig.2. There are 1) laboratory soil tests on disturbed and undisturbed samples, 2) numerical simulations, 3) soil tank tests of seepage and failure, 4) Field measurement of suction, temperature and precipitation and 5) some in-situ tests for identification of geological and geotechnical characteristics of slope.

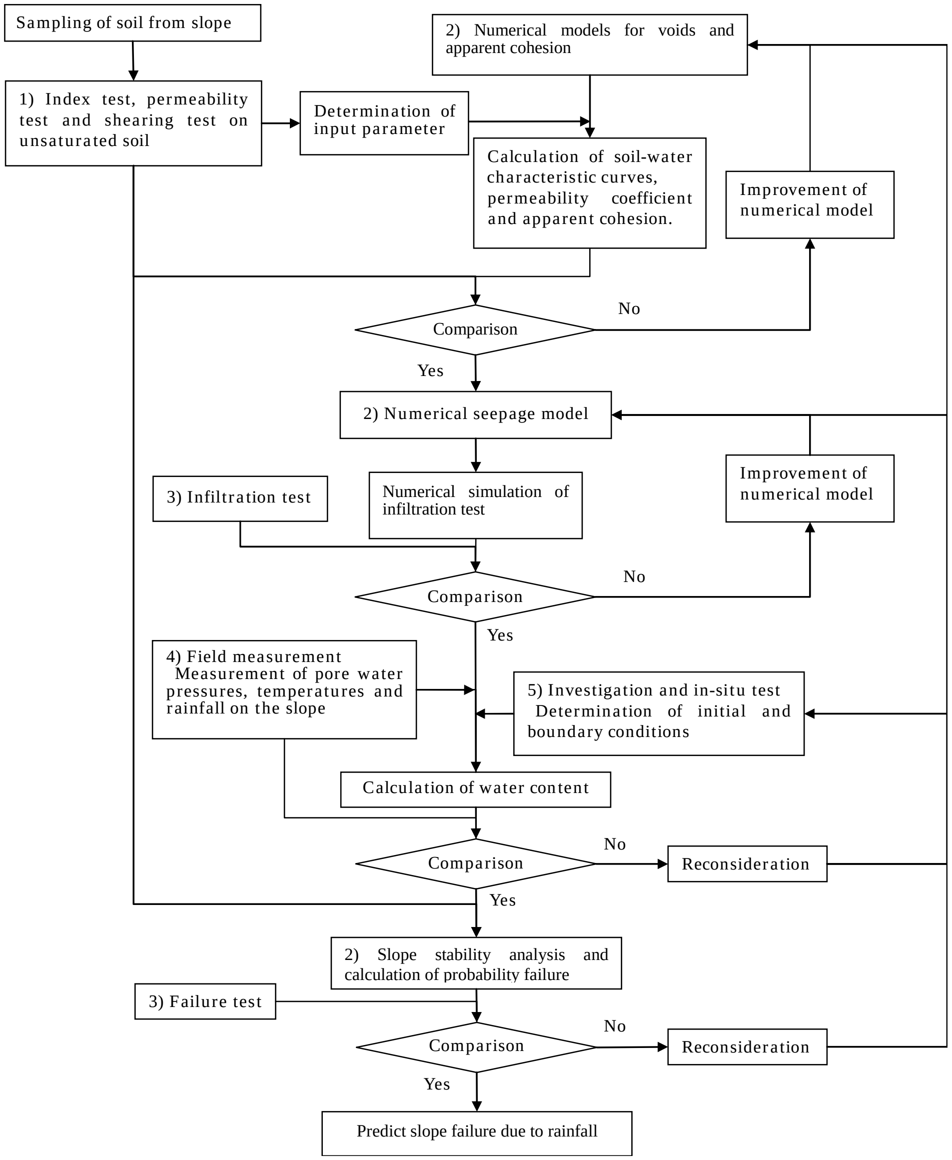


Figure 2. Research strategy for monitoring and warning system for slope failure due to rainfall

The purposes of each item will be explained as follows:

1) The results of laboratory soil tests are used as the input parameters for the numerical models and also used to validate the simulation.
2) The numerical simulations are important items for the prevention system. These items consist of a numerical model for voids, a numerical model for apparent cohesion, a 2-D unsaturated saturated seepage analysis and a slope stability analysis. The use of numerical model for voids [2] computed the unsaturated seepage characteristics of soil, i.e. the soil-water characteristic curve and the relationship between degree of saturation and unsaturated saturated permeability coefficient. The use of numerical model for apparent cohesion [3] computed the change in apparent cohesion with the change in water content. This change is one of the main causes of the slope failures due to rainfall. The Finite Element Method is used as the numerical seepage model. The results of numerical model for voids are applied to the above numerical seepage model. The Janbu method is used as the slope stability analysis. A probability of failure [4] is introduced as the new estimation method of slope stability in the rainfall.

