Stability Evaluation of Volcanic Slopes with Crushable Particles Subjected to Freezing and Thawing

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***Abstract*- In order to elucidate failure mechanisms of volcanic slopes with crushable particles due to rainfall and freeze-thaw action, a series of rainfall tests were performed on model volcanic slopes having several water contents and slope angles. In the consideration of model test results, it was found that surface slope failures were changed depending strongly on both slope angle and the initial water content. Furthermore, it was shown that the softening of the slopes by freeze-thaw action is important for evaluating the stability of volcanic slopes; in particular, its effect is attributed to the reduction of the shearing resistance due to particle breakage, and cannot be ignored for evaluation of slope stability.**

Keywords- Slope stability; volcanic soils; freezing and thawing; model tests

I. INTRODUCTION

Collapse of slopes formed from volcanic soils induced by either rainfall or snow-thawing water has been recently caused in cold regions such as Hokkaido, Japan. It has been known that volcanic slopes in Hokkaido have a strong potential to cause such failures, for example the slope failures of cut slope in the Hokkaido Express Way in the spring season, 1999 [1].

Figure 1 shows the mechanism of frost-heaving in a cut slope and failure modes in cold regions [2, 3]. Slopes freeze from their surface with the formation of ice lenses during the winter season (see Fig. 1 (a)). Thereafter, the frozen soil thaws gradually from the ground surface until the summer season. In the freezing and thawing sequence, the surface layer of a slope may exhibit high moisture content over the liquid limit of its soil owing to the melting of snow and thawing of the ice lenses. As a result, surface failure occurs at the boundary between loose thawing soil and the frozen layer due to water infiltration from both rainfall and snowmelt, because the frozen layer works as an impermeable layer (see Fig. 1 (b): Failure pattern 1). On the other hand, another failure due to the piping phenomenon of ground water may also be observed in the spring season when pore water pressure increases over the strength of the frozen layer (see Fig. 1 (c): Failure pattern 2). This reason is that the ground water level increases with the formation of a frozen layer. In addition, hollows of ice lenses created by thawing may generate looser structures in the frozen layer compared with before the freeze-thaw process (see Fig. 1 (d): Failure pattern 3). Due to this phenomenon, a deeper slope failure may be induced from summer to autumn seasons.

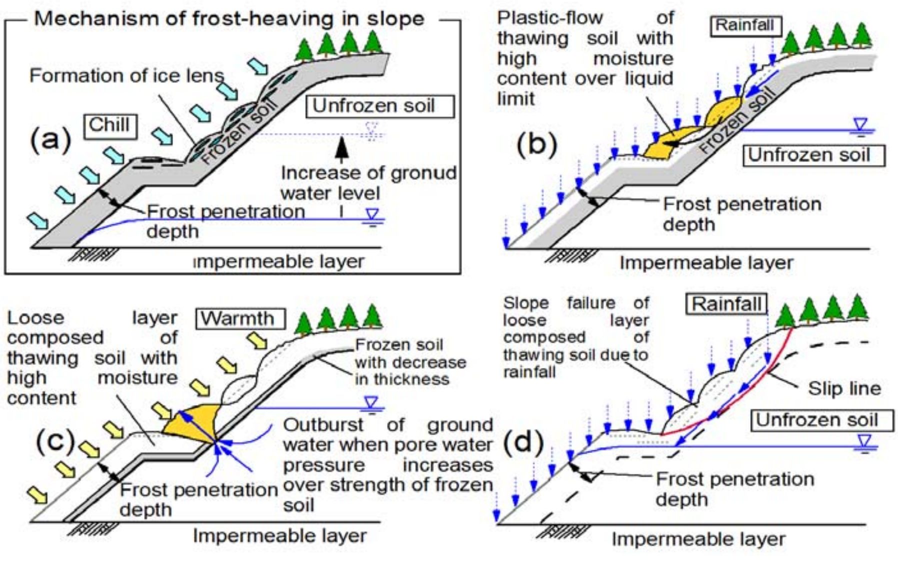

Fig. 1 Mechanism of frost-heaving in cut slope observed for cold regions and failure modes; (a) mechanism of frost-heaving in slope, (b) surface failure of thawing soil with high moisture content over liquid limit (Failure pattern 1), (c) slope failure due to piping by increase of pore water pressure (Failure pattern 2), (d) slope failure of loose layer composed thawing soil due to rainfall (Failure pattern 3)

The purposes of this paper are to reveal failure mechanisms of volcanic slopes and to elucidate the effects of freezing and thawing phenomena on the mechanical behavior in volcanic slopes during rainfall. A series of model test was performed on model volcanic slopes to reveal failure mechanism, especially on failure mode illustrated in Fig. 1 (d). In previous studies [4, 5], the effect of freeze-thaw actions on failure mechanisms of Kashiwabara volcanic slope during rainfall was elucidated in detail. In this study, especially failure mechanisms of volcanic slope formed from soil particles having high crushability and the frost-heaving ability were mainly investigated on experimental approaches. A prediction method for the slope failure of volcanic slope was discussed based on a series of the model test results.

II. TEST MATERIALS AND TEST PROCEDURES

Volcanic coarse-grained soils which were sampled from the ejectas of Shikotsu and Mashu calderas in Hokkaido were used in this study. Sampling sites are shown in Fig. 2. In the figure, the site of Kashiwabara volcanic soil (Spfa-1) reported in previous studies [4, 5] is indicated additionally. These samples are hereafter referred to as Komaoka (Spfl) and Touhoro (Ma-l) volcanic soils, respectively. The index properties and grain size distributions of samples are shown in Fig. 3 and Table I, compared to those of Kashiwabara volcanic soil [4] and Toyoura sand. As shown in Table I, their finer contents range from 1.3 % to 26 %. The low value of dry density for volcanic soils is also shown in the samples because their constituent particles are very porous and extremely vulnerable to crushing, additionally natural water content w_n is a high value. In particular, the crushability of Touhoro volcanic soil indicated the highest value among volcanic soils which were investigated in previous studies [6, 7]. On the other hand, the index property of Komaoka volcanic soil differs from that of Kashiwabara volcanic soil due to the differences in deposits (flow-deposits; Spfl and fall-deposits; Spfa-1) although they are in the same Shikotsu ejecta. The details of mechanical behavior of their volcanic soils were reported by Miura et al. [6] and Yagi and Miura [7].

