

Research Article

Stability Evaluation of Volcanic Slope Subjected to Rainfall and Freeze-Thaw Action Based on Field Monitoring

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Rainfall-induced failures of natural and artificial slopes such as cut slopes, which are subjected to freezing and thawing, have been frequently reported in Hokkaido, Japan. In particular, many failures occur intensively from spring to summer seasons. Despite numerous field studies, explanation of their mechanical behavior based on in situ data has not yet been completely achieved due to the difficulty in grasping failure conditions. This study aims at clarifying the aspects of in-situ volcanic slopes subjected to rainfall and freeze-thaw action. The changes in soil moisture, pore pressure, deformations, and temperatures in the slope were investigated using soil moisture meters, tensiometers, thermocouple sensors, clinometers, settlement gauges, an anemovane, a snow gauge, and a rainfall gauge. The data generated from these measures indicated deformation in the slope examined mainly proceeded during the drainage process according to changes in soil moisture. Based on this data, a prediction method for failures is discussed in detail.

1. Introduction

In Hokkaido, Japan, there are over 40 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.

Such volcanic soils have been used as a useful construction material, especially on foundations or man-made geotechnical structures (embankments and cut slopes, etc.). However, research on volcanic coarse-grained soils from an engineering standpoint is extremely limited in comparison with cohesionless soils (Miura et al. [1]).

Recent earthquakes and heavy rainfalls in Hokkaido generated the most serious damage in the ground, natural slopes, cut slopes, and embankments, which are composed of volcanic soils (e.g., JSSMFE [2], JSCE [3]), as seen in the slope failure of a residential embankment due to the 1991 Kushiro-oki earthquake (JSSMFE [2]). Furthermore, cut slope failures attributed to freezing and thawing have also been observed in the Hokkaido expressway in spring and summer seasons.

Figure 1 shows the mechanism of frost heaving in cut slope and failure modes in cold regions. In cold regions such as Hokkaido, Japan, slopes freeze from their surface with the formation of ice lenses during the winter season (see Figure 1(a)). Thereafter, the frozen soils thaw gradually from the ground surface until 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 by water infiltration due to both rainfall and snow-melting, because the frozen layer works as an impermeable layer (see Figure 1(b)). On the other hand, another failure due to the piping phenomenon of ground water may also be observed in spring season when pore water pressure increases over the strength of the frozen layer (see Figure 1(c)). Additionally, hollows of ice lenses created by thawing may generate loose structures in the frozen layer compared with before the freeze-thaw process (see Figure 1(d)). Because of this phenomenon, a deeper slope failure may be induced from summer to autumn seasons.

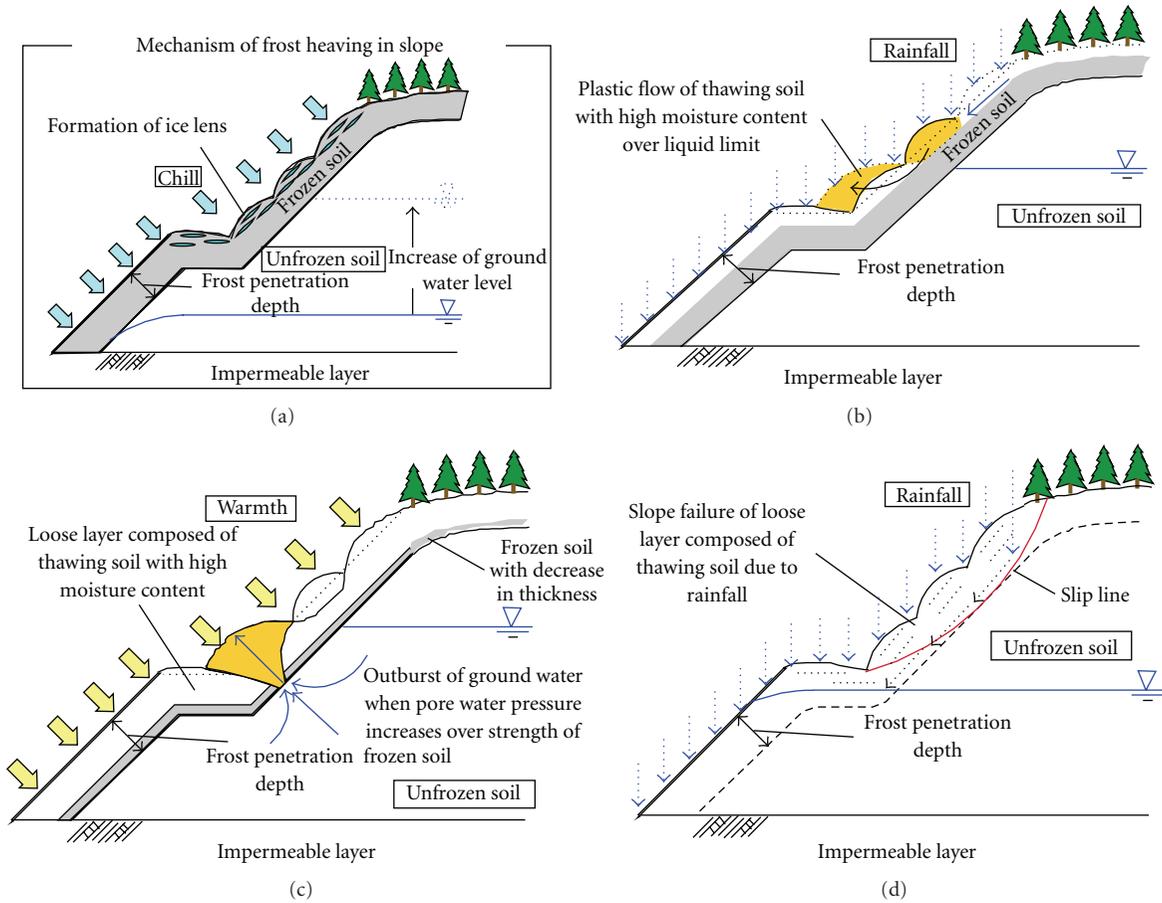


FIGURE 1: Mechanism of frost heaving in cut slope observed for cold regions and failure modes. (a) Mechanism of frost heaving in slope, (b) surface failure of thawing soil with high moisture content over liquid limit, (c) slope failure due to piping by increase of pore water pressure, and (d) slope failure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

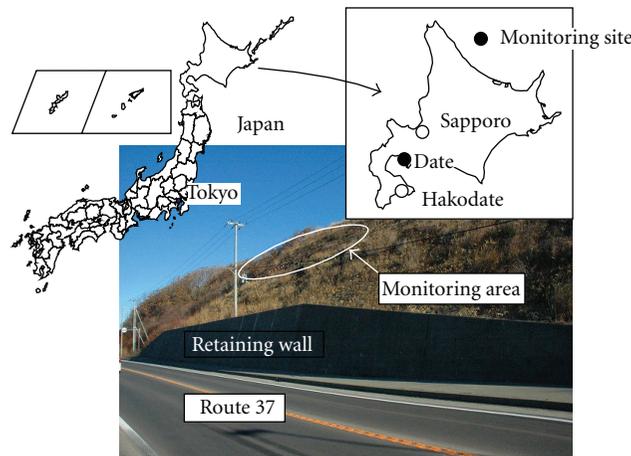


FIGURE 2: Location of monitoring site in Date, Japan.

