Stability evaluation of full-scale embankment constructed by volcanic soil in cold regions

S. Kawamura i), S. Miura ii) and S. Matsumura iii)

i) Associate Professor, Department of Civil Engineering, Muroran Institute of Technology, 27-1 Mizumoto, Muroran 050-8585, Japan.
ii) Emeritus Professor, Graduate School of Engineering, Hokkaido University, Kita 13 Nishi 8, Kita-ku, Sapporo 060-8264, Japan.
iii) Research fellow, Port and Airport Research Institute, 3-1-1 Nagase,Yokosuka 239-0826, Japan.

ABSTRACT

The aim of this study is to reveal failure mechanisms of volcanic slopes in cold regions and to propose a prediction method on the failure. In order to achieve the purposes, a full-scale embankment slope which was 5 m in height, 2.7 m in width and 4 m in length and the angle of 45 deg., was constructed in Sapporo city, Japan. A typical volcanic soil in the field was adopted as an engineering material. After the construction of the embankment, the changes in soil moisture, temperature, pore water pressure in the embankment were investigated until slope failure by using several monitoring devices such as soil moisture meters, etc. Simultaneously, a series of model tests was performed on small size slopes constructed by the same soil material as that in the field. As a result, a reasonable prediction method of slope failure was proposed based on change in water content, and its validity was confirmed in the behavior of the full-scale embankment.

Keywords: slope stability, embankment, volcanic coarse grained soils, field monitoring, model test

1. INTRODUCTION

In Hokkaido, there are over forty Quaternary volcanoes, and pyroclastic materials cover over 40% of its area. Significant volcanic activities occurred in the Neogene’s Quaternary period, and various pyroclastic materials such as volcanic ash, pumice and scoria were formed during those eruptions. The volcanic soils have been utilized as useful construction materials, especially man-made earth structures (embankments and cut slopes, etc.). However, earthquake- and rainfall-induced failures of artificial slopes such as cut slopes or embankments have been frequently reported in Hokkaido, Japan.

In this study, a full-scale embankment of which the boundary conditions of each sides (the right and left sides and back and bottom) were controlled, was constructed to generate slope failure with large deformation. The aim of this study is to grasp the mechanical behavior of the volcanic embankment in cold regions during all seasons and to confirm the validity of the prediction method based on slope failure of embankment under boundary conditions controlled properly. During field monitoring, the changes in soil moisture, temperature, pore water pressure in the embankment with the increase of rainfall and water supply were investigated using several devices such as laboratory testing. Simultaneously, a series of model tests was performed under the same soil material and compaction conditions (e.g., the desired water content and dry density) as that in the field. In consideration of the results of both model test and field monitoring, the aspects of slope failure are discussed.

2. TEST MATERIAL AND MODEL TEST PROCEDURES

Volcanic coarse grained soil which was sampled from the Shikotsu caldera in Hokkaido was used in this study. The sampling site is shown in Fig.1. This sample is hereafter referred to as Komaoka volcanic soil (flow-deposits, the notation is Spfl). Index property values of the sample are shown in Table 1 with the property values of Toyoura sand. As shown in Table 1,
the fine content of the sample is 35.2~42.6 %. The details of Komaoka volcanic soil was also described by Japanese Geotechnical Society (JGS), Hokkaido Branch (2011).

Fig. 2 depicts the whole view of the apparatus used in rainfall testing. The soil container was 2,000 mm in length, 700 mm in depth and 600 mm in width, and its front wall was made of a reinforced glass to observe deformation with failure. The compaction curve of Komaoka volcanic soil was also obtained by the A-c method of Japanese Geotechnical Society (2009), as shown in Fig.3. On the basis of the result, model slopes were constructed by tamping the volcanic soil to the degree of compaction, $D_c$ of 85 % (the desired dry density is $\rho_d=0.9$ g/cm$^3$, and its variation in density is within 5 %) where constituent particles were not broken by tamping under the initial water content. In this study, the initial water content of the model slopes was $w_0=43$ %. Thereafter, the slope surface was carefully cut to the angle of 45 deg. (relative to horizontal) using a straight edge to eliminate surface disturbance. After

Table 1 Index property of Komaoka volcanic soil

| Sample name      | $\rho_s$ (g/cm$^3$) | $\rho_{d\text{-in situ}}$ (g/cm$^3$) | $w_s$ (%) | $D_{50}$ (mm) | $\text{Uc}$ | $\text{Fc}$ (%) |
|------------------|---------------------|----------------------------------|----------|--------------|-------|-------|
| Komaoka Embankment | 2.47                | 1.01 (average)                  | 43       | 0.27         | 46.0  | 35.2~42.6 |
| Toyoura sand     | 2.68                | -                                | -        | 0.18         | 1.5   | 0     |

$w_s$: Natural water content, $D_{50}$: Mean grain size, $\text{Uc}$: Coefficient of uniformity, $\text{Fc}$: Finer content

The model slope was constructed, the surface of slope was frozen with dry ice over 8 hours and then thawed at 20˚C (over a thawing period of 8 hours). According to this procedure, the frozen layer of around 50 mm in thickness was formed in the model slope (Kawamura and Miura, 2014). Typical locations of measurement devices for the slope are illustrated in Fig.4.