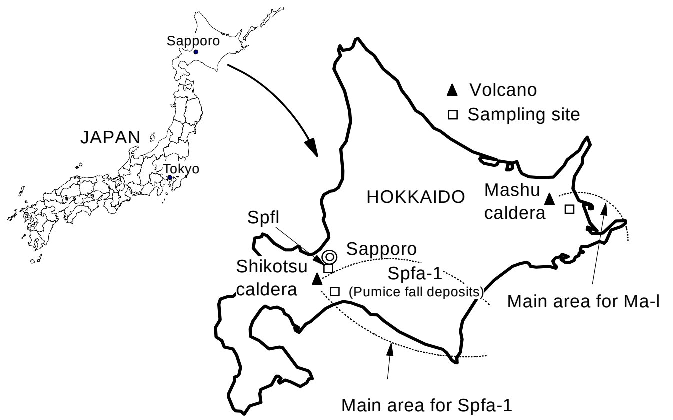

Fig. 2 Locations of sampling sites

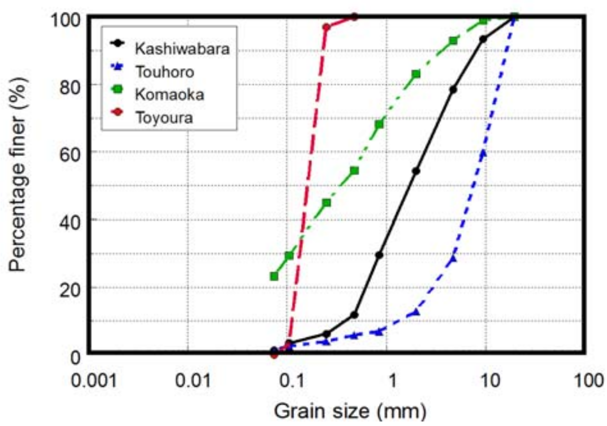

Fig. 3 Grain size distributions of samples

TABLE I INDEX PROPERTIES OF SAMPLES

Sample name	ρ_s (g/cm^3)	$\rho_{d\ in\ situ}$ (g/cm^3)	$\rho_{d\ max}$ (g/cm^3)	$\rho_{d\ min}$ (g/cm^3)	w_n(%)	D_{50} (mm)	Uc	Fc (%)
Kashiwabara	2.34	0.53	0.55	0.35	60-80	1.3	3.1	1.3
Touhoro	2.59	0.44	0.85	0.52	106-206	7.60	7.0	1.3
Komaoka	2.50	-	1.12	0.76	43	0.27	3.6	26.0
Toyoura sand	2.68	-	1.63	1.37	-	0.18	1.5	0

w_n : Natural water content, D_{50} : Mean grain size, U_c : Coefficient of uniformity, F_c : Finer content

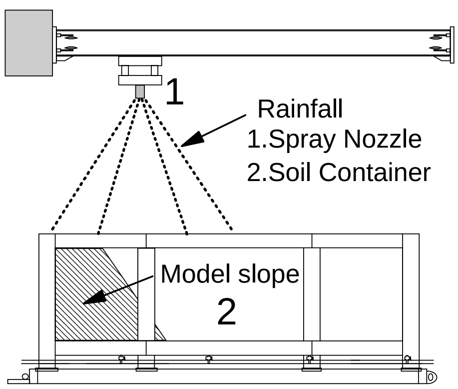

Fig. 4 The whole view of apparatus

Figure 4 depicts the whole view of 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. Model slopes was constructed by compacting so as to be the desired value (see Table II, variations in dry density were within 5 %, respectively) where constituent particles were not broken by compaction under the initial water contents. The desired initial water content of the model slope w_0 is shown in Table II. Thereafter, the slope surface was carefully cut to the angle of 45, 55, 60 or 65^o (relative to the horizontal) using a straight edge so as to free from disturbance of the surface.

After the model slope was constructed, the surface of slope was made to freeze up by dry ice during 8 hours and was basically thawed in 20 ^{o}C (the period of thawing was 8 hours). According to this procedure, the frozen layer of around 30 mm in thickness was formed in this model slope. Typical changes in temperature (T1-T9) in Touhoro volcanic slope during freeze-thaw action are shown in Fig. 5.

TABLE II TEST CONDITIONS IN THIS STUDY

	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
Sample name	Touhoro volcanic soil					Komaoka volcanic soil				
Slope condition	No Freeze-thaw action			Freeze-thaw action		No Freeze-thaw action			Freeze-thaw action	
Slope angle (°)	55	60	65	55	65	45	55	65	45	65
Length of base, B (mm)	572	507	442	572	442	750	557	442	750	442
Initial water content(%)	45, 65, 80	65	45, 50, 65	45, 65, 80	45, 65, 80,100	34, 38, 43				
Dry density ρ_d(g/cm^3)	0.44					0.90				
Ranfall intensity, R(mm)	100					100				
Freeze-thaw action cycles				1					1	
Thaw time(hr.)				8					8	

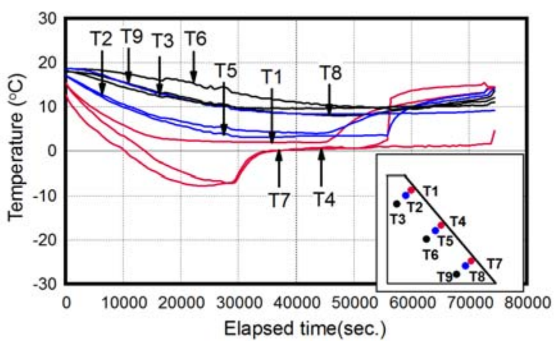

Fig. 5 Changes in temperature in Touhoro volcanic slope during freeze-thaw action