3) The soil tank tests of seepage and failure are carried out to prove the validity of numerical scheme by means of the above-mentioned models in the soil tank where the initial and boundary conditions can be easily controlled.
4) The data of the field measurement, which are the pore water pressure, rainfall and temperature, are used to determine the initial and boundary conditions of 2-D unsaturated-saturated seepage analysis and to discuss the validity of numerical models.
5) Some in-situ tests such as CPT and boring are carried out to identify the geological and geotechnical characteristics of the slope. The calculation domain, the structure of layers and the potential slip plane are determined based on the data obtained from some in-situ tests.

FIELD MONITORING SYSTEM

Figure 3 shows the schema of the field monitoring system. This system is made up of tensiometers, tipping bucket type rain gage and thermometers, camera and data logger. Photo 1 shows the field monitoring system, which has already set up in the field.

Five tensiometers are laid to the depth of 20, 40, 60, 80 and 100cm, respectively. The pore water pressure at each depth is obtained by tensiometers. The tensiometers are composed of a porous cup, a semiconductor type pressure sensor and an acrylic pipe filled with degassed water. The porous cup is made of ceramic that is saturated and the air cannot pass through under a pressure smaller than its air entry value. The upper part of the tensiometer from the ground surface is covered by a box, which is surrounded by a thermal insulator, in order to avoid the influence of change in atmospheric temperature [5]. The tipping type rain gage is used to measure the rainfall. The thermometers are laid to the depth of 0, 10 and 30cm. And, the data are used for a numerical simulation of evaporation. The photographs of 350,000 pixels of the measuring point are taken in order to check the condition of the slope.

The pore water pressure, rainfall, temperature and photograph are measured by the data logger after every 10 minutes. All of the measuring data are the transmitted to our laboratory through the cellular phone after every 2 hours.