For the above reasons, natural disasters such as slope failure in cold regions is frequently induced in snow-melting season and is deemed to be caused by both the increase in degree of saturation arising from thawing water and the change in deformation strength characteristics of soil resulting from freeze-thaw action.

A significant amount of research on the mechanisms of slope failures induced by rainfall has been conducted primarily in warm regions. Recently, research on the failure mechanisms in unsaturated conditions as well as those under saturation conditions have been investigated and have been reported (e.g., Olivares et al. [4], Yagi et al. [5], Orense et al.

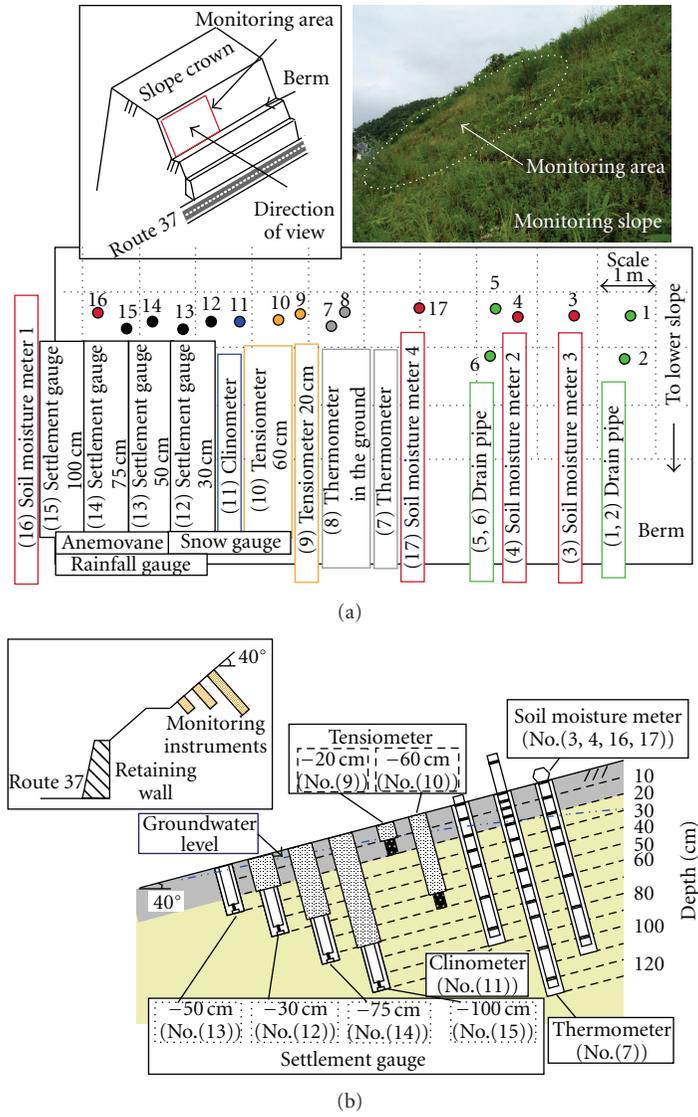


FIGURE 3: Setting positions of monitoring instruments; (a) plane section, and (b) cross section.

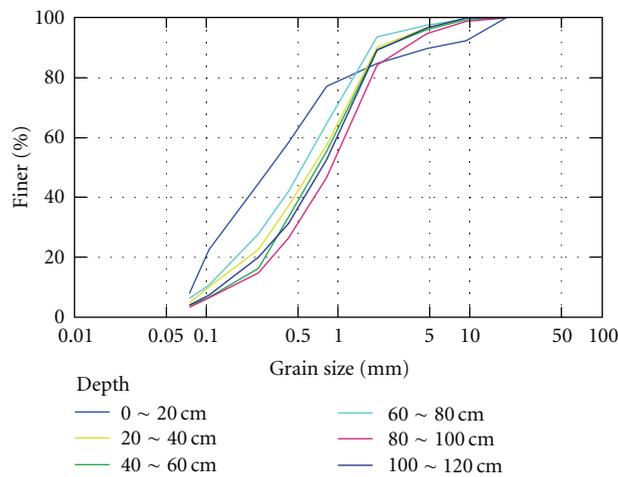


FIGURE 4: Distributions of grain size of soil samples.

TABLE 1: Specifications of monitoring instruments.

Monitoring instruments	Specifications	Symbols (unit)
(1) Soil moisture meter	Precision: $\pm 0.003\%$ vol, Reading Range: Oven dry to saturation	θ (%)
(2) Tensiometer	Precision: 0.5% FS, temperature/humidity: -10 to 80°C (ice-free)/35 to 85% RH	P (kPa)
(3) Thermometer	Class A, $\pm(0.15 + 0.002 t)^\circ\text{C}$	T_A, T_G ($^\circ\text{C}$)
(4) Clinometer	Precision: ± 10 deg, (multiple inclination transducer: 7-layers)	(mm)
(5) Settlement gauge	Reading range: 0 to 100 mm, temperature: -10 to 70°C	S (mm)
(6) Anemovane	Precision: $0.3 \text{ m/s} \pm 3$ deg, reading range: 0 to 100 m/s	(m/s)
(7) Snow gauge	Precision: ± 10 mm or 0.4% FS, reading range: 0.5 to 10 m	(mm)
(8) Rainfall gauge	Precision: ± 0.5 mm, reading range: 20 mm	(mm/min)

θ : water content by volume, P : pore pressure, T_A and T_G : temperatures in the air and in the slope, S : settlement.

	Natural water content W_N (%)	Liquid limit W_L (%)	Plastic limit W_P (%)
Soil moisture meter 1 (0 ~ 20 cm)	76.46	60.25	43.02
Settlement gauge (0 ~ 20 cm)	69.62	65.27	46.90
Soil moisture meter 3 (0 ~ 20 cm)	75.26	56.80	41.36
Soil moisture meter 4 (0 ~ 20 cm)	78.44	58.73	33.03
Soil moisture meter 1 -20 ~ -40 cm	40.43	51.94	25.76

Soil moisture meter 1	Depth (cm)	W_N (%)	ρ_s (g/cm^3)	$\rho_{d\max}$ (g/cm^3)	$\rho_{d\min}$ (g/cm^3)	D_{50} (mm)	U_c
Soil dressing	0-20	76.46	2.59	1.09	0.827	0.30	5.25
Volcanic soil with silt (strong weathering soil)	20-40	40.43	2.73	1.13	0.861	0.62	8.09
	40-60	45.77	2.78	1.04	0.810	0.70	7.58
	60-80	47.47	2.75	1.06	0.822	0.51	7.00
	80-100	47.96	2.78	1.02	0.793	0.89	8.46
	100-120	52.69	2.79	0.960	0.752	0.72	8.17

$\rho_{d \text{ in situ}} = 0.915 \text{ g}/\text{cm}^3$ W_N : natural water content, D_{50} : mean grain size, U_c : coefficient of uniformity.