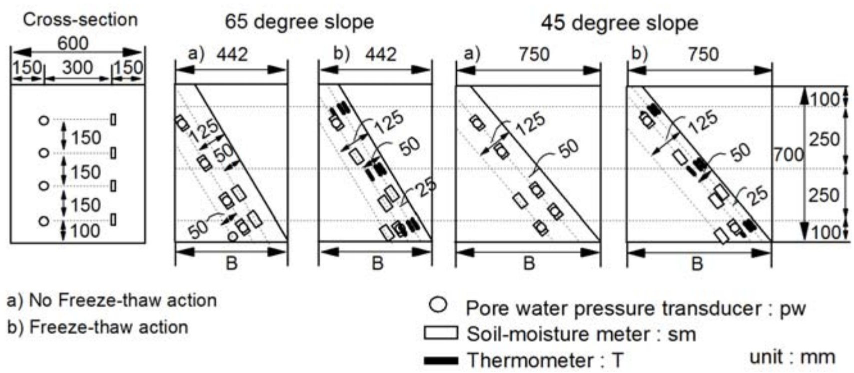

Fig. 6 Typical model shapes (65 and 45degree slopes) and the setting positions of measurement devices

Rainfall intensity was 100 mm/hr. and was accurately simulated by using a spray-nozzle. The rainfall from the slope bottom was mandatorily drained by a pump. During the rainfall testing, 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 [8]. Pore water pressure (pw1-pw5) was monitored simultaneously, however its value was very small and its behavior at the slope failure was not sensitive as compared with the soil moisture behavior [9]. Therefore, the behavior of deformation and saturation was mainly illustrated in this study. Figure 6 and Table II show typical shapes of model slope and the setting positions of measurement devices (the slope angles of 65^o and 45^o), and test conditions (Case 1 - Case 10), respectively.

For all model tests, variation in the initial saturation degree for each position was within around 5 % because there was no difference in failure mechanisms. A series of rainfall model tests was performed until 3 hours or slope failure. According to the test data in previous study which investigated the effects of slope angle, density and base friction of impermeable layer on failure mechanisms for volcanic slopes and Toyoura sand slope [4, 5, 9], since slope failure was rapidly developed after shear strain of 4-6 % was induced at the peak of saturation degree, the mechanical behavior at shear strain of 4-6 % was regarded as that at the plastic equilibrium state, namely that at failure.

III. TEST RESULTS AND DISCUSSIONS

Before commencing discussions on failure mechanisms of volcanic slope subjected to freeze-thaw action, the dependencies of slope angle and the initial water content on the failure caused by rainfall were investigated for unsaturated volcanic slopes (see Case 1 - Case 3, Case 6 - Case 8).

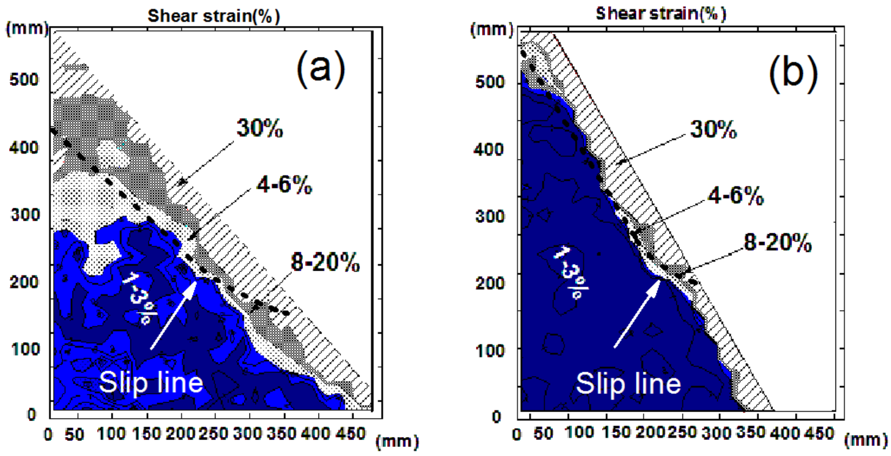

Fig. 7 Typical deformation behavior at failure for Touhoro volcanic slope; (a) 55 degree slope, (b) 65 degree slope

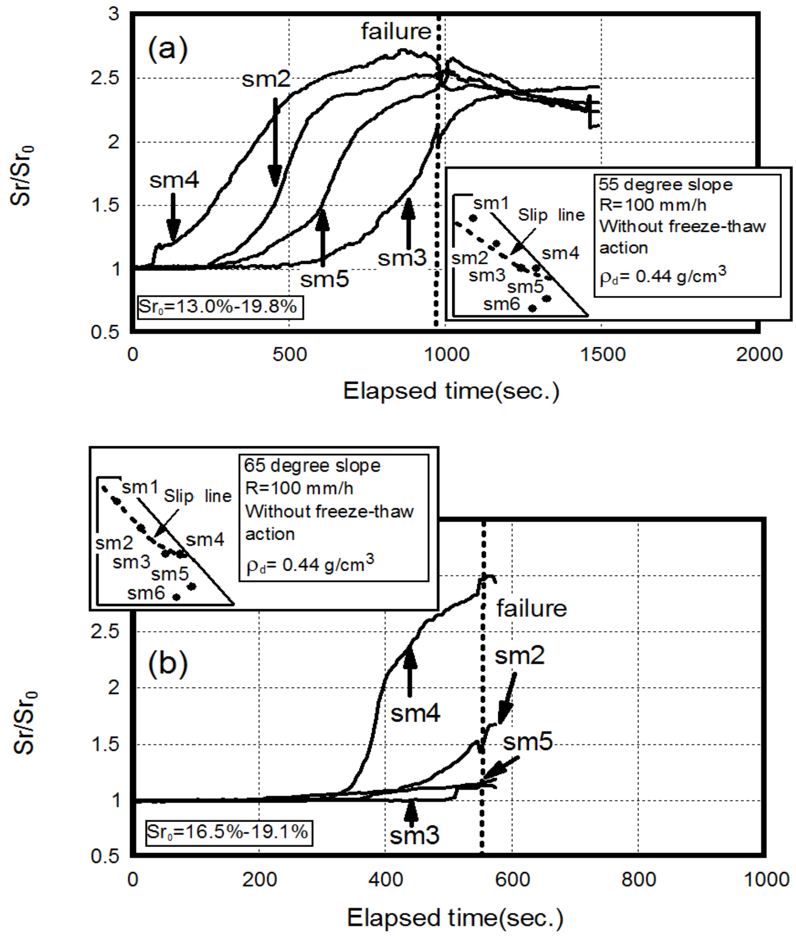

Fig. 8 Changes in saturation degree for Touhoro volcanic slope during rainfall test; (a) 55 degree slope, (b) 65 degree slope

