Multi-layered shear model test to simulate rain-induced pre-failure shear deformation in surface layer of slopes

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ABSTRACT

The time-dependent developments of the strain observed on the slope surface in pre-failure stages are often expressed in analogy with the development of strain at creep fracture of metals. Therefore, several equations for prediction of slope failure using the creep models have been proposed and used. In this study, multi-layered shear model test apparatus was developed to observe detailed movement of the surface layer of slope before failure. And, the conventional methods to predict the failure time were validated based on the test results.

Keywords: Early warning; Slope failure; Pre-failure deformation; Failure time prediction

1 INTRODUCTION

It is known that the surface of slope deforms continuously for several hours or several tens of hours in pre-failure stage. Extensometer is widely used to observe such deformation on the slope surface. Recently, pre-failure shear deformation in surface layer of slope has been observed using an inexpensive and easy-setting tilt sensor (e.g. Uchimura et. al., 2009).

Time histories of the strain in the surface layer before failure are often modeled in analogy with creep failure of metal. Several equations based on the creep models have been proposed to predict the failure time (e.g. Fukuzono, 1985).

In this study, the authors developed a multi-layered shear model of surface layer of slope to observe detailed of its behaviors before failure, and validate the conventional failure time prediction methos.

2 MODEL TEST SETUP

As shown in Fig. 1, the multi-layered shear model test apparatus has a height of 1 m by stacking 20 layers of soil. Every layer is 5 cm-high, 54 cm-long, and 54 cm-wide, and supported by metal frame which is in contact with next ones by wheels to reduce friction. According to Osanai, et. al (2009), the depth of slip surface is 1.2 m in average for surface failures reported in Japan. Therefore, this model can be considered as nearly full-scale.

A pair of air cylinders, together with a pair of load cells, is installed on the sides of every frame to apply constant shear load on the boundary between layers. A pair of displacement sensors is also installed to measures the relative displacement between layers.

The model simulates a soil mass from the slope surface to the depth of 1 m. Each frame was loaded with a constant shear load of approximately 40% (corresponding to a slope of about 21 degrees) of the soil weight above respective boundary. Continuous rainfall (1.5 mm / h) was applied on the top of the model from the start of the test, and the progress of shear displacement by seepage of rain water was observed. In addition, volumetric water contents were measured at the centers of four layers by moisture sensors. Edosaki sand (D50=0.18mm, fine fraction content 9%, relative density 70%, water content 7%) was used for the model.

Fig. 1. Multi-layered shear model test apparatus

3 TEST RESULTS

3.1 Displacement of each layer

Fig. 2 shows the time history of the horizontal displacement of each layer relative to the fixed bottom of the model after the rainfall started at time = 0. The displacement of the top layer (Layer 1) corresponds to what is measured by extensometer on the slope surface in practice. Shear deformation started earlier, and the displacements were larger at the upper layers, as the rain water infiltrate from the top surface. However, the relative displacement between every layer was larger at the lower part of the model in the later stage. Deformation stabilized after about 10 hours of rainfall.

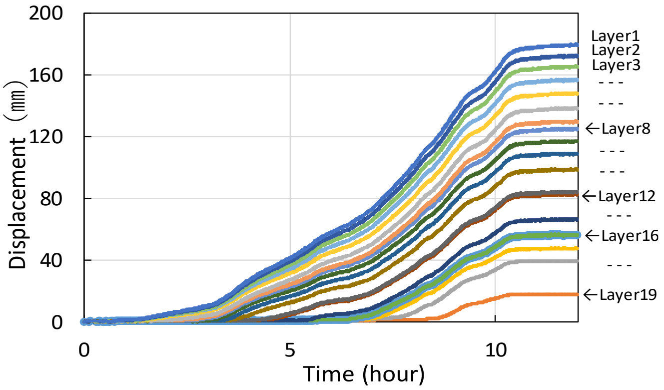

Fig. 2. Time history of displacement of each layer

3.2 Relative displacement and volumetric water content at each layer

Fig.3 shows the time history of the volumetric water contents at the layers 7, 12, 16 and 19, together with the displacements relative to the upper and lower next layers. The volumetric water content increased earlier at the upper layers. It increased up to around 30% for every layer. The relative displacement started when the water content started increased for every layer. The rate of displacement was lower in the upper layer and higher in the lower layer.