FIGURE 5: Index properties of soil samples.

[6], and Kitamura et al. [7]). In particular, Yagi et al. [5] indicated the importance of the amount of limited rainfall and proposed a prediction method of failure based on field and experimental data for volcanic slopes. On the other hand, prediction methods of slope failure based on the monitoring techniques, for instance prediction using satellite systems and so on, have also been proposed (e.g., Kitamura [8]).

Geotechnical problems on both freeze-thaw and frost heaving actions have been reported by many researchers (e.g., Aoyama et al. [9], Nishimura et al. [10], and Ishikawa et al. [11]). Mechanical behavior of frozen and thawed soils has been clarified through their efforts, and the importance

of estimation on geotechnical problems has been pointed out.

Additionally, Harris and Davies [12], Harris and Lewkowicz [13] have investigated the deformation behavior of slopes subjected to freezing and thawing for slope stability. However, field, experimental, and analytical studies on slope stability due to freezing and thawing sequence have been rather limited.

The authors have similarly investigated rainfall-induced failure of volcanic slopes subjected to freezing-thawing and its mechanisms (Kawamura et al. [14-17]). In previous studies, a series of model tests was performed on volcanic slopes

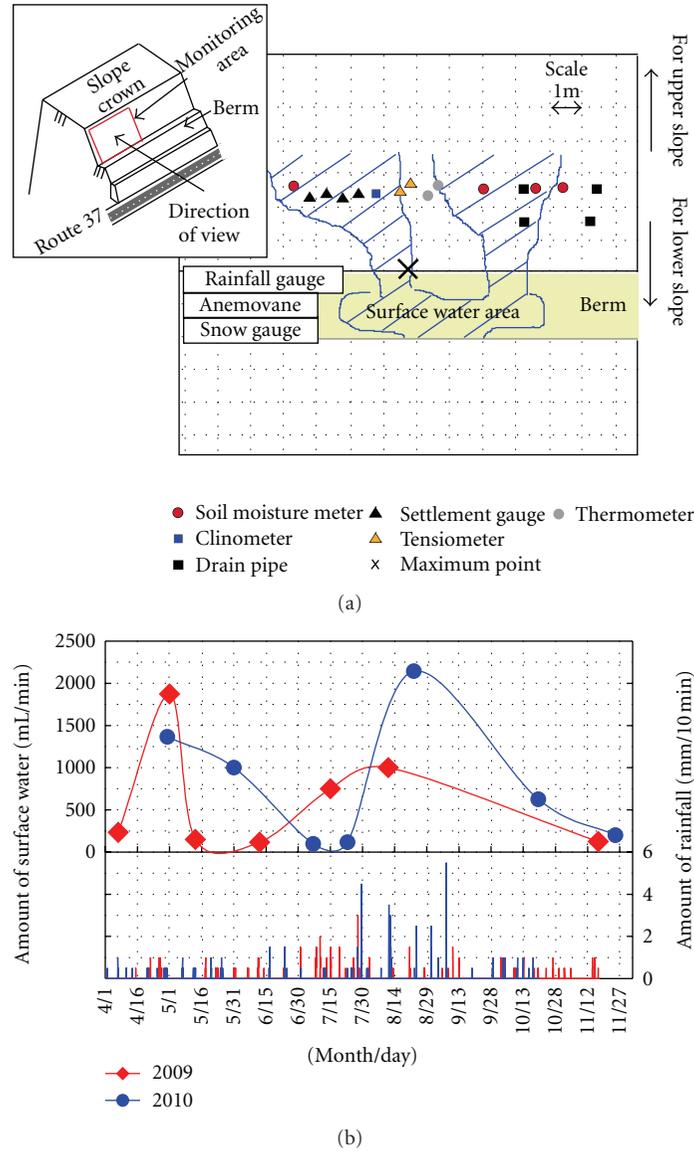


FIGURE 6: Change in amount of surface water at the maximum point during monitoring; (a) the maximum point at plane section and (b) relationship between the amount of surface water and rainfall.

having several slope shapes and water contents. Rainfall intensities were 60 mm/hr, 80 mm/hr and 100 mm/hr, and were accurately simulated through use of spray nozzle. During rainfall tests, pore water pressure behavior, deformation behavior, and variation in saturation degree were monitored, and the deformation of model slopes was estimated by the particle image velocimetry (PIV) method. The effects of the geometric condition of a slope, rainfall condition, geo-mechanical condition, and freeze-thaw action on the mechanism were clarified in detail. Of particular significance was the finding that the slip line is induced around the depth of the frozen area and can be evaluated by the dilatancy behavior of soil attributed to freeze-thaw action.

The purposes of this paper are to elucidate the aspects of soil behaviour in volcanic slopes by various monitoring

instruments and to propose a prediction method for a rapid assessment of failure development in slopes. Field monitoring has continued to date from December 1, 2008. Presented herein are reliable data collected over this period, although there were intervals in which monitoring was not carried out.

2. Location of Monitoring Site and Monitoring Instruments

The monitoring site is located at a cut slope along the Route 37 in Date, Japan, where the slope height and the angle are around 28 m and around 40 degrees, respectively. According to preliminary investigations, the top 20 cm of the surface was comprised of silty soil. The layer below 20 cm consists

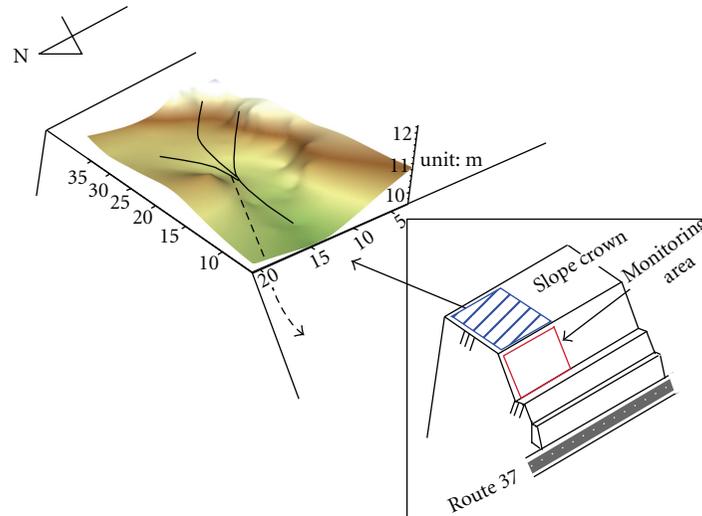


FIGURE 7: Topography of the crown of slope based on surveying.