Figures 7 (a) and (b) show typical deformation behavior at failure for 55 and 65 degree slopes for Touhoro volcanic soil. In the figures, the slip line observed in the model test is also depicted. The initial water content, w_0 of each slope is 65 %. It is conspicuous from these figures that the deformation behavior is changed depending on the magnitude of slope angle. For example, the depth of collapse area for 55 degree slope is deeper than that for 65 degree slope. Such a dependency of slope angle on the depth of collapse area has been also observed in field [10]. For the behavior of saturation normalized by its initial value Sr_0, its ratio of saturation degree for 55 degree slope is increasing faster than that for 65 degree slope (see Figs. 8 (a) and (b)). Additionally, the saturation degree around the collapse area is increasing until slope failure and then is suddenly decreasing. For example, sm4 is remarkable. On the other hand, the pore water pressure normalized by effective overburden pressure $\Delta u/\sigma'_{vo}$ around slip line seems to be developing just before failure (see Figs. 9 (a) and (b)). The similar tendency is also obtained from the results of Komaoka volcanic soil although the drawings are omitted [5].

Figure 10 depicts the relationships between slope angle and elapsed time until failure. It is apparent that the elapsed time to cause failure becomes faster with the increase of slope angle, as mentioned above. In general, it has been well known that phenomenon such as that observed above is attributed to the magnitude of slope angle in field. Therefore, it can be said that the test data well explain such failure mechanisms. In the consideration of the model test results, it is pointed out that the difference in slope angle affects the characteristics of seepage, the collapse area and the slope stability due to rainfall.

In order to clarify the effect of the difference in the initial water content on mechanical behavior of unsaturated volcanic slopes (see Case 3), the developments of saturation degree for model slopes for three kinds of water content are shown in Fig. 11. The angle of slope is 65 degree for Touhoro volcanic slope. In the figure, the data of sm1 which is placed around slip line is typically depicted. As shown in the figure, the normalized saturation degree at failure increases with the decrease in w_0 (see black symbol). This reason is that Touhoro volcanic soil has high holding ability of water due to that soil particles are porous and high crushable, as shown in Table I. In comparison with the behavior of pore water pressure for the case of w_0=65 % (see Fig. 9(b)), the pore water pressure around slip line is rapidly increasing until failure (see Fig. 12), however its behavior is not sensitive compared with that of saturation degree.

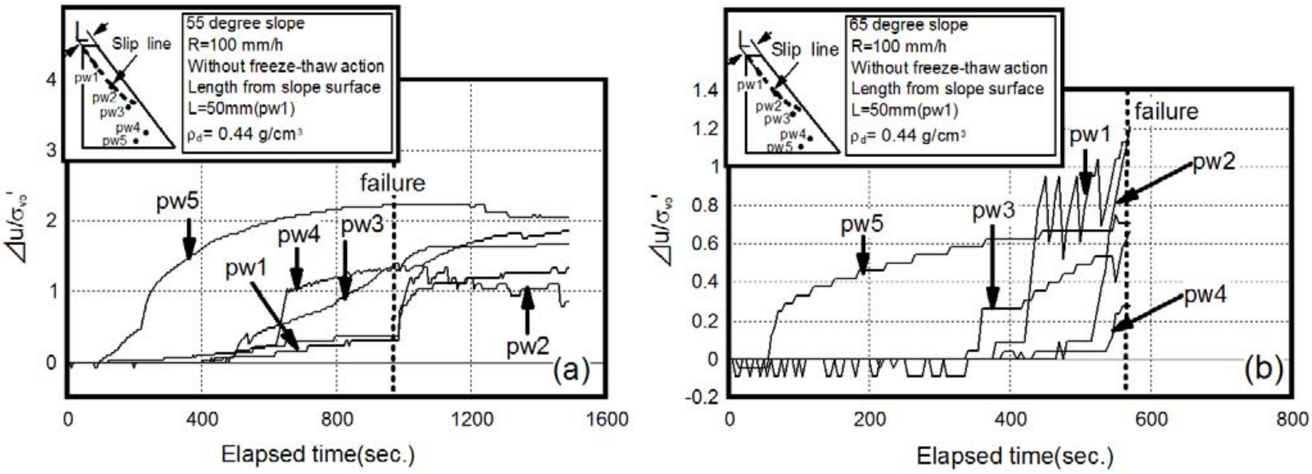

Fig. 9 The behavior of pore water pressure for Touhoro volcanic slope during rainfall test; (a) 55 degree slope, (b) 65 degree slope

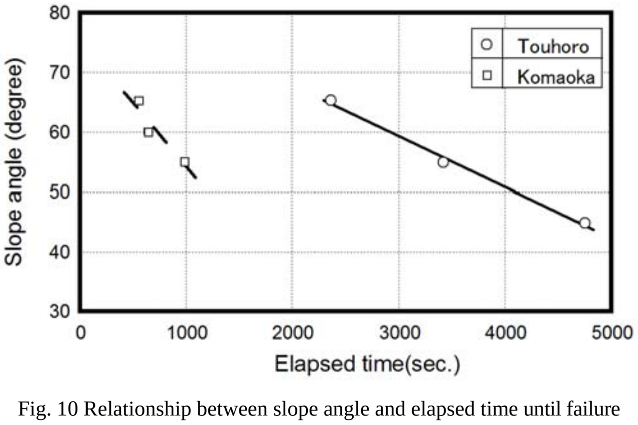

Fig. 10 Relationship between slope angle and elapsed time until failure

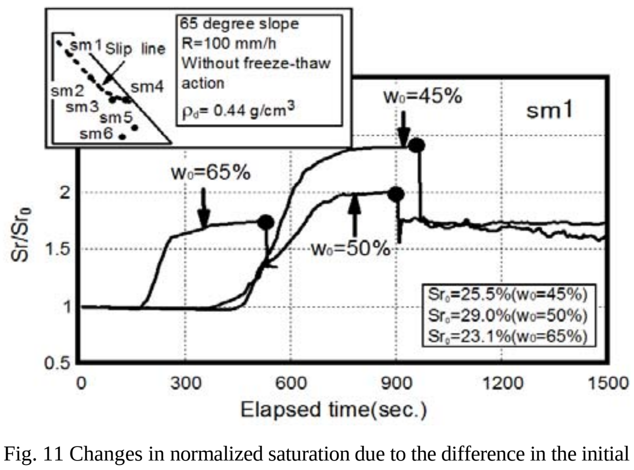

Fig. 11 Changes in normalized saturation due to the difference in the initial water content for Touhoro volcanic slope

