International Journal of GEOMATE, Oct., 2022, Vol.23, Issue 98, pp.164-170
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2022.98.6262
Geotechnique, Construction Materials and Environment

VERIFY THE PREDICTION OF SLOPE FAILURE BY SOIL CREEP WITH LABORATORY EXPERIMENTS

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*Corresponding Author, Received: 02 Aug. 2022, Revised: 07 Sept. 2022, Accepted: 10 Oct. 2022

ABSTRACT: More than a thousand cases of rainfall-induced slope failure occur in Japan every year. Predict the slope failure is social needs. In this paper, we propose and verify a method to predict the instability of the slope surface layer by soil creep combined with the creep theory of metallic materials. To investigate the creep theory affected by soil moisture and deformation and to verify the relationship between creep and soil moisture, and deformation, two kinds of laboratory experiment was conducted to simulate the process of rainfall-induced slope failure, the first one was a multi-layer shear model and the second one was the direct shear test. The soil moisture was controlled by artificial rainfall in the multi-layer shear model, whereas water infiltrates in the direct shear test. The inverse number of velocity calculated by Fukuzono's equation and the surface displacement have been compared; the results show that the tendency of the change of the inverse number of velocity is similar in both model tests. The effect of volumetric water content on the displacement also has been confirmed; when the volumetric water content increased, the displacement trended to start increasing at an accelerated rate. From these results, the prediction of slope failure time can be improved with higher accuracy.

Keywords: Slope failure, Early warning, Soil creep, Shear deformation

1. INTRODUCTION

Rainfall-induced slope failure occurs commonly in Japan. Before the slope failure, the continuous slow movement of soil mass has been traditionally considered soil creep[1]-[2], the time to slope failure can be predicted from the process of soil creep. So the prediction of the time to slope failure is very important for the countermeasures designed to avoid human losses and reduce property damages from slope failure. Nowadays with the development of technology, the movement can be easily monitored by means of simple wire extensometers[3], inclinometers[4], or tilt sensors[5]. Uchimura [6] has proposed a simple monitoring method for the early warning of rainfall-induced slope failure, the distinct behaviors of mass movement expressed by tilting angles at several sites can be detected in the pre-failure stages. The methods to predict the time of slope failure had been developed by many researchers [7],[8],[9],[10], they showed that the behavior of the soil creep is similar to the metal creep. In this paper, we focus on one of the methods, Fukuzono's equation[8], to predict the instability of the slope surface layer.

To verify the accuracy of the prediction of the time to slope failure, two kinds of laboratory experiments were conducted to simulate the process of rainfall-induced slope failure. The inverse number of velocity calculated by Fukuzono's equation and the surface displacement have been compared and the effect of volumetric water content on the displacement also has been confirmed.

2. BEHAVIOR DURING SLOPE FAILURE

2.1 Deformation Until Failure

The creep can be explained by the time-dependent deformation of solids under constant stress. In general, three creep stages of movement are included in creep behavior before failure:

- -Primary: strain rate decreases over time.
- -Secondary: strain rate is constant.
- -Tertiary: strain rate is rapidly increasing until failure.

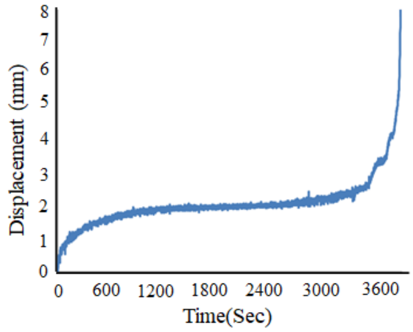

Fig. 1 Example of soil creep in slope failure.

In the case of soil failure (Fig.1), displacement rate increases at a constant at the secondary creep, and then increases rapidly at the tertiary creep, finally failure. The behavior of soil creep varies depending on conditions such as particle size, soil moisture, and slope angle, etc., the duration of tertiary creep may be different from sites. Metal creep is shown in Fig.2. It shows that the behavior of the soil creep (Fig.1) and metal creep is similar.