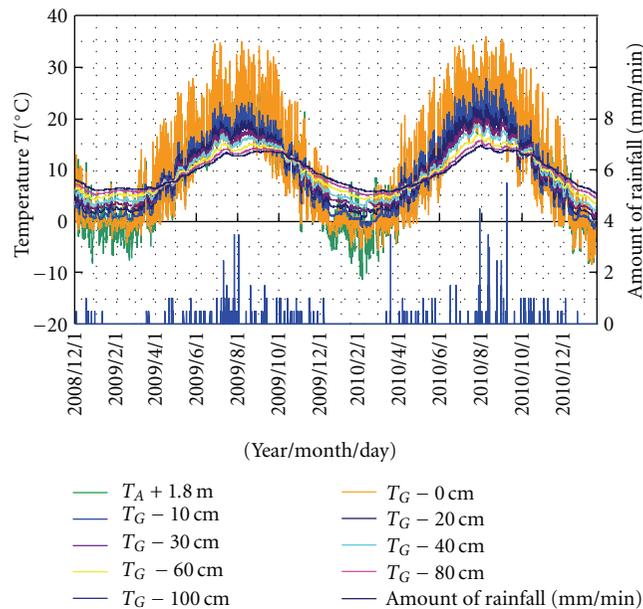


FIGURE 8: Changes of temperatures in the air and in the slope during monitoring.

mainly of volcanic soil with silty soil. The monitoring site is shown in Figure 2.

In the present study, the following instruments were adopted in order to monitor soil behavior and temperature in the air and in the slope: (1) soil moisture meters (time domain reflectometry type: TDR), (2) tensiometers, (3) thermocouple sensors, (4) clinometer (multiple inclination transducers), (5) settlement gauges, (6) anemovane, (7) snow gauge, and (8) Rainfall gauge, as shown in Figures 3(a) and 3(b). These instruments were basically set up at each depth of 20 cm. The specifications of instruments are shown in Table 1. The subscripts in the figures indicate the depths of position of the instruments. The symbols used in this study are also indicated in Table 1. Each data was collected within

the sampling period of 10 minutes and was recorded into a data logger. The data for every 1 hour is depicted herein. The instruments in this study have been used for another cold region site in order to discuss slope stability subjected to freeze-thaw action and their validity has also been confirmed.

The index properties and the grain size distributions of soil samples taken from the slope are shown in Figures 4 and 5, respectively. As shown in Figure 5, the natural water content w_N of the slope surface is almost the same as, or more than, the liquid limit w_L of its soil. Owing to this, a part of the slope surface (the thickness of 20 cm) progressively eroded and flowed downward. The deeper parts in the slope were not destabilized because natural water content is lower than the liquid limit.



Photo 1: Aspect of slope surface in winter season (2010).

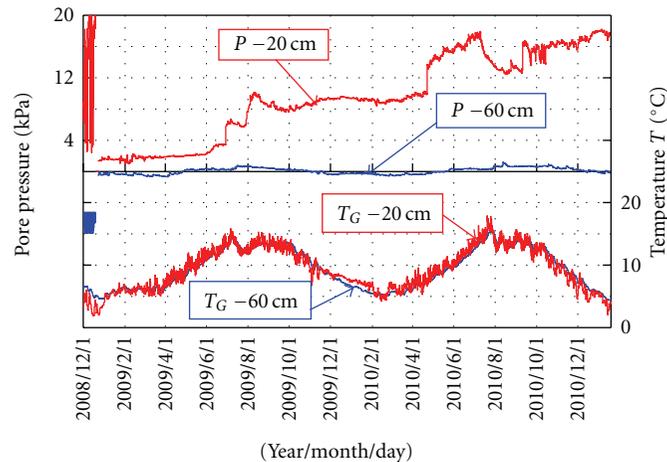


FIGURE 9: Relationship between pore pressures and temperatures in the slope.

It has been also confirmed that there were no differences in index properties due to freeze-thaw actions for 2 years. Figure 6 also illustrates the changes in the amount of surface water (including water from underground) at the maximum point from April 1, 2009 to November 27, 2010 as compared with variation of rainfall. These figures demonstrate that the amount of surface water varies through seasons and indicates the maximum value in the snow-melting season although the peak time differs for each year. Figure 7 shows the topography of the slope crown, which is depicted in 3D based on surveying. It is obvious from this figure that rainfall and snowmelt runoff easily gather around this monitoring area. As a result, the reason for the high water content in the slope may be derived from the topography and the characteristics of seepage in the slope.

Figure 8 depicts the changes in temperatures (T_A : in the air, T_G : in the slope) during monitoring. In the figure, the number of freeze-thaw cycles of the slope surface (T_G : 0 cm) was 44 times from December 1, 2008 to April 1, 2009 and 48 times from December 1, 2009 to April 1, 2010. As shown in Photo 1, which was taken in the winter 2010, a part of the surface was covered with snow and an ice layer, therefore, it can be said that this slope is located in a severe environment. On the other hand, Yamaki et al. [18] reported that the number of freeze-thaw cycles was 6 times during the winter season (from December 8, 2007 to April 1, 2008) in Sapporo, Japan, which is near the data collection site for this study. In comparison with other places in cold regions, it is also pointed out that this area is severe from a geotechnical perspective. For this reason, field monitoring was carried out

on a volcanic slope under severe environmental conditions to clarify the features of soil behavior and to propose an evaluation method for slope stability.

3. Monitoring Results and Discussions

3.1. Aspects of In Situ Volcanic Slope Subjected to Freeze-Thaw Action and Rainfall. Figure 9 shows the relationship between pore pressure and temperature (T_G : in the slope). In the figure, pore pressure, P , indicates a positive value at the depth of 20 cm and is around 0 kPa at 60 cm although these values vary through seasons. Therefore, the monitoring point in this slope can be evaluated and can be mainly discussed as saturated soil behavior.

Figures 10(a) to 10(d) depict the changes in the consistency index, $I_C = (w_L - w)/(w_L - w_P)$ at each depth, based on the index properties shown in Figure 5. The volumetric water content θ gained by using soil moisture meters can be converted to water content w by the following relation $w = (\rho_w/\rho_d)\theta$, where ρ_w and ρ_d are densities of water and dry soil, respectively. In this study, $\rho_{d \text{ in situ}}$ was 0.915 g/cm³ according to the sampling data. In the figures, the values in the depth of 30 cm indicate around 0.5 or less. This fact implies that the slope may be destabilized by either the amount of rainfall or the increase of water from underground. It is also interesting that slope stability can be easily assessed using soil moisture and a simple index.