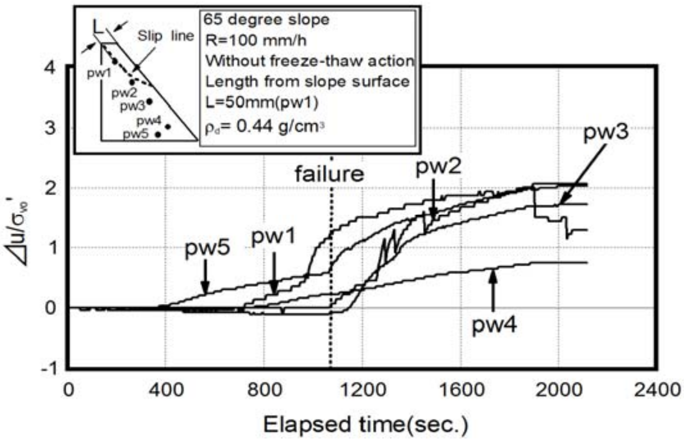

Fig. 12 The behavior of pore water pressure for Touhoro volcanic slope, w_0 =45%

Similarly, the effect of the difference in the initial water content on mechanical behavior of Komaoka volcanic slope was investigated (see Case 6). The angle of slope is 45 degree. For the cases of Komaoka volcanic soil, the deformation behavior differed from that of Touhoro volcanic soil or Kashiwabara volcanic soil [4, 5]. Figures 13 (a), (b) and (c) illustrate typical slope shapes after slope failure. From the figures, it is found that the first failure (slip line 1) is generated at the toe of slopes, and then the second failure (slip line 2) is rapidly induced with an increase of pore water pressure for the cases of lower water contents of 34 % and 38 %. On the other hand, a surface flow failure proceeds until the slip line indicated in Fig.13 (c) for the case of high water content. In preliminary test, it was found that the optimum water content was 40.3 % in compaction curve. The difference in failure mode is also apparent from the changes in the development of saturation degree and pore water pressure (see Figs. 14 and 15). Therefore, a flow slope failure seems to be induced for the case of 43 % because the permeability generally decreases for higher water content over the optimum water content.

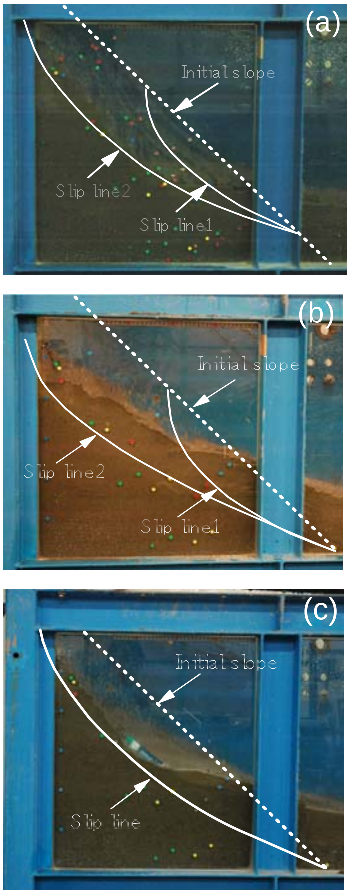

Fig. 13 Typical slope shapes after slope failure for Komaoka test for volcanic slope; (a) w_0 =34%, (b) w_0 =38%, (c) w_0 =43%

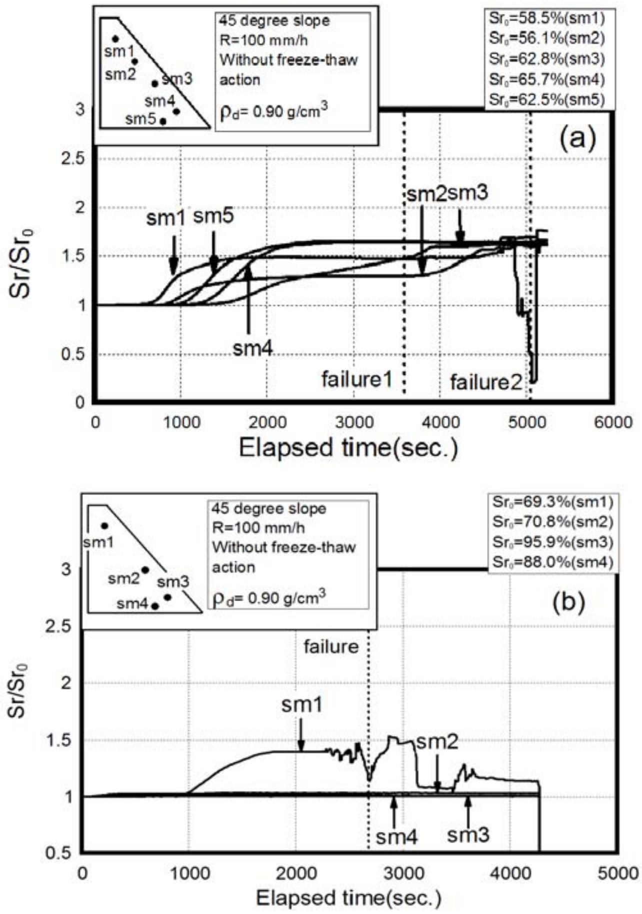

Fig. 14 Changes in saturation degree during model Komaoka volcanic slope; (a) w_0 =38%, (b) w_0 =43%