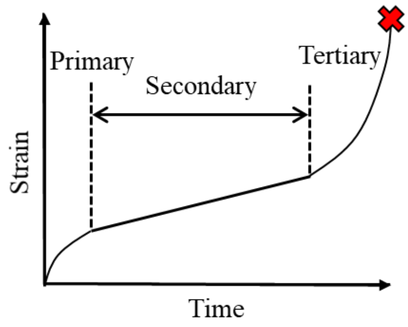

Fig. 2 The development model of Metal creep

2.2 The Method of Failure Prediction

Fukuzono[8] found that rapid failure in the tertiary creep base on an experimental study of small scale slope model tests under monotonically increasing load, and proposed the following general expression:

【Fukuzono method】

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

Where v **is** the velocity of the slope surface displacement, t is the current time, t_r is the estimating time to failure, a: constant.

In the case of α = 2, Eq.1 can be expressed in terms of deformation, proposed by Saito[7]:

【Saito method】

$$\varepsilon = C \cdot \log\frac{(t_r - t_0)}{(t_r - t)} \qquad (2)$$

Where ε is the strain, t_r is the estimating time to failure, t_0 is the time at strain = 0, t is the current time, C is constant.

Fig. 3 shows the typical figures of Fukuzono's method. The changes of the inverse number of velocity of surface displacement (1/v) are represented by y-axis and the elapsed time is represented by the x-axis. The failure time is defined by an intersection point which is an extension of the dotted line to the x-axis.

This prediction method is verified by laboratory experiments that were conducted to simulate the process of rainfall-induced slope failure. Even if the results show complicate behavior of soil creep, but it is possible to predict the time to failure from the linear part corresponding to the tertiary creep.

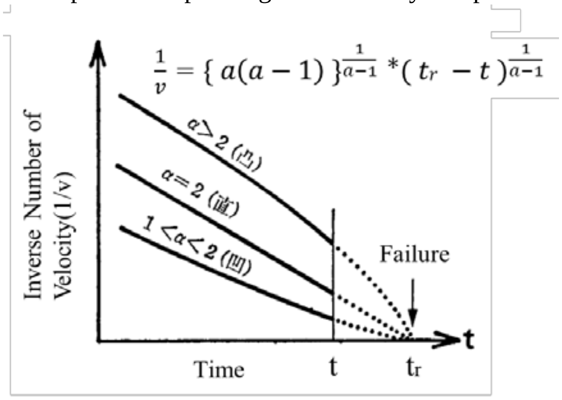

Fig. 3 Typical figures of the changes of the inverse number of velocity of surface displacement just before the failure. (after Fukuzono[8])

3. LABORATORY TEST METHOD

3.1 Properties of the Test Soils

In this study, two types of material were used in laboratory tests. The first one is mixed sand which is comprised of Silica sand No4, No5, No7, and No8 mixed with a ratio of 1:1:3:1. The other one is Silica No.7. The soil property is shown in Table 1 and the grain size distribution curve is shown in Fig. 4.

Table 1 Soil property of material

Soil property		Mixed Silica	Silica No.7
Relative density(Dr)	%	50	50
Dry density(ρd)	g/cm^3	1.481	1.340
Initial volumetric water content(θ)	%	7	7
Strength parameters(Φ)	Φ°	43.9	37.1
Strength parameters(C)	kN/m^2	7.4	28.6