4 DISCUSSION

4.1 Application of conventional creep model

One of conventional methods to predict the failure time was validated with the result of model test. The method assumes the following relationship:

$$L = A \cdot \log\{(t_r - t_0)/(t_r - t)\}$$

L : displacement A : constant
t_r : failure time t_0 : time at $L = 0$
t : current time

The remaining time before failure (t_r - t) is plotted in log scale against the displacement (L) in normal scales assuming various failure times (t_r) as shown in Fig. 4. The plot is linear if appropriate t_r is assumed. For example, Fig. 4a shows the plots for Layer 1 assuming t_r = 10 and 14 hours are shown respectively. The plot is nearly linear when t_r = 14 hours, while it is curved when t_r = 10 hours. Thus, the failure time for this layer is predicted to be t_r = 14 hours.

Consequently, Fig. 5b plots it for every layer assuming t_r = 14 hours. The relations were nearly linear for most of the upper layer. Meanwhile, the plots for the lower layers were not linear. They never be linear even other various values of t_r were tried. As observed in Fig. 3, the relative displacement between layers progressed under nearly constant volumetric water contents in upper layers. Meanwhile, the volumetric water content in lower layers increased rapidly together with the relative displacement developed. The changes in the water content may be the reason of the mismatching of the creep model.

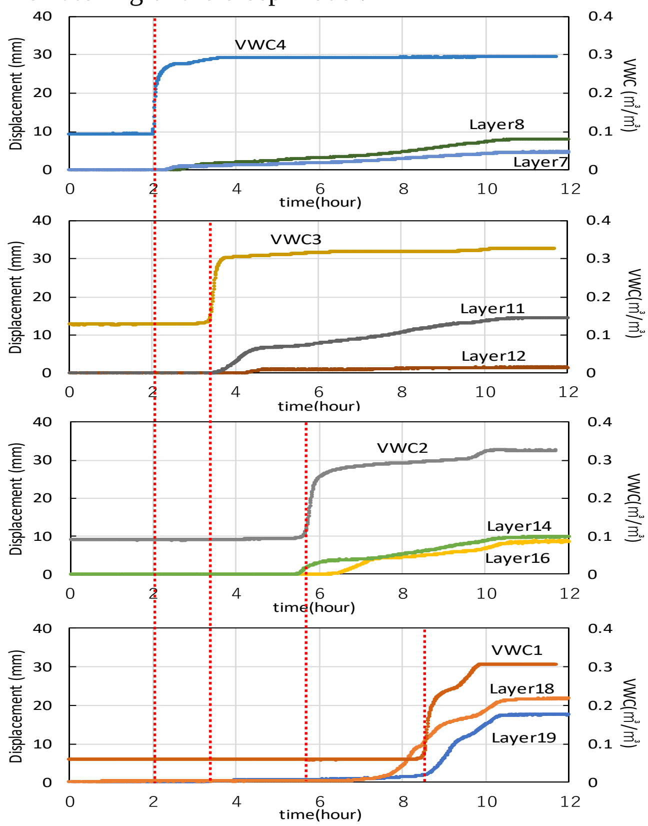

Fig. 3. Time history of water content and relative displacement at respective layer