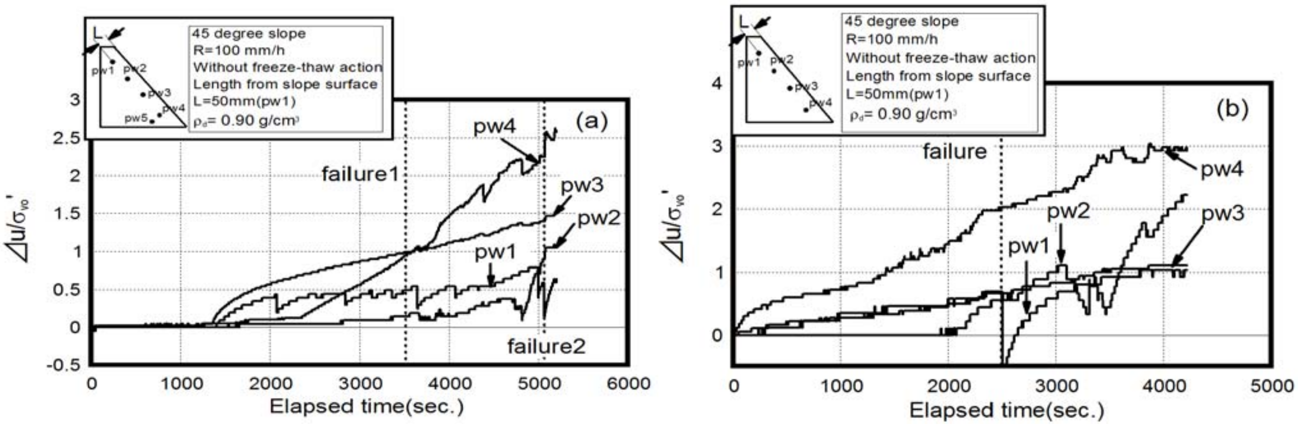

Fig. 15 The behavior of pore water pressure for Komaoka volcanic slope; (a) w_0 =38%, (b) w_0 =43%

For the reason, it is important for predicting the mechanisms of slope failure to monitor the changes in water content.

The effect of freeze-thaw action on mechanical behavior at failure was investigated herein. Yamaki et al. reported that the number of freeze-thaw cycles was 6 times during winter season (from December 8, 2007 to April 1, 2008) in Sapporo Hokkaido, Japan, and indicated that the reduction ratio of shear modulus of the volcanic ground due to the increase of freeze-thaw cycle became a steady state within 1-2 times of freeze-thaw action [11]. In this study, therefore, 1 cycle of freeze-thaw action was adopted (see Case 4 - Case 5, Case 9 - Case 10).

Figures 16 show the changes in normalized saturation degree and pore water pressure of Touhoro volcanic slope during rainfall test after freeze-thaw action. The initial water content, w_0 of each slope is 65 %. In comparison with that without freeze-thaw action (see Fig. 8(b) and Fig. 9(b)), it is noted that there is no difference in the development of saturation and pore water pressure between both cases, but the difference in elapsed time until failure is apparently confirmed. The elapsed time subjected to freeze-thaw action is 364 s and is 1.5 times faster than that without its action (557 s). The similar tendency is recognized for the results of Komaoka volcanic soil, as shown in Fig.14 (a), Fig.15 (a) and Figs.17.

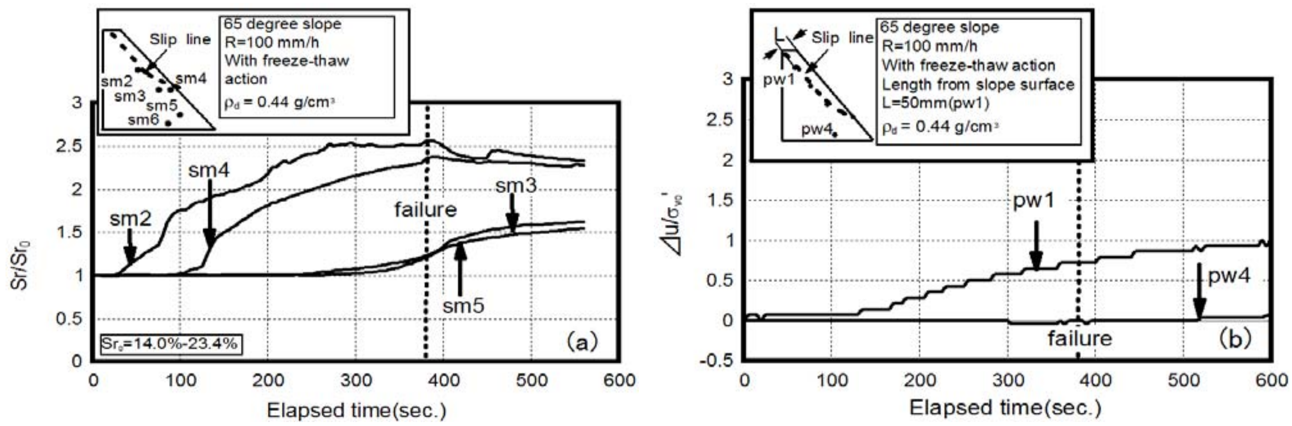

Fig. 16 Changes in saturation degree and pore water pressure during model test for Touhoro volcanic slope; (a) the degree of saturation, (b) pore water pressure

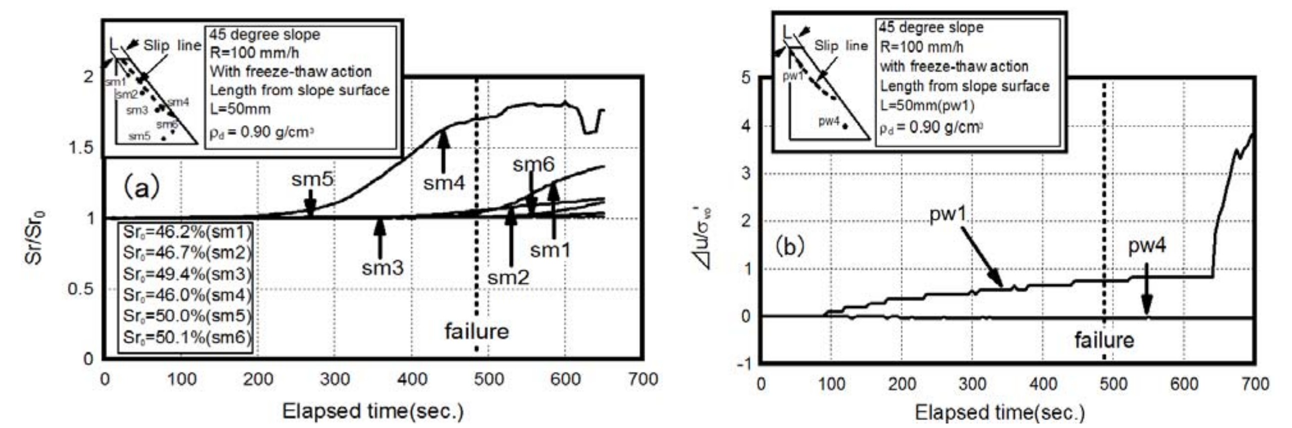

Fig. 17 Changes in saturation degree and pore water pressure during model test for Komaoka volcanic slope; (a) the degree of saturation, (b) pore water pressure

Figures 18 illustrate typical deformation behavior for volcanic soils. It is evident that the changes in shear strain during freeze-thaw action are larger than that during freeze action, and its area of more than 4 % strain is almost the same as the collapse area (slip line), as shown in the figure.