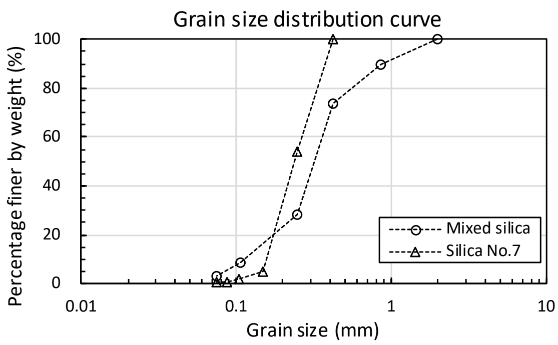

Fig. 4 Grain size distribution curve of test soil

3.2 Multi-Layer Shear Model

Laboratory experiments were performed using a multi-shear model to simulate the process of rainfall-induced slope failure. The concept and the detail of the multi-shear model were summarized at [11]. It is a model including 20 frames with a total height of 1m. Every frame has a height of 0.05m, length of 0.6m, and width of 0.54m, the soil is filled in the frame. Wheels are setup at every frame to reduce friction. A constant horizontal force is applied on every interface between the layers by air cylinders to simulate the shear force corresponding to the slope angle. Load cells and displacement meters are also set at every layer. The artificial rainfall intensity is 60mm/h. Rainwater infiltrates into the top layer and drains out from the bottom. The volumetric water content is measured by the Soil moisture sensor EC-5. (Fig.5)

3.3 Direct Shear Test

Direct shear tests also are conducted to simulate the slip surface failure. Two layers are included. Every layer has a height of 0.035 m, length of 0.31m, and width of 0.21m. Vertical stress is applied by the upper layer; Constant horizontal force is applied by air cylinders. Water is infiltrated to the soil via ceramic disks which set up at the bottom (Fig.6).

Fig. 5 Multi-layer shear model test apparatus

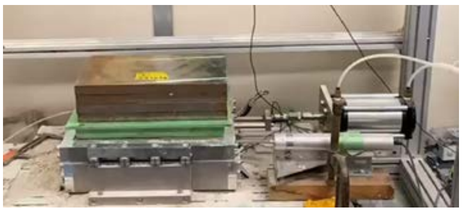

Fig. 6 Direct shear test apparatus

4. EFFECT OF DISPLACEMENT RATE ON PREDICTING THE TIME TO FAILURE

4.1 Results of Multi-Layer Shear Model Test

The method of prediction the time to failure by the displacement rate has been studied at many slop surface using extensometers. However, the progress of ground deformation is not constant in the depth direction. In this study, laboratory experiments using multi-layer shear model can confirm the detailed displacements of a part of soil subdivided into many layers at the depth direction (Fig.7).

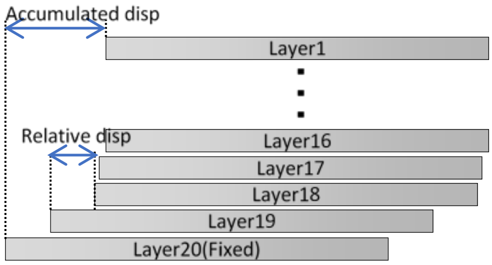

Fig. 7 Concept of displacement in multi-layer shear model test

The effect of the displacement rate on the time to failure was verified by multi-layer shear model tests. Fig. 8 shows the time history of the displacement in the test using silica No. 7. Fig. 8 a) shows the relative displacement of layer 19 and layer 18 are large, especially the displacement of layer 18 progresses rapidly after 0.1 hours, whereas the displacements of the other upper layers are small. Fig. 8 b) shows the accumulated displacement at to top layer, layer 19, and layer 18.

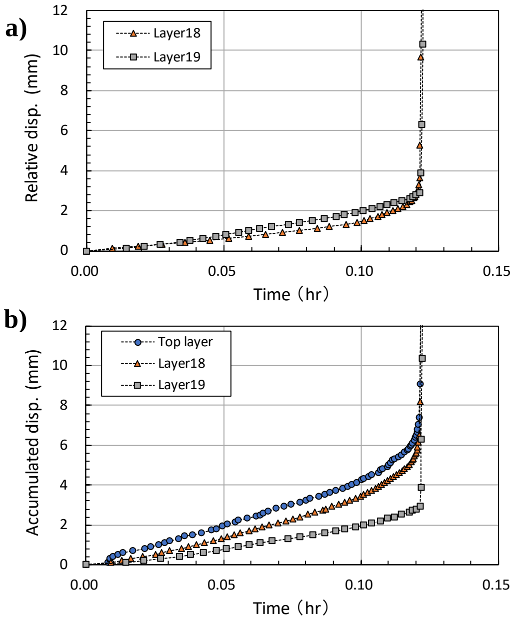

Fig. 8 Time history of displacement (Silica No. 7)

4.2 Application of Failure Prediction Method

To obtain the time to failure, the following data were calculated by the prediction method (Eq.1).