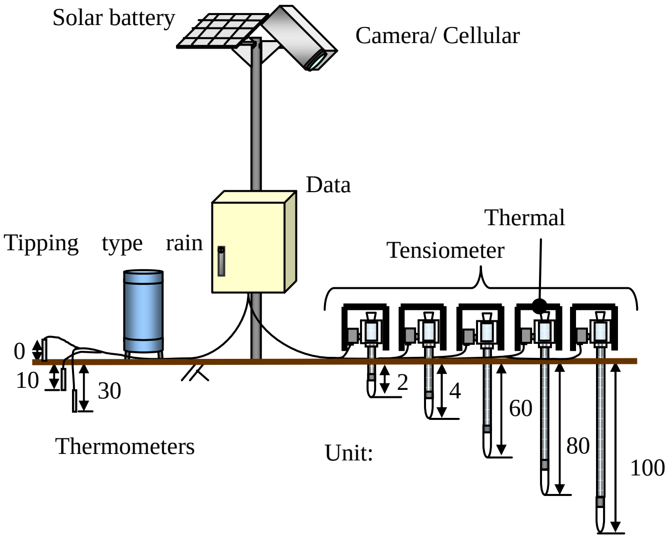


Figure 3. Schematic of the field measuring system

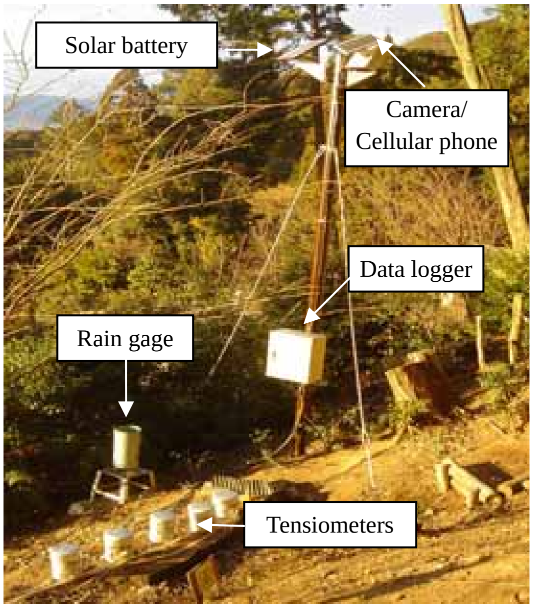


Photo 1. Field monitoring system

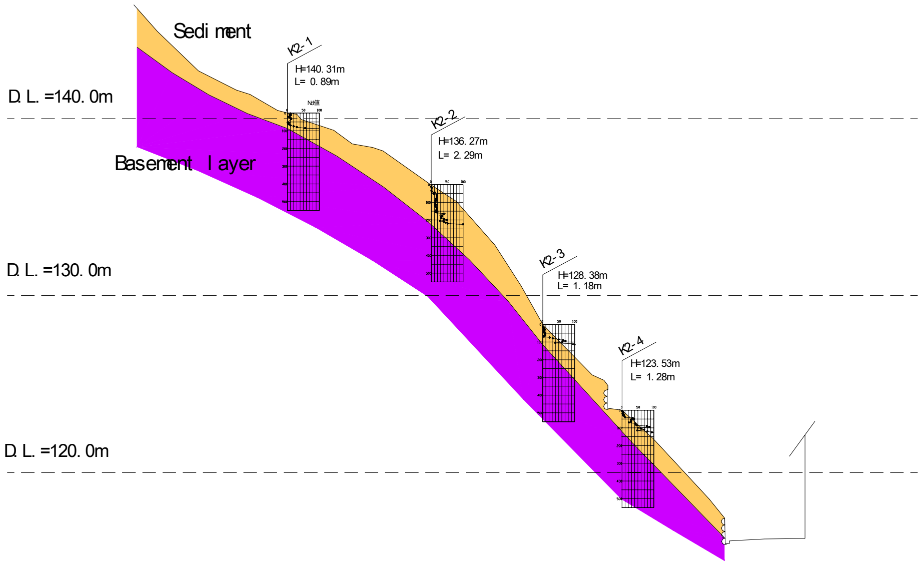


Figure 4. Cross-section of the slope and measuring point of the field monitoring system

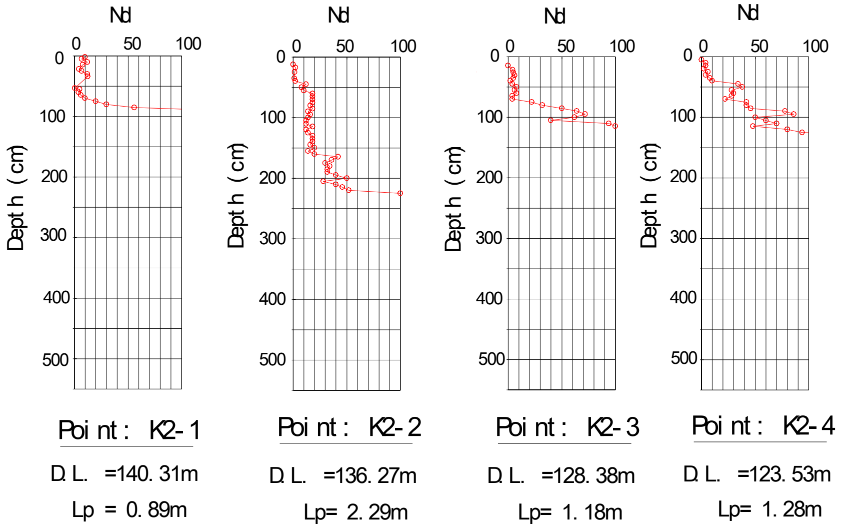


Figure 5. Penetration test results

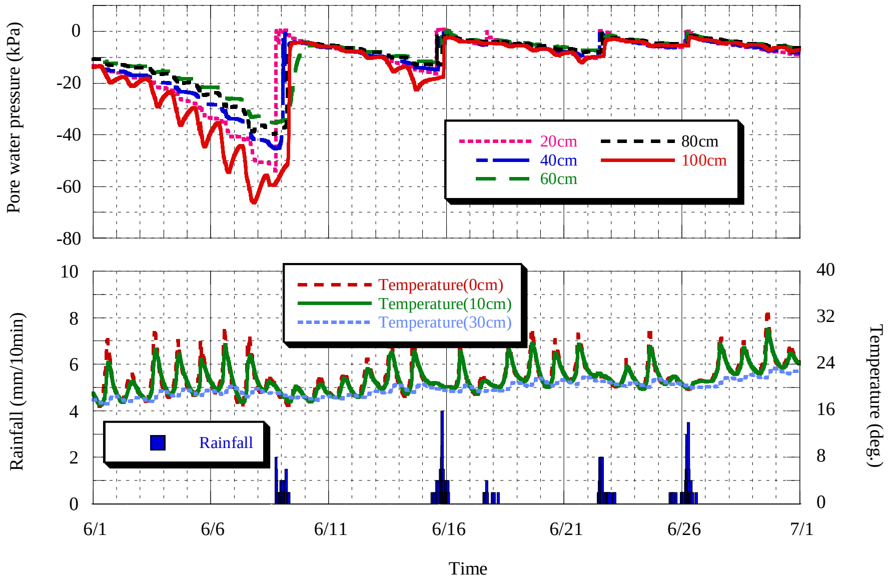


Figure 6. Field measuring data (June, 2006)