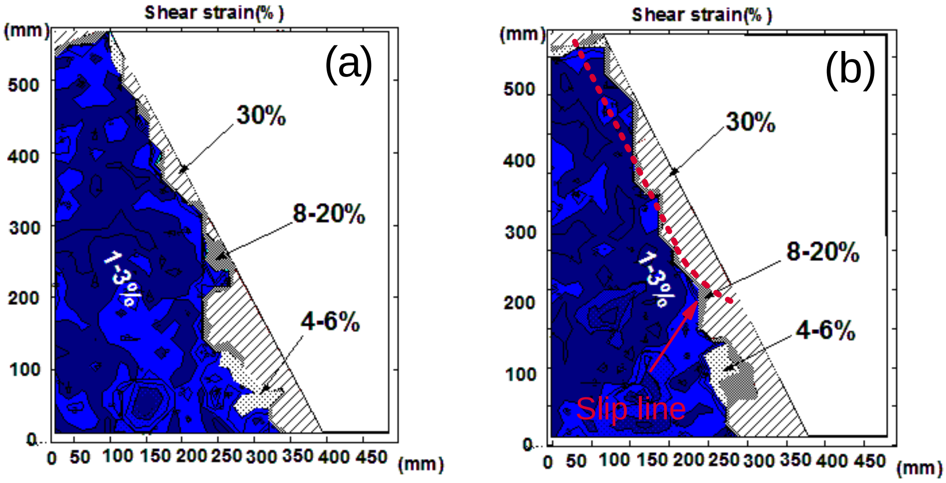

Fig. 18 Changes in shear strain for Touhoro volcanic slope; (a) after freeze action, (b) after freeze-thaw action

In order to obtain a better understanding, the changes in volumetric strain during freeze-thaw action are shown in Figs. 19 and 20, where expansion is expressed as a plus (+). In the figures, the dilatancy of around surface indicates the expansive tendency for 1 hour after freeze-thaw action (see Fig. 19 (a) and Fig. 20 (a)), and its area expands gradually with time during freeze-thaw action (see Figs. 19 (b) and (c), Figs. 20 (b) and (c)). It is also found that the depth of the area is almost the same for each case. The similar result was obtained for Kashiwabara volcanic slope [4, 5]. Therefore, the surface slope failure may be predicted if the depth of frozen area in the slope can be estimated by monitoring in the field.

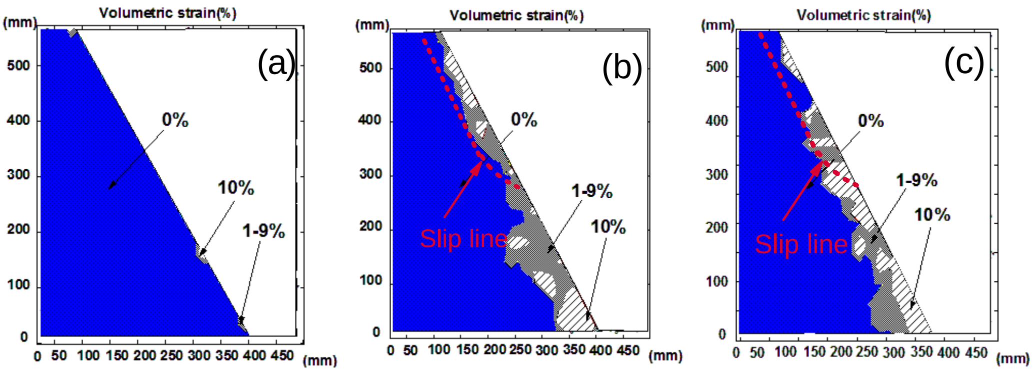

Fig. 19 Changes in volumetric strain for Touhoro volcanic slope; (a) after 1hour, (b) after freezing , (c) after thawing

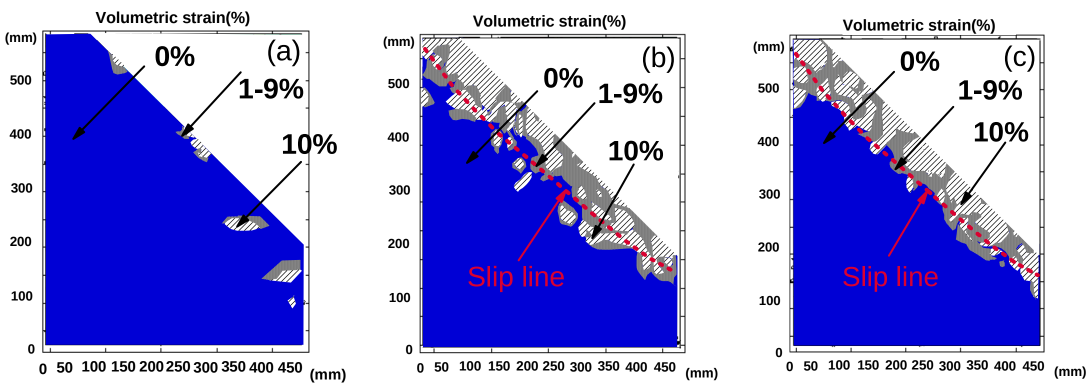

Fig. 20 Changes in volumetric strain for Komaoka volcanic slope; (a) after 1hour, (b) after freezing, (c) after thawing

In order to clarify the effect of particle breakage on slope failure, the comparison of the distributions of grain size after tests for each case (see Case 3 and Case 5) is shown in Figure 21. It is apparent from the figure that the distribution of grain size varies by freeze-thaw action, especially the case of w_0 =100 % is remarkable among all test cases. Figure 22 shows the increment of finer content before and after tests, ΔFc (%) based on Figure 21. In the figure, the data for Kashiwabara volcanic soil [4] and Komaoka volcanic soil were similarly examined, and were plotted. ΔFc increases with the increase of the initial water content for both materials. It is interesting that particle breakage becomes larger by giving the stress histories such as rainfall and freeze-thaw action. This implies that failures of unsaturated volcanic slopes with crushable particles are derived by the reduction of the shearing resistance due to particle breakage during rainfall and freeze-thaw action. The reduction of the shearing resistance due to particle breakage was described by Yagi and Miura [7].