Figure 11 illustrates the behavior of settlement gained by using settlement gauges. In the figure, a positive value means settlement toward the inside of the slope. As this figure

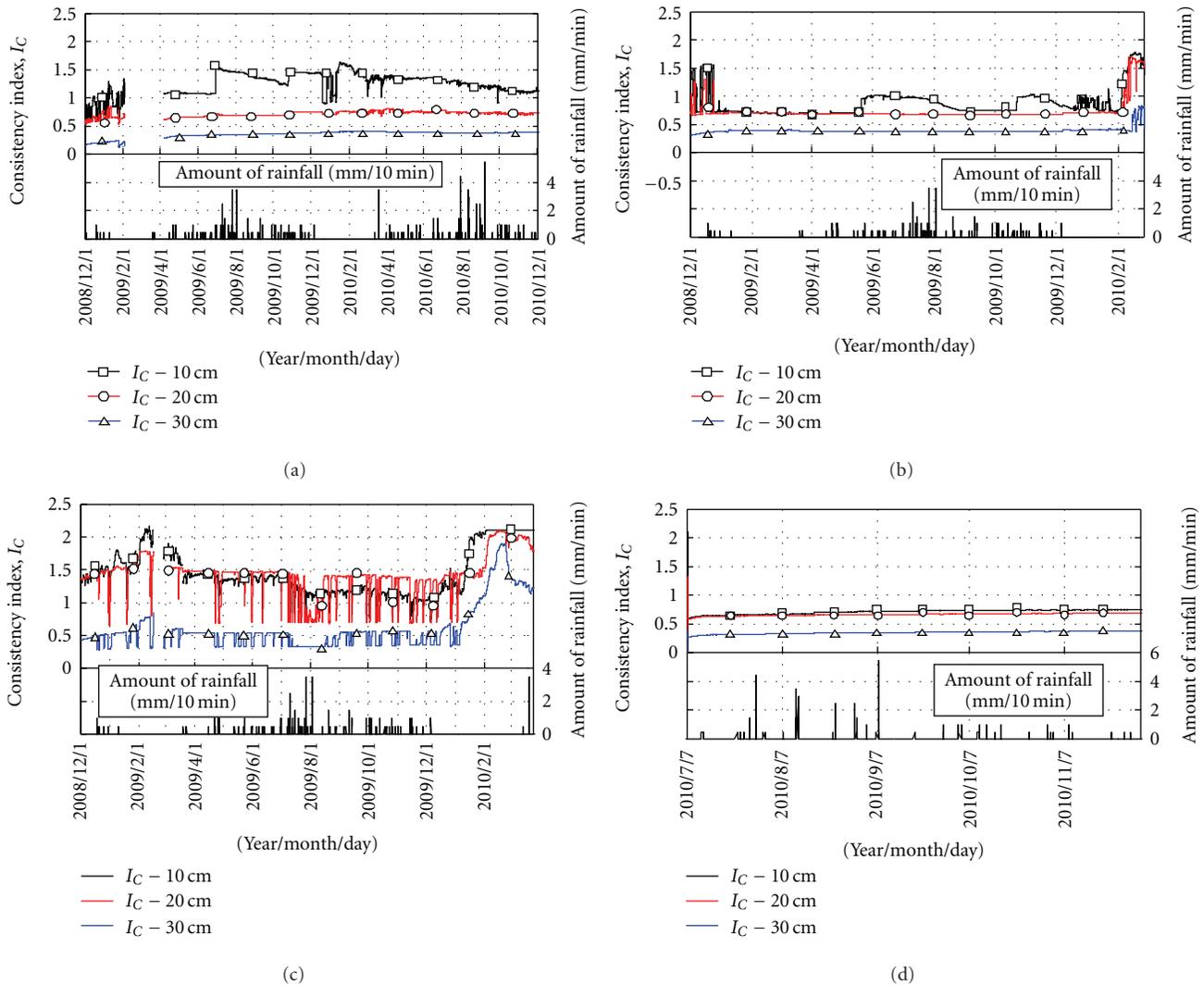


FIGURE 10: Changes in consistency index, I_C , for each depth; (a) soil moisture meter 1, (b) soil moisture meter 2, (c) soil moisture meter 3 and (d) soil moisture meter 4.

indicates, significant changes were not recognized for each position during monitoring, except at the depth of 100 cm. Although the reason for variation at the depth of 100 cm was not made clear, the surface seems to deform toward the upper side due to frost heaving. On the other hand, changes in displacement using the multiple inclination transducers were observed over the 2 years (see Figure 12). In particular, it is noted that the displacement gradually increased year by year and its value induced in the winter season increases 7 times more than that in the summer.

The surveying results for the monitoring site are depicted in Figures 13(a) and 13(b). Surveying was performed on 9 points in the slope, as shown in the figures. The figures are illustrated as cross and plane sections. As shown in the figures, the slope deforms perpendicularly and in an upward direction on its surface in the winter season, and its direction changes to a gravitational course in the snow-melting season.

Harris and Davies [12] explained that surface displacements during freezing and thawing sequences are composed

of “frost creep” and “gelifluction”, as shown in Figure 14. In the figure, the frost creep denotes mass movement when frozen soil thaws and subsides with gravity-induced closure of voids in ice lenses. On the other hand, the gelifluction indicates mass movement with thawing soils slipping down the slope. A similar tendency has also been obtained from the results of a series of model tests (Kawamura et al. [14, 15]). For the above reason, it is important for the evaluation of slope stability to monitor the deformation of the slope from winter seasons to summer seasons.

Figures 15(a) and 15(b) show the changes in water content by volume θ for summer and winter seasons, respectively. It should be noted from the figures that volumetric water content increases with an increase of rainfall and then decreases with elapsed time over the summer season. In contrast, the water content increases with a decrease of temperature (less than 0°C) in the slope for winter season and decreases conversely with an increase of temperature (more than 0°C). This indicates that the changes in volumetric

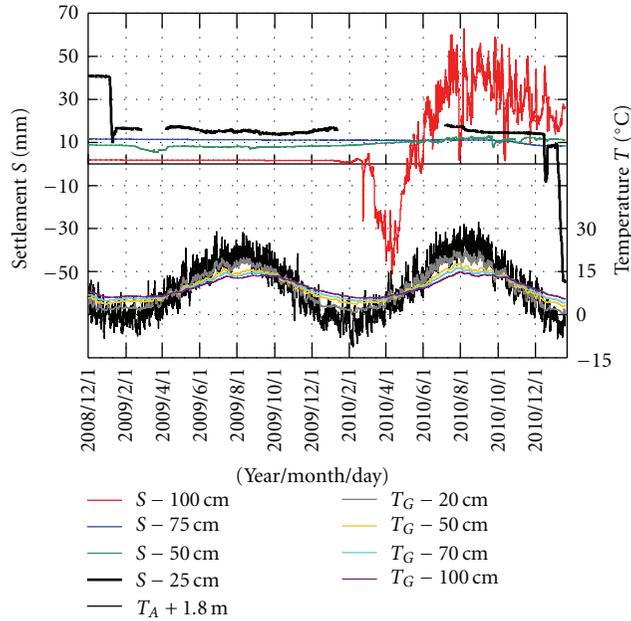


FIGURE 11: Settlement behavior monitored using settlement gauges.