Figure 4 shows the cross-section of the slope and the measuring point of the field measuring system. In July 2004, the measuring system has been set up on this slope behind a concerning building, which was one of the important cultural assets in Japan. The penetration tests were carried on this slope by using the simplified dynamic penetrometer before setting up the field measuring system. These results are shown in Figure 5. From these tests, a potential slip plane from ground surface was found from 80cm to 200cm depth. The measuring point in our research was set at the depth of 120cm.

Figure 6 shows the field monitoring data in which we presented the change in pore water pressures, rainfall and temperatures with respect to the time. This monitoring data show the data in June 2006. From this figure, it is seen that the pore water pressures increase during rainfall, and decrease at the fine weather. The daily variation of temperature appears clearly at the depth of 0cm and 10cm, except at the depth of 30cm. Furthermore, it is also seen that a little influence of the temperature on the pore water pressure can be perceived from the measuring results.

NUMERICAL SIMULATION

2-D Unsaturated-saturated seepage analysis and slope stability analysis are applied to calculate the change in slope stability due to rainfall. It is important to get the soil water characteristic curve, unsaturated-saturated permeability coefficient and the relationship between degree of saturation and apparent cohesion in these calculations.

Kitamura et al. (1998) proposed a numerical model to simulate the unsaturated seepage characteristics of soil. Figure 7(a) shows the imaged soil particles in the small element. This situation can be modeled as shown in Figure 7(b), i.e., voids are modeled by pipes and soil particles are modeled by the other impermeable parts. Based on mechanical and probabilistic considerations in Figure 7(b), the void ratio (e), volumetric water content (W_v), unsaturated-saturated permeability coefficient (k) and suction (s_u) can be derived as follows:

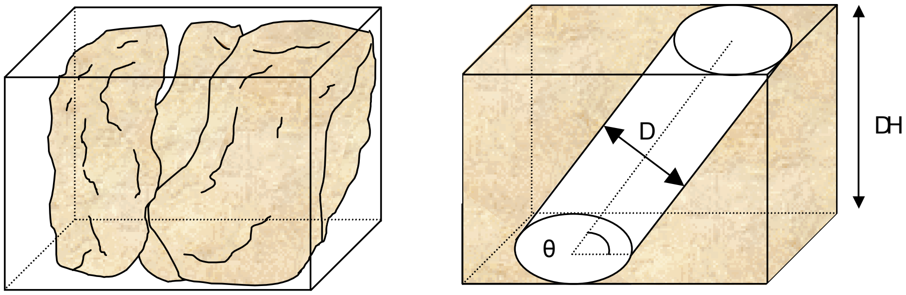
$$e=\int_0^\infty \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{V_P}{V-V_P}\cdot P_d(D)\cdot P_c(\theta)d\theta dD \tag{1}$$

$$W_v=\frac{e(d)}{1+e}=\frac{1}{1+e}\int_0^d \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{V_p}{V-V_p}\cdot P_d(D)\cdot P_c(\theta)d\theta dD \tag{2}$$

$$k = \int_0^d \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{\gamma_w \cdot D^3 \cdot \pi \cdot \sin\theta}{128 \cdot \mu \cdot \left[\frac{D}{\sin\theta} + \frac{DH}{\tan\theta} \right]} \cdot P_d(D) \cdot P_c(\theta) d\theta dD \tag{3}$$

$$s_u = \gamma_w \cdot h_c = \frac{4 \cdot T_s \cdot \cos\alpha}{d} \tag{4}$$

where V is volume of element, V_p is volume of pipe, D is diameter of pipe, θ is inclination angle of pipe, d is maximum diameter of pipe filled with water and DH is height of element as shown in Figure 7(b). $P_d(D)$ is probability density function of D, $P_c(\theta)$ is probability density functions of θ, γ_w is unit weight of water, μ is viscous coefficient of water, T_s is surface tension of water, h_c is height of water column due to surface tension and α is contact angle between pipe and water.