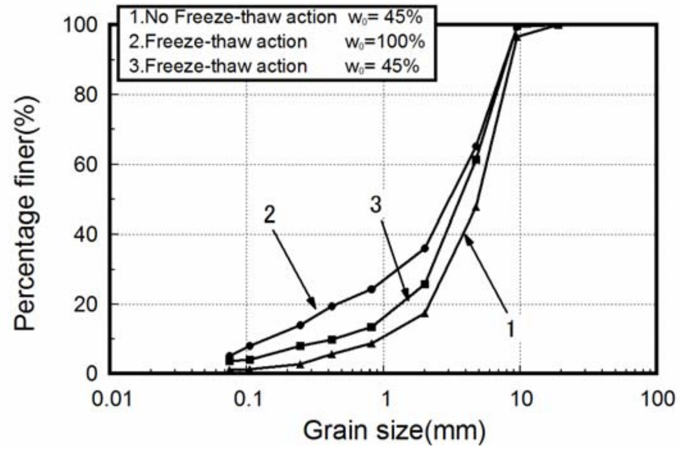

Fig. 21 Changes in distribution of grain size for Touhoro volcanic soil after model test

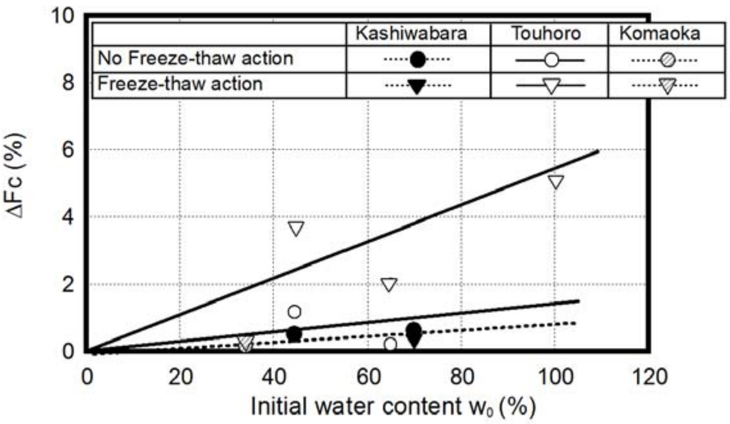

Fig. 22 Changes in the increment of finer content after model test

As mentioned above, the difference in development of saturation (the difference in the water holding ability of volcanic slope) is one of the causes of failure. Namely, surface slope failure seems to be induced by the expansion of some area having high retention ability of water. A prediction method against the slope failure of such volcanic slopes was proposed by considering the characteristics of the ability of water retention (e.g., water content).

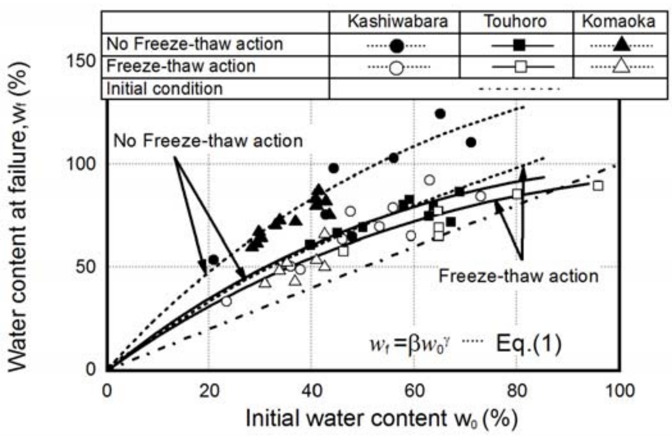

Fig. 23 Relationship between water content at initial and at failure

Figure 23 depicts the relationship between water content at initial w_0 and at failure w_f based on a series of the model test results [5]. 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 for each material, although its relation varies by freeze-thaw action. For instance, the following expression can be also obtained;

$$w_f = \beta \cdot w_0^{\gamma} \tag{1}$$

where β and γ are coefficients, for example these values are shown in Table 3. 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. However, the above results may change with variations in soil materials and inherent errors such as scale effect. In any case, further investigations in this direction are required.

TABLE III COEFFICIENTS OF β AND γ

	Kashiwabara		Komaoka		Touhoro	
	β	γ	β	γ	β	γ
No Freeze-thaw action	**2.4**	**0.9**	**2.4**	**0.9**	**4.3**	**0.7**
Freeze-thaw action	**2.8**	**0.8**	**2.8**	**0.8**	**2.4**	**0.8**

IV. CONCLUSIONS

On the basis of the consideration on the limited number of model testings, the following conclusions were derived.

(1) Slope failures of volcanic slopes are changed depending strongly on both slope angle and the initial water content.

(2) The softening of the slope by freezing and thawing is significant for evaluating the stability of volcanic slopes with crushable particles; in particular, its effect is attributed to the reduction of the shearing resistance due to particle breakage, and cannot be ignored for evaluation of slope stability.

(3) Volcanic slopes subjected to freeze-thaw action has already been the plastic equilibrium state. If the change in dilatancy of slope is estimated, the influence of freeze-thaw action on surface slope failures can be evaluated.

(4) Slope failures 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.

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2. S. Kawamura, S. Miura, S. Yokohama, A. Kudo and N. Kaiya, Field monitoring of embankment constructed by volcanic soil and its evaluation, Stability and Performance of Slopes and Embankments III, GeoCongress2013, ASCE-Geotechnical Special Publication, No.231, pp.373-382, 2013.

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