Rainfall intensity was 100 mm/hr. which is accurately simulated through use of a spray-nozzle. During model tests, the changes in deformation behavior, saturation degree and temperature were monitored using digital video cameras, soil moisture meters (sm1-sm6) and thermocouple sensors, respectively. In particular, the deformation behavior was estimated according to the particle image velocimetry (PIV) analysis. Pore water pressure (pw1-pw5) was monitored simultaneously.

A series of model tests was performed for 3 hours period or until the slope failure with large deformation. According to the preliminary test, since slope failure was rapidly developed after shear strain of 4~6 % was
induced at the peak of saturation degree, therefore, the mechanical behavior at shear strain of 4~6 % was regarded as that at failure (e.g., Kawamura and Miura, 2013).

3. RESULTS OF MODEL TESTS

Fig.5 (a) and (b) illustrates typical slope shapes after slope failure for the case without freeze-thaw action. Surface flow with gully erosion proceeded until the slip line indicated in Fig.5 (a). A similar tendency was obtained for the case of high water content which is over the optimum water content of 40.5 %.

The changes in the development of saturation degree and in the excess pore water pressure \( \Delta u \) normalized by effective overburden pressure \( \sigma_v' \) are shown in Fig.6 (a) and (b). They are gradually developed; especially pore water pressure is significant. As a result, surface flow seems to be generated for this case, because the permeability generally decreases for higher water content over the optimum water content.

Similarly, the effect of freeze-thaw action on mechanical behavior was clarified. Fig.7 (a) and (b) depicts distribution of shear strain at failure with freeze-thaw process and without. It is apparent from the figures that there is the difference in the shape at failure between both cases. For example, the depth of slip line with freeze-thaw action is shallower than that without freeze-thaw action. This fact implies that hollows caused by thawing generate loose structures in the frozen layer compared with before the freeze-thaw process. As a result, surface slope failure was induced for the frozen area. A similar tendency was observed in the other water contents and volcanic soils (e.g., Kawamura and Miura, 2013). Additionally, the developments of saturation and pore water pressure were almost the same as those without freeze-thaw action; however the difference in the elapsed time until failure was clearly confirmed (see Fig.6 (b) and Fig.8). For instance, the elapsed time subjected to freeze-thaw action is 765 sec. which is around 3.5 times faster than that without (2,690 sec.) although the drawing on the behavior of pore water pressure was omitted.

Fig. 9 depicts relationship between water content at initial \( w_0 \) and at failure \( w_f \) based on a series of the model test results which performed under the same geometry and soil density of slope (e.g., Kawamura and Miura, 2013). As shown in the figure, there is a unique relationship between both water contents. The increment of water content at failure \( w_f \) from the initial line becomes a steady state, although its relation varies by freeze-thaw action. For instance, the following expression can be also obtained;

\[
 w_f = \beta w_0^\gamma
\]

where \( \beta \) and \( \gamma \) are coefficients, for example these values
are shown in Table 2. In a previous study (e.g., Kawamura and Miura, 2013), a similar tendency was obtained in the case of which slope failure was generated, despite of the differences of volcanic soils and of slope geometry. Therefore, it is possible to evaluate the slope failure due to rainfall and freeze-thaw action if such a relation can be obtained for the in-situ slope. Considering the results, slope failure can be predicted if the depth of frozen area and the water holding capacity in slope are estimated by monitoring an index property such as water content.

Through the discussions on the above results, the authors also conducted a field monitoring from November 2012 to November 2013 for a full-scale embankment which was constructed to 5 m in height, 2.7 m in width and 4 m in length, 45 deg. in angle by using the same soil material as that of model test.

4. CONSTRUCTION PROCEDURES OF FULL-SCALE EMBANKMENT

A failure mechanism of volcanic slopes was revealed using small-scale slopes, and a prediction method on failure was proposed. However, the above results may change with the increase of confining pressure because the changes in slip line and other mechanical behavior are predicted. For the reason, a field monitoring was performed on a full-scale embankment constructed using volcanic soil to clarify soil behavior until slope failure, based on the above results of the model tests.