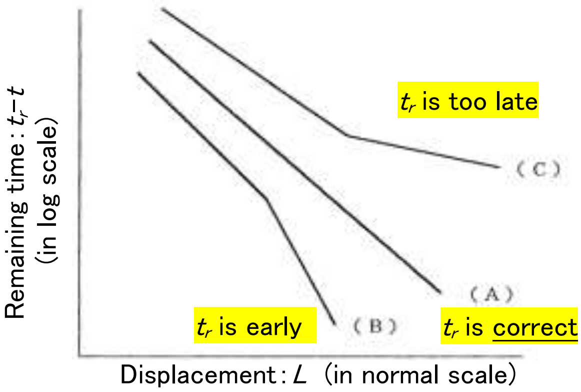

Fig. 4. Relationship between time to collapse and amount of displacement

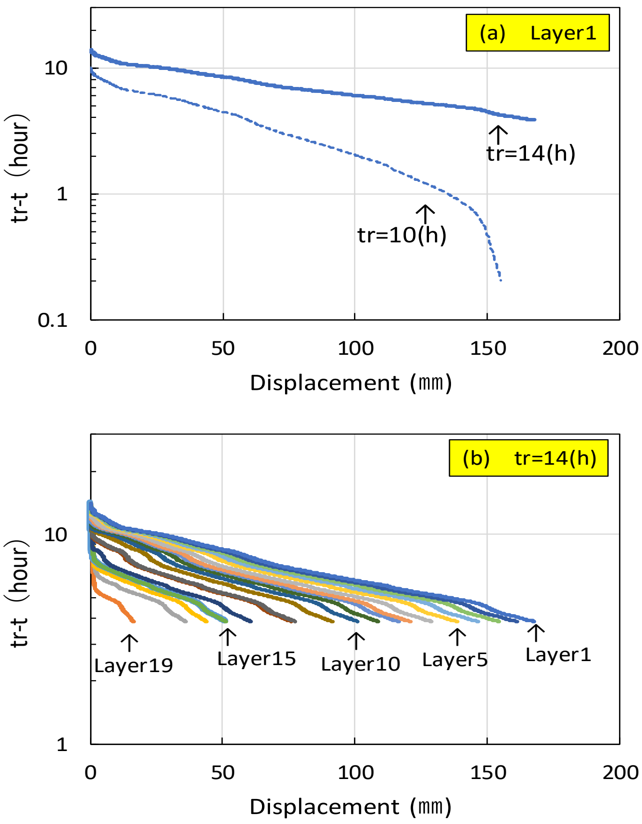

Fig. 5. Plot for the absolute displacement of each layer

4.2 Application of other models

Another method to predict the failure time proposed by T. Fukuzono (1985) was validated with the result of model test. Following relation is assumed in this model:

$$\frac{1}{v} = \{a(\alpha-1)\}^{1/(\alpha-1)} (t_r - t)^{1/(\alpha-1)}$$

v : displacement rate a, α : constants

t_r : failure time t : current time

The reciprocal of the rate of displacement is plotted against time in normal scales (Fig. 6). By assuming α = 2 as a typical value for soils, the plot will be linear. By extending the plot, and the time crossing the horizontal axis (1/v = 0) is the predicted failure time.

This method was applied to the displacement of the top layer relative to the bottom of the model (Fig. 7). In these plots, the displacement was translated into tilt angle by dividing with the height of the model (Fig. 8a). This is simulating the tilt angle of a steel rod which is inserted in to the slope surface in vertical direction, which is a practical slope monitoring method proposed by Uchimura et. al. (2015) (Fig. 8b).

Fig.9 shows the time history of the tilting rate and its reciprocal, respectively. As shown in Fig. 7, the tilt angle increased from the start of rain, and stabilized at about 10 degree after 10 hours probably due to limitation of the apparatus. During this period of 10 hours, the tilting rate gradually increased, and the plot of reciprocal of the tilting rate showed linear trend toward a predicted failure at t_r = 15.1 hours. This is nearly consistent with the failure time t_r = 14 hours predicted by the previous method in Fig. 5.

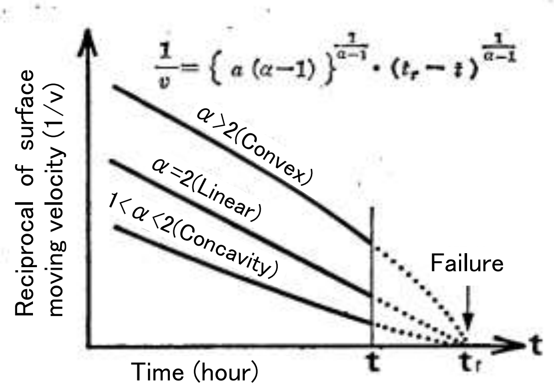

Fig. 6. Plot of reciprocal of surface moving velocity against time.