- Accumulative displacement at the top layer (corresponding to the bottom layer).
- Relative displacement near the bottom (layer18 and 19) which shows particularly remarkable changes.

Fig. 9 shows the results of the time history of displacement and the inverse number of velocity at the multi-layer shear model. The time to failure obtained from the accumulative displacement of the top layer is 0.126 hour. The time calculated from the relative displacement is different, 0.122 hour at layer 18 and 0.144 hour at layer 19. The inverse number of velocity at layer 18 gradually increased from 0.1 hours, whereas at layer 19 did not change so much but increased rapidly before failure. It is observed that the inverse number of velocity at the top layer is the sum of layer 18 and layer 19, so it is considered that the time to failure is the following relationship of the prediction method.

[Early] [Late]
Layer 18 → Surface layer → Layer 19

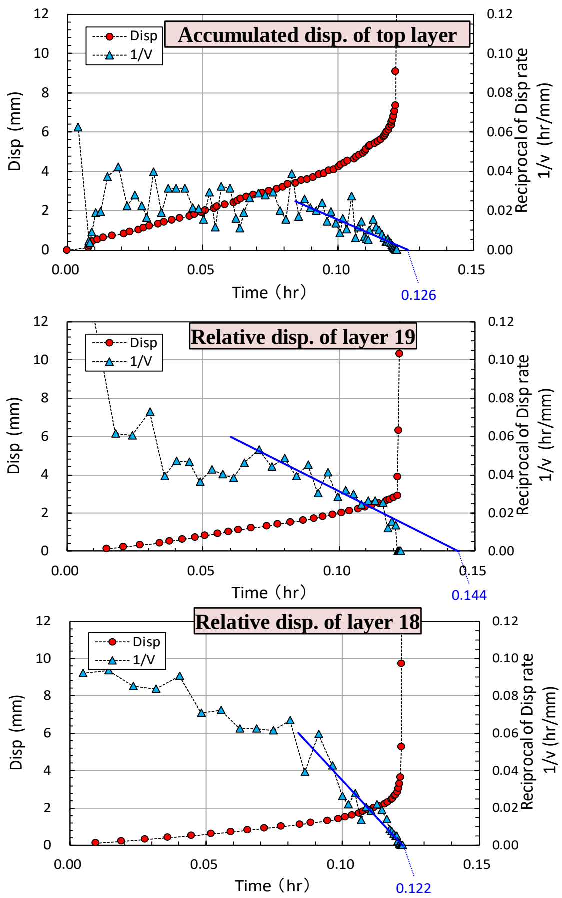

Fig. 9 Time history of displacement and the inverse number of velocity(Silica No. 7)

Fig. 10 shows the time history of displacement and the inverse number of velocity at direct shear test. In this case, the surface layer progresses slowly displacement, the time to failure which calculated by the prediction method was later than the actual time. Therefore, it is safe to predict the failure time using the layer which observed fast displacement to prevent damage due to failure.