(a) A container with a few soil particles

(b) Pipe and the other impermeable parts

Figure 7. Modeling of particles and void in soil mass

Using the above model, the soil-water characteristic curves and the relationship between the unsaturated permeability coefficient and the degree of saturation can be calculated by using some simple parameters as: grain size distribution curve, density of soil particles, void ratio, viscous coefficient of pore water, and surface tension of pore water.

Kitamura et al. (2000) have proposed a numerical model for apparent cohesion in order to obtain the relationship degree of saturation and apparent cohesion [3]. The inter-particle force between two adjacent particles is generated by the surface tension of pore water. The inter-particle force F_i can be expressed by the following equation.

$$F_i = 2\pi r' T_s + \pi r'^2 s_u \tag{5}$$

where F_i is inter-particle force, T_s is surface tension, s_u is suction ($=u_a-u_w$), r' is radius of meniscus, a is radius of curvature of meniscus.

Equation 5 includes the suction in the second term of right side and then the volumetric water content in soil mass must be estimated to obtain the inter-particle force. Based on mechanical and probabilistic consideration, the apparent cohesion due to inter-particle force c_1 is obtained as the following equation.

$$c_1 = \frac{\pi}{\pi - 2} \cdot \overrightarrow{F_i} \cdot Nc \cdot \tan\phi \tag{6}$$

where Nc is total number of contact points per unit area, φ is internal friction angle.

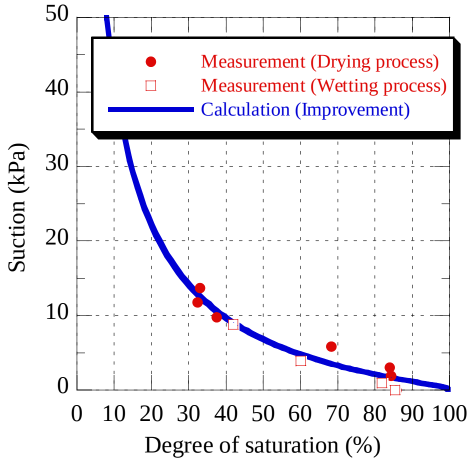


Figure 8. Soil-water characteristic curve obtained from Kitamura model.

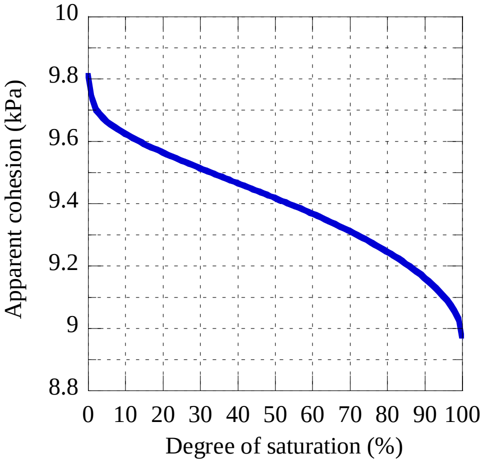


Figure 9. Relationship between the apparent cohesion and the degree of saturation obtained from Kitamura model.

The apparent cohesion obtained by shear test, c, includes some components due to interlocking, physical and chemical action, and the inter-particle force (or suction and surface tension). So apparent cohesion obtained by shear test is shown in the following equation.

$$c = c_0 + c_1 \tag{7}$$

where c is apparent cohesion obtained by shear test, c_0 is apparent cohesion that included some components due to interlocking, physical and chemical action.

Figure 8 show the Soil water characteristic curve obtained from Kitamura model. Substituting the results as shown in Fig.8 into Eq.6, the Relationship between the apparent cohesion and the degree of saturation are derived as shown in Fig.9. In Fig.9, c_0 is equal to 9.0 kPa.

These results are used to the 2-D seepage analysis and slope stability analysis. And, the results of field monitoring system and the subsurface investigation are used to determine the initial and boundary condition. Finally, the change in slope stability with time can be estimated on the real time.

CONCLUSIONS

In this paper, the monitoring and warning system for the slope failure due to heavy rainfall was introduced. The rainfall, pore water pressure and temperature can be obtained from the field monitoring system. The obtained data of rainfall, suction and temperature are acquired in the data logger and transferred to the laboratory and other organizations through the cellular phone. The data of the field measurement will be used to determine the initial and boundary conditions of 2-D unsaturated-saturated seepage analysis.

The Kitamura models for the soil water characteristic curve, unsaturated permeability coefficient and unsaturated seepage behavior of rainwater are applied to simulate the change in water content in unsaturated soil with time. Then the change in slope stability with time can be estimated on the real time. This calculation result on the slope stability can be applied to the warning system.

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