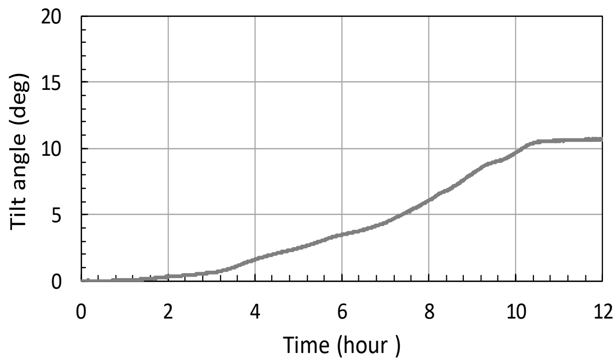

Fig. 7. Time dependence of tilt angle

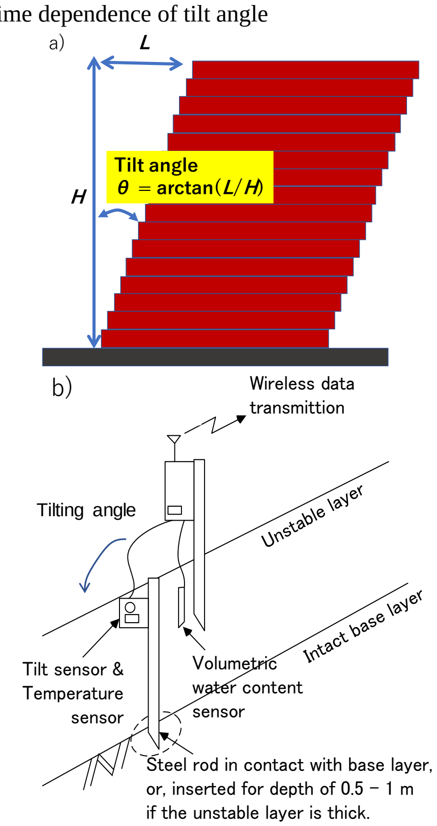

Fig. 8. Tilt angle of the model and its measurement on site

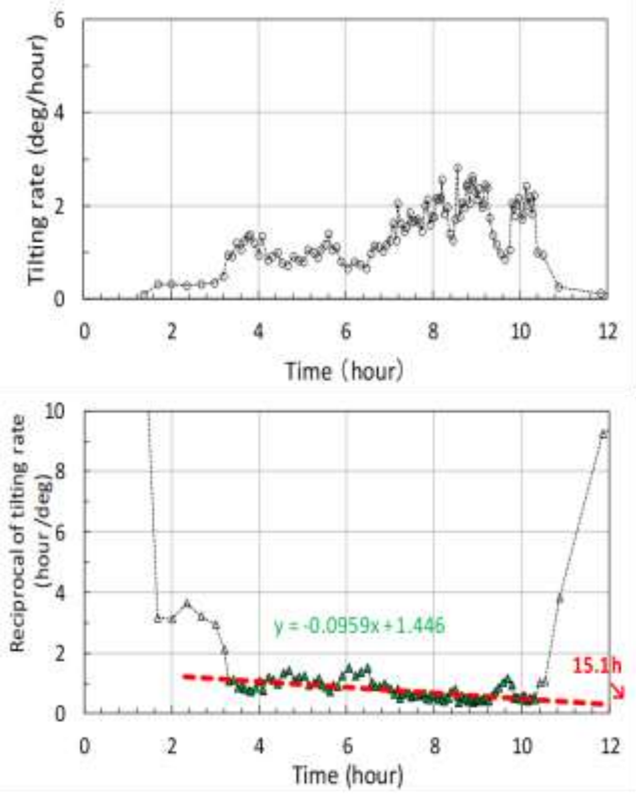

Fig. 9. Failure time prediction based on reciprocal of tilting rate

Uchimura et. al. (2015) summarized the tilting behaviors of surface layers of slopes before failure in various practical sites (Fig. 10). The remaining times before failure are plotted against the tilting rate measured by the method shown in Fig. 8b. There is a unique relationship with some range, even though the conditions of every sites are largely different.

By assuming the failure time is 15.1 hours as estimated in Fig. 9, the pre-failure behavior of the model is also plotted in Fig. 10. It is nearly the upper limit of the range.

5 CONCLUSION

The progress of shear deformation in surface layer of slopes due to rainfall was simulated using multi-layered shear model in the laboratory. The deformation started sequentially from the upper layer corresponding to penetration of rain water, and displacement was different depending on the depth. Some prediction methods for failure time were examined with the test results. The relation between the remaining duration before failure and tilting rate observed in the model agreed with that observed in several cases with real slopes which the authors has studied.

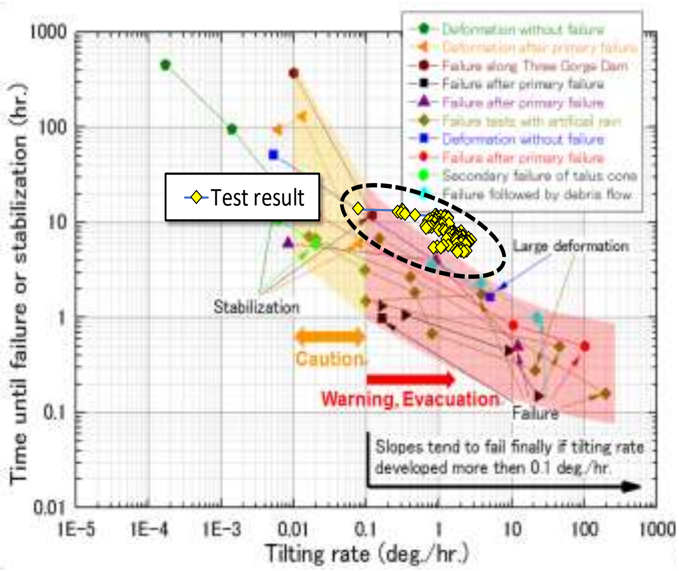

Fig. 10. Remaining time before failure and tilting rate

In the model test, a constant shear load was applied to each layer in the horizontal direction. However, when the water content increases due to rainfall, the weight of each layer increase, and the shear load also increase gradually. Current test apparatus can't simulate such loading condition. The author will revise the apparatus to deal with this matter.

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