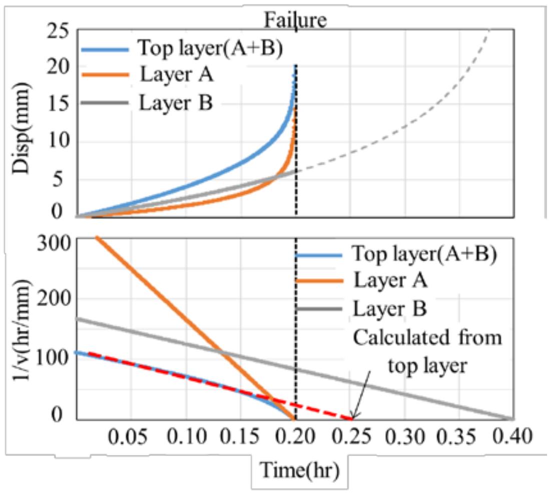

Fig. 10 Displacement and the inverse number of velocity at direct shear test

5. CHANGE IN DISPLACEMENT RATE DURING THE TERTIARY CREEP STAGE

5.1 Test Results for Each Method

The method of prediction the time to failure is performed by the tertiary creep. The time to failure is obtained by plotting the time and the inverse number of velocity. In the secondary creep stage, the inverse number of velocity shows a large value because the displacement proceeds at a constant small speed. During the tertiary creep stage, the displacement increases at an accelerating rate, so the inverse number of velocity gradually decreases. In particular, when $\alpha = 2$, the inverse number of velocity becomes linear as shown in fig.3.

5.1.1 Results of direct shear test

Direct shear test was performed using the mixed Silica sand under the conditions shown in Table 2. Fig. 11 shows the time history of the displacement and the corresponding inverse number of velocity. According to the test results of case 1, the tertiary creep stage starts from 0.4 hour, the inverse number of velocity decreases from 0.4 hour and then accelerates from 0.6 hour, finally failure at 0.82 hour. In case 2, the tertiary creep stage starts from 0.3 hour, the inverse number of velocity decreases from 0.3 hour and then accelerate from 0.4 hour, finally failure at 0.55 hour.

5.1.2 Results of multi-layer shear model test

Multi-layer shear model test (10 layers) was conducted using the mixed Silica sand, Fig. 12 shows the relationship of displacement and the inverse number of velocity in time series. The inverse number of velocity decreases from 2.4 hours, and accelerate decreases from 3 hours, showing the same tendency as the result of the direct shear test.

5.2 The Effect of Volumetric Water Content on Displacement

The changes of inverse number of velocity(1/v) in the tertiary creep stage have been confirmed by both of direct shear test and multi-layer shear model test. The effect of volumetric water content on soil creep also has been investigated by both tests. In the multi-layer shear model test, artificial rainfall (60mm/h) was applied, and the rainwater infiltrated into the top layer. In the direct shear test, water was injected into the soil from mode bottom. The following results show how volumetric water content affects the soil creep.

5.2.1 Direct shear test

Fig.13 shows the relationship of the volumetric water content and the inverse number of velocity(1/v) in time series in the direct shear test. starts to increase at a constant rate after the supply of water from the time history. At the same timing that the volumetric water content starts to increase at an accelerated rate, the inverse number of velocity(1/v) also starts to decreases quickly.

5.2.2 Multi-layer shear model test (10 layers)

Fig. 14 summarizes the results of the multi-layer shear test. In this test, the volumetric water content at each layer was different depending on the time for water infiltration from the upper layer. The volumetric water content began to increase with the infiltration of rainwater from the upper layer, and changed at a constant rate from 1.4 hours, increased again from 2.6 hours. The slope of the inverse number of velocity(1/v) changed from 3 hours. The change timing is different from the result of the direct shear test. However, the timing of the accelerate of the inverse number of velocity(1/v) is the same when the volumetric water content increases to over 0.25.

5.2.3 Discussion

Because the speed of water infiltration was different between the two kinds of laboratory experiments, the failure time also showed differently. From these results, it is confirmed that in the tertiary creep stage, the slope of the inverse number of velocity(1/v) tended to increase rapidly when the water content rose high. This phenomenon may be considered that the increase of soil moisture leads to a decrease in soil matric suction, resulting in the weakening of soil strength.

In the direct shear test, the changes of inverse number of velocity(1/v) in the tertiary creep stage have been confirmed that it is the same results with the previous research [6]. Considering the uniform of the soil and the various physical properties of strata, it is possible to predict the time to failure more accurately by understanding not only the ground surface but also the deformation in ground.