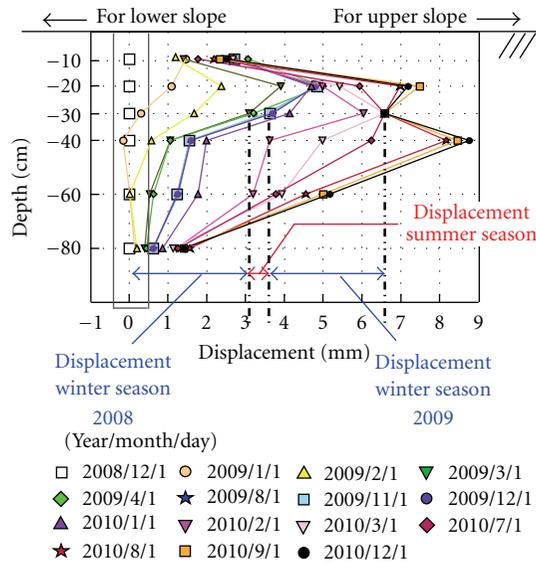


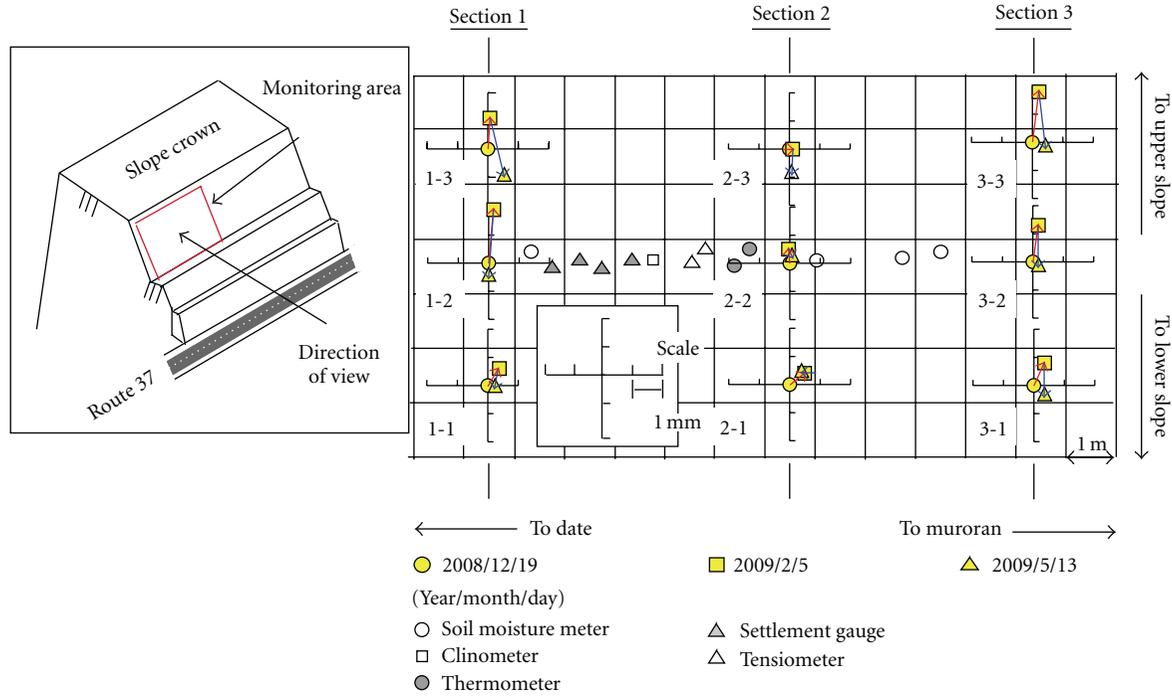
FIGURE 12: Changes in displacements using clinometer (multiple inclination transducers) during 2 years.

water content are induced during the seepage-drainage process. In the case of surface failure, it is said that one of the causes of surface failure for cohesionless soils is an increase of self-weight due to the expansion of an area with high water retention ability. In a previous study in which a series of rainfall model tests was performed on volcanic slopes (Kawamura et al. [14, 15]), the model slopes suddenly failed at the peak of saturation degree after the degree of saturation gradually increased. After the failure, the saturation degree decreased, similar to the data revealed in field monitoring (see Figures 15(a) and 15(b)).

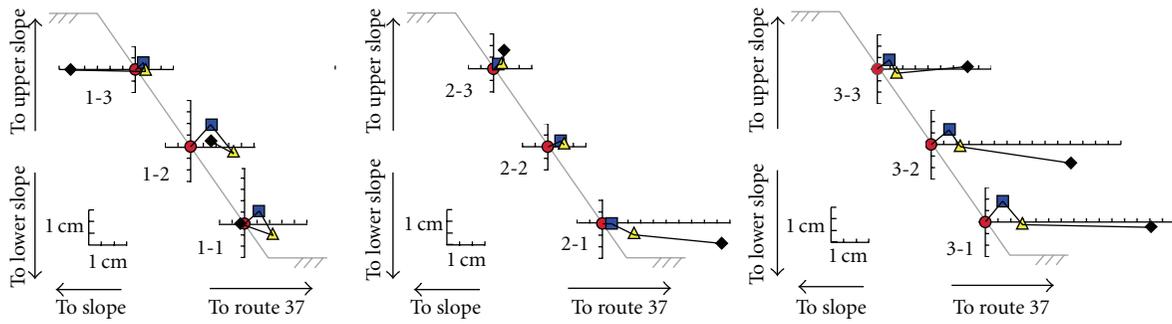
Additionally, it is noteworthy that the value is constant when deformation proceeds, for instance it is around 38%

in the slope although the magnitude of deformation is very small. If it is assumed that the slope fails progressively by integration of small displacements, this finding is significant for the assessment of slope stability on local areas. Hence, the failure may be predicted if water content at failure is defined.

Figures 16(a) and 16(b) depict the typical changes in water content by volume θ for drainage process based on the zone in dotted line in Figure 15. In the figures, a fitting curve on the drainage process is also depicted as a solid line. As shown in Figure 16(b), variation in the data is observed. The reason for variation was due to the effect of rainfall in the winter season although the data was omitted here. It is conspicuous from the figures that the behavior of soil



(a)



(Year/month/day)

(b)

FIGURE 13: Surveying results for monitoring site; (a) plane section, and (b) cross section.

moisture is explained by a simple expression according to the fitting curves based on the least-squares method. Namely the following expression can be obtained:

$$\theta = \kappa \cdot e^{-\alpha(t'/T')}, \quad (1)$$

where t' and T' are elapsed time from the peak of θ and one period from the peak of θ to the end of drainage process, κ and α denote the peak value and the reduction ratio of volumetric water content obtained from fitting curves and are 45.6 and 0.01 in the summer season, 45.3 and 0.006 in the winter season, respectively. It should be pointed out that both values in summer and winter seasons are almost the same

although it is difficult to define its peak value in field data. As a consequence, it may be useful for disaster mitigation if such a relation may be simply defined for each slope. Further considerations will be required because the quantity of data is limited.

3.2. A Prediction Method for Surface Failure of In Situ Volcanic Slopes Subjected to Rainfall and Freeze-thaw Action. As mentioned above, except for the cases of failure due to the increase of ground water level, it is significant for the evaluation of slope stability to grasp variation in saturation degree (the difference in the water holding ability of volcanic slopes) for the seepage-drainage process.