The monitoring site was located in Sapporo, Japan, as shown in Fig.1. A full-scale embankment of which the boundary conditions of each side (the right and left sides and back and bottom) were controlled, was constructed using a road roller (weight of 5.88kN) by compacting the same soil material as that of model test so as to be more than the degree of compaction $D_c$ of 85% (the desired dry density is more than $\rho_d=0.9$ g/cm$^3$) for each layer of 0.25 m. In particular, both sides were confined by wooden boards, back and bottom are covered by plastic sheets. The number of roller compactions was 3 times for each layer. According to the in-situ tests, the degree of compaction and water content was 95.9% (average) and 42.5% (average), respectively. The slope size was 5 m in height, 4 m in length, 2.7 m in width and the angle of 45 deg. (see Fig.10).

The following instruments were adopted in order to monitor soil behavior and temperature in the air and in the embankment: 1) Soil moisture meter (Time Domain Reflectometry type: TDR), 2) Thermocouple sensor, 3) Anemovane, 4) Snow gauge, 5) Rainfall gauge, 6) Accelerometer and 7) Tensiometer, as shown in Fig.10 and Fig.11.

Soil moisture meters were basically set up at each depth of 0.2 m until the depth of 1.5 m. The specifications of instruments are reported by Kawamura and Miura (2014). Each data was collected within the sampling period of under 10 minutes. In this study, volumetric water content $\theta$ obtained from monitoring
devices was converted by water content $w$ by the following relation $w = \frac{\rho_w}{\rho_{\text{din-situ}}} \theta$, where $\rho_w$ and $\rho_{\text{din-situ}}$ are densities of water and dry soil, respectively.

After the construction of embankment, 10 pipes for water supply and 3 water tanks were set in order to generate freeze-thaw process under natural condition and to cause slope failure. The locations of pipes are also shown in Fig.12.

In order to cause slope failure of the embankment subjected to stress histories (freezing and thawing, rainfall) under climatic conditions, water supply through the surface of embankment has been started from May 7, 2013. The amount of water supply was 1000–3000 l/day. The details are shown in Fig.13. Field monitoring has been continued to November 15, 2013 from November 01, 2012. The details of construction procedures was reported by Matsumura (2014).

5. RESULTS OF MONITORING AND DISCUSSIONS

Fig.14 shows the changes in temperature in the embankment during field monitoring. During field monitoring, snow removing was carried out for winter season. In the figure, temperature for each depth varies for seasons; especially the value at a depth of 0–0.2 m indicates less than 0 °C for winter months (from December, 2012 to March, 2013). Therefore, it is found that the slopes in the monitoring site are affected by freeze-thaw action.

During field monitoring, surface failure with large deformation was induced on October 17-18, 2013 due to the increase of rainfall and water supply. Fig.15 shows the slope shape after surface slope failure. Failed soil volume of around 7.5 m$^3$ was moved lower. The depth of slip line was 0.6–0.9 m.

Fig.16 shows typical changes in water content for R2 in R section and in pore water pressure (at the depth of 0.6 m) for C3 in C section. It is noted that water content and pore water pressure increases with the increase of rainfall and water supply, and decreases after slope failure. In comparison with model test results, the failed shape and behavior appears to be almost the same as the case subjected to freeze-thaw action. In addition, slope analysis was also performed to investigate the mechanical behavior of full-scale embankment. The analytical results expressed well the behavior of embankment at failure although the drawing was omitted (Fukutsu et al., 2014).
Soil samples were also taken from failed areas to investigate water content at failure. The water content in the failed area was 54% in average. Based on the above results of water contents at initial (at construction) and at failure, the validity of Eq. (1) was also revealed (see Fig. 9). It is noteworthy that the field data of $w_f=54\%$ (see star symbols) is around the failure line with freeze-thaw action for Komaoka volcanic soils. From the results, Eq. (1) may explain well the field data for the volcanic embankment.

Additionally, the amount of rainfall to cause slope failure was estimated on the basis of water content at failure. It is assumed that the amount of rainfall equivalent to water content at failure infiltrates the failed area (until the depth of 0.6 m) of the embankment. As a result, the amount of rainfall was estimated as 263 mm (without freeze-thaw action) or 70 mm (with freeze-thaw action). For example, rainfall of 70 mm means that slope failure is induced for the case subjected to freeze-thaw action when rain water infiltrates into the embankment having the coefficient of permeability of $10^{-5}$ m/s for 16 hours. Therefore, risk evaluation of embankment will be enabled based on the proposed method if threshold of slope failure can be prescribed.

6. CONCLUSIONS

From the results of model test and field monitoring, the following conclusions were derived;

1) Evaluation of freeze-thaw action on failure mechanisms of volcanic slopes is significant for cold regions.
2) Slope failure can be predicted if the changes in water content in slope are simply estimated by field monitoring using soil moisture meters.

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