Table 2 Test conditions of direct shear test

Case	Vertical pressure (kPa)	Horizontal pressure (kPa)	Water injection pressure (kPa)	Water injection speed (%/min)
1	7	6.7	0.3	0.41
2	7	7.5	0.15	0.59

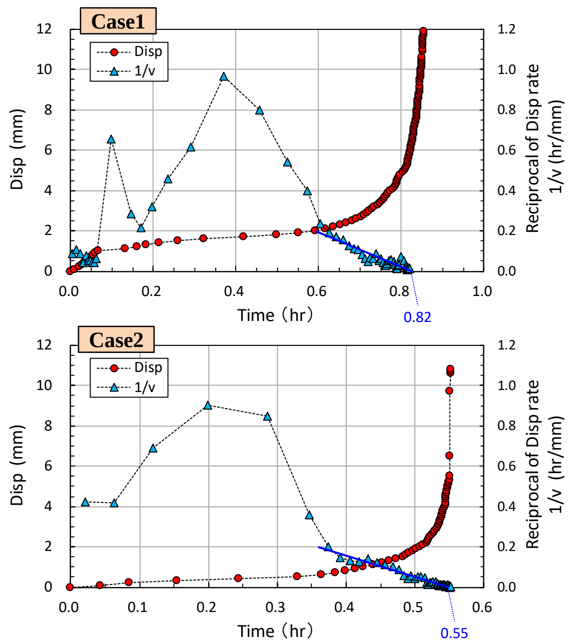

Fig. 11 Time history of displacement and the inverse number of velocity (Direct shear test)

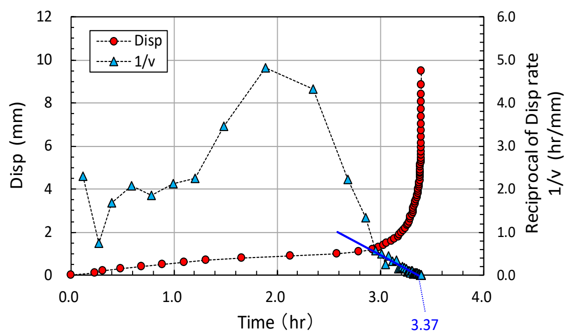

Fig. 12 Time history of displacement and the inverse number of velocity (multi-layer shear model test (10 layers))

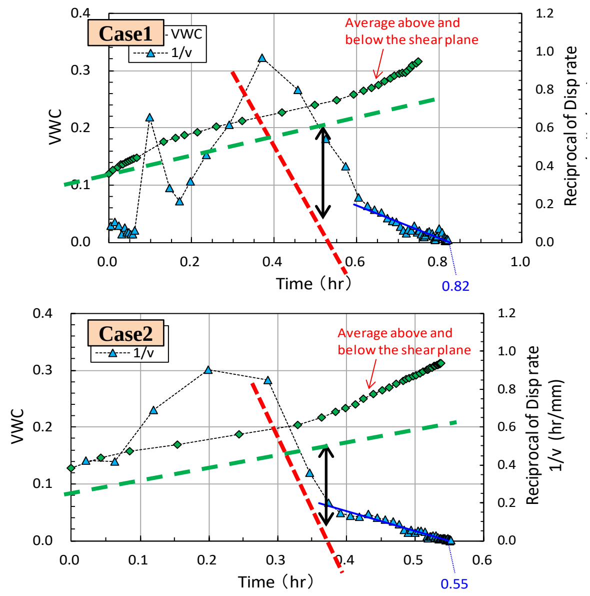

Fig. 13 Time history of VWC and displacement rate(1/v) (direct shear test)

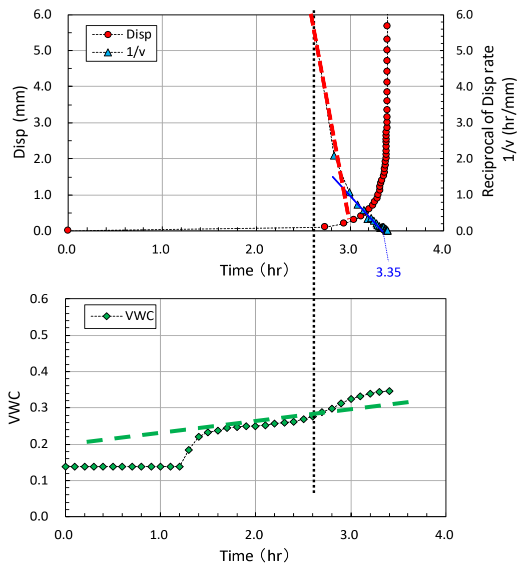

Fig. 14 Time history of VWC and displacement rate (1/v) (multi-layer shear model (10 layers))