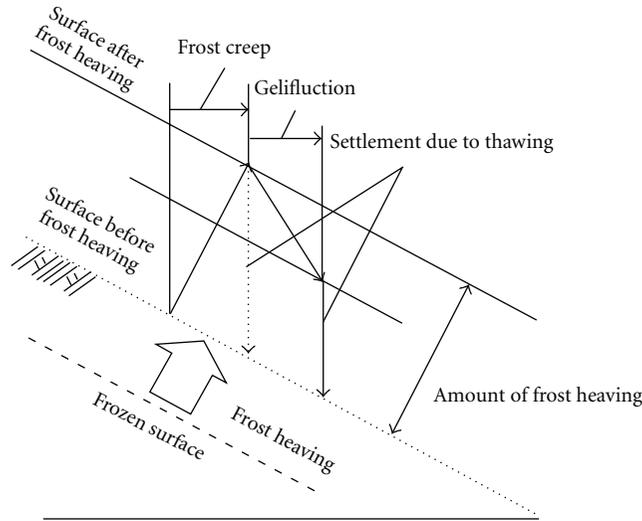


FIGURE 14: Solifluction process composed of “frost creep” and “gelifluction”.

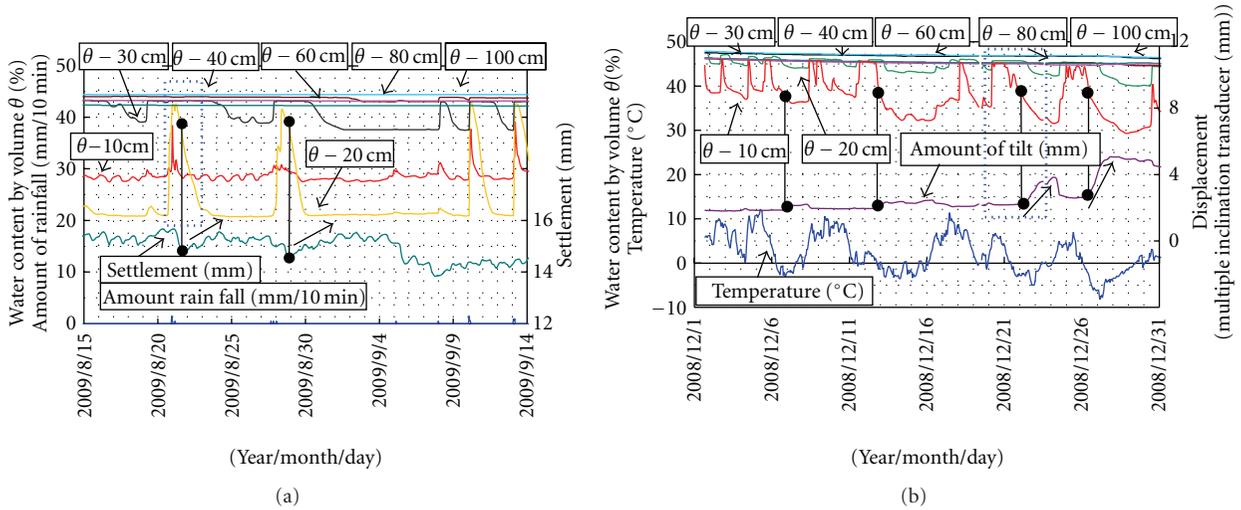


FIGURE 15: Changes in water content by volume, θ ; (a) in summer season, and (b) in winter season.

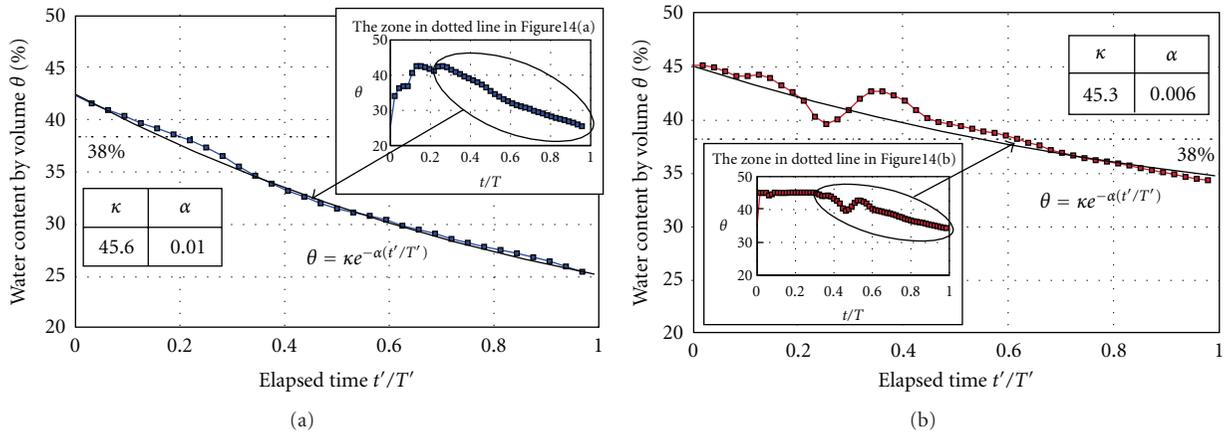


FIGURE 16: Relationship between water content by volume, θ , and normalized time, t'/T' , for drainage process and fitting curve proposed in this study; (a) in summer season, and (b) in winter season.

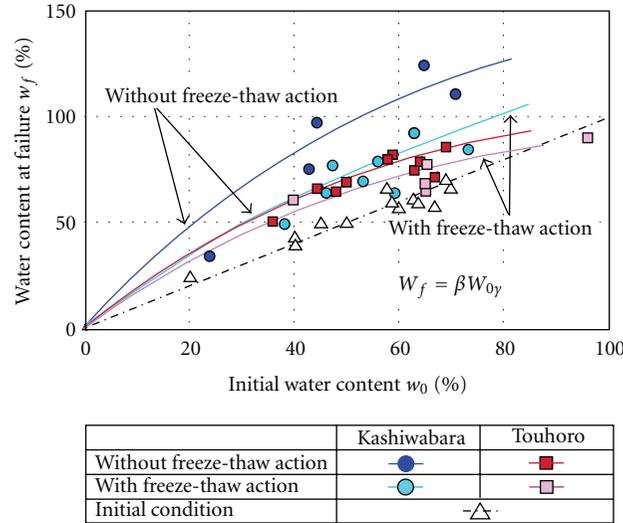


FIGURE 17: Relationship between water contents at initial w_0 and at failure w_f for typical volcanic soils (Kawamura et al. [17]).