6. CONCLUSION

Two kinds of laboratory experiments were conducted to simulate the process of rainfall-induced slope failure. Predicting the time to failure using the inverse number of velocity calculated by Fukuzono's equation has been verified. The conclusion is summated as following:

- The method of prediction the time to failure time by the inverse number of velocity(1/v) in the tertiary creep stage has been confirmed that it was the same results as the previous research.
- The deformation tended to increase rapidly when the soil moisture increased to a high level.

By comparing the failure time from two kinds of laboratory experiments, the Fukuzono method, as a theoretical basis on soil creep, is considered to be the current understanding of slope failure on the prediction the failure time in terms of precision, simplicity, and acceptability. This study provides a clear presentation on calculating the failure time on shallow slope failure, giving us insights on this method is appropriate and useful for prediction the failure time. Specifically, this research will benefit to using tilt sensors to monitoring the unstable slope and predict when this slope will be failure.

7. ACKNOWLEDGMENTS

This research was supported by Grant-in-Aid for JSPS Scientific Research (B).

8. REFERENCES

[1] Terzaghi K., Mechanism of Landslides. In Application of Geology to Engineering Practice, Geological Society of America, New York, 1950, pp. 83–123, ISBN 9780813759418.

[2] Varnes D.J., Landslide Types and Processes. Highway Research Board Special Report. 1978, pp. 1–4, doi:Fact Sheet 2004-3072.

[3] Angeli M.G., Pasuto A., Silvano S. A critical review of landslide monitoring experiences. Engineering Geology. 2000, 55, pp. 133–147, doi:10.1016/S0013-7952(99)00122-2.

[4] Lollino G., Arattano M., Cuccureddu M., The use of the automatic inclinometric system for landslide early warning: The case of Cabella Ligure (North-Western Italy). Physics and Chemistry of the Earth. 2002, 27, pp. 1545–1550, doi:10.1016/S1474-7065(02)00175-4.

[5] Uchimura T., Towhata I., Anh T.T.L., Fukuda J., Bautista C.J.B., Wang L., Seko I.,Uchida T., Matsuoka A.,Ito Y., et al., Simple monitoring method for precaution of landslides watching tilting and water contents on slopes surface. Landslides.2010, 7, pp. 351–357, doi:10.1007/s10346-009-0178-z.

[6] Uchimura T., Towhata I., Wang L., Nishie S., Yamaguchi H., Seko I., Qiao J., Precaution and early warning of surface failure of slopes using tilt sensors. Soils and Foundations. 2015, 55, pp. 1086–1099, doi:10.1016/j.sandf.2015.09.010.

[7] Saito M., Forecasting time of slope failure by tertiary creep. Proceedings of 7th international conference on soil mechanics and foundation engineering, 1969, Mexico, pp. 677–683.

[8] Fukuzono T., A Method to Predict the Time of Slope Failure Caused by Rainfall Using the Inverse Number of Velocity of Surface

Displacement. Landslides. 1985, 22, pp. 8-13_1, doi:10.3313/jls1964.22.2_8.
[9] Voight B., A Relation to Describe Rate-Dependent Material Failure. Science. 1989, 243, pp.200–203, doi:10.1126/science.243.4888.200.
[10] Federico A., Popescu M., Elia G., Fidelibus C., Internò G., Murianni A., Prediction of time to slope failure: a general framework. Environmental Earth Sciences. 2012, 66, pp. 245–256, doi:10.1007/s12665-011-1231-5.
[11] Tao S., Uchimura T., Fukuhara M., Tang J., Chen Y., Huang D., Evaluation of Soil Moisture and Shear Deformation Based on Compression Wave Velocities in a Shallow Slope Surface Layer. Sensors, 2019, 19, pp.3406, doi:10.3390/s19153406.