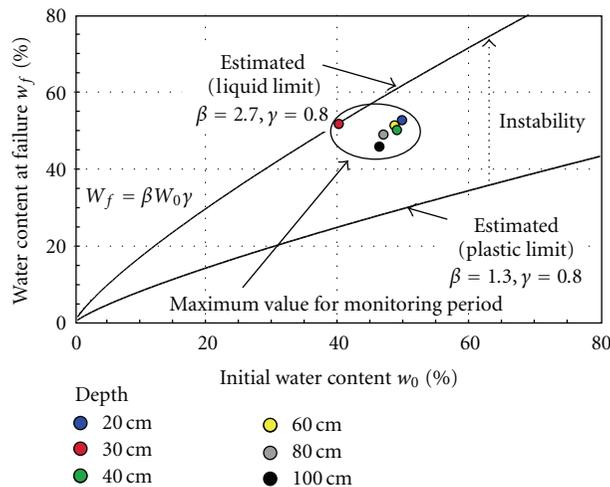


FIGURE 18: Relationship between water contents at initial w_0 and at failure w_f for monitoring site in Date, Hokkaido (using soil moisture meter 1).

The authors have proposed a prediction method for surface failure of volcanic slope by considering the characteristics of the ability of water retention (e.g., water content) and have revealed that a slip line is induced around the depth of a frozen area. A summary of these findings is provided in (Kawamura et al. [14, 17]).

Figure 17 shows the relationship between water contents at the initial w_0 and at failure w_f based on a series of model test results. The details of volcanic soils used in a previous study were reported by Miura et al. [1]. Those typical volcanic soils in Hokkaido, Japan have been referred to as Kashiwabara and Touhoro volcanic soils. As shown in the figure, there are unique relationships between both water contents for both types of volcanic soil. The increment of water content at failure w_f from the initial line becomes a steady state for each material although the relation varies

according to freeze-thaw action. For instance, the following expression can be also obtained:

$$w_f = \beta \cdot w_0^\gamma, \tag{2}$$

where β and γ are coefficients, these values are shown in Table 2. From Table 2, it should be noted that these parameters of volcanic soils subjected to freeze-thaw process become almost the same. Consequently, it is also possible to evaluate slope failure due to rainfall and freeze-thaw process if such a relation can be obtained for the in situ slope.

Similarly, monitoring data is shown in Figure 18. The maximum value for each layer (20 cm, 30 cm, 40 cm, 60 cm, 80 cm, and 100 cm) gained by soil moisture meter 1 was depicted based on Figure 17. In the present study, it is difficult to actually define slope failure for this site. Therefore, water content at failure was tentatively defined as the liquid limit

TABLE 2: Coefficients of β and γ .

	Kashiwabara		Touhoro	
	β	γ	β	γ
Without freeze-thaw action	2.4	0.9	4.3	0.7
With freeze-thaw action	2.8	0.8	2.4	0.8

to indicate slope instability, because the monitoring slope deformed gradually around the liquid limit. The failure line was predicted based on the liquid limit and $\gamma = 0.8$ in (2) of which the consistent value was indicated for both volcanic soils. It is evident from the figure that the maximum value is within the range of both limits for each depth and is slightly near to a prediction line based on the liquid limit. In particular, it was noted that the value at 30 cm was on the failure line. According to Figure 10(a), this data was collected on February 1, 2009. The reason for high water content is that the depth of 30 cm is strongly affected not only by surface water due to thawing and melting snow but also water from underground. From the results, (2) may explain well the field data in volcanic slopes and may evaluate slope stability.

Considering the results of this study, surface failure may be predicted if the depth of frozen area and the water holding capacity at failure in a slope are simply estimated by monitoring an index property such as water content. However, it is difficult to accurately define slope failure. In addition, the above results may change with variations in soil materials and because of this, changes in the slip line are predicted. At any rate, further considerations will be required.

4. Conclusions

In consideration of the limited results of field monitoring, the following conclusions were derived.

- (1) A slope subjected to freezing and thawing deforms perpendicularly and in an upward direction on its surface in the winter season, and its direction changes to a gravitational course in the snow-melting season.
- (2) According to the data collected using soil moisture meters, water content increased regularly with an increase of rainfall and then decreased with an increase of elapsed times in the summer season. On the other hand, it increased with a decrease in ground temperature due to freezing and thawing and then decreased with an increase of temperature. As a result, evaluation of soil moisture may be done for seepage and drainage processes despite variations in all seasons.
- (3) Water content by volume became a constant value when deformation in the slope was induced, for instance it was around 38% in this case. Surface failure may be predicted if the depth of frozen area and the water holding capacity at failure in a slope is simply estimated by monitoring an index property such as water content.

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References

- [1] S. Miura, K. Yagi, and T. Asonuma, "Deformation-strength evaluation of crushable volcanic soils by laboratory and in-situ testing," *Soils and Foundations*, vol. 43, no. 4, pp. 47–57, 2003.
- [2] JSSMFE, "The disaster investigative report of the 1993 Kushiro-oki Earthquake and Notohanto-oki Earthquake," The 1993 Earthquake Disaster Investigative Committee, 1995.
- [3] JSCE, "The disaster investigative report of the Typhoon 10th (2003)," *Committee on Hydroscience and Hydraulic Engineering*, pp. 1–95, 2004 (Japanese).
- [4] L. Olivares, E. Damiano, R. Greco et al., "An instrumented flume to investigate the mechanics of rainfall-induced landslides in unsaturated granular soils," *Geotechnical Testing Journal*, vol. 32, no. 2, pp. 108–118, 2009.
- [5] N. Yagi, R. Yatabe, and M. Enoki, "Prediction of slope failure based on amount of rainfall," *Journal of Geotechnical Engineering*, vol. III-13, no. 418, pp. 65–73, 1990 (Japanese).
- [6] R. Orense, K. Farooq, and I. Towhata, "Deformation behavior of sandy slopes during rainwater infiltration," *Soils and Foundations*, vol. 44, no. 2, pp. 15–30, 2004.
- [7] R. Kitamura, K. Sako, S. Kato, T. Mizushima, and H. Imanishi, "Soil tank test on seepage and failure behaviors of Shirasu slope during rainfall," *Japanese Geotechnical Journal*, vol. 2, no. 3, pp. 149–168, 2007 (Japanese).
- [8] R. Kitamura, "Monitoring technique of slope stability in the rain," *Tsuchi-to-kiso*, vol. 55, no. 9, pp. 1–3, 2006 (Japanese).
- [9] O. Aoyama, S. Ogawa, and M. Fukuda, "Temperature dependencies of mechanical properties of soils subjected to freezing and thawing," in *Proceedings of the 4th International Symposium on Ground Freezing*, pp. 217–222, 1985.
- [10] T. Nishimura, S. Ogawa, and T. Wada, "Influence of freezing and thawing on suction and shearing strength of unsaturated soils," *Journal of Geotechnical Engineering*, vol. III-24, no. 475, pp. 59–67, 1993 (Japanese).
- [11] T. Ishikawa, Y. Ozaki, and S. Miura, "Influence of freeze-thaw action on mechanical behavior of crushable volcanic coarse-grained soils," *Journal of Geotechnical Engineering*, vol. III-64, no. 3, pp. 712–717, 2008 (Japanese).
- [12] C. Harris and M. C. R. Davies, "Gelification: observations from large-scale laboratory simulations," *Arctic, Antarctic, and Alpine Research*, vol. 32, no. 2, pp. 202–207, 2000.
- [13] C. Harris and A. G. Lewkowicz, "An analysis of the stability of thawing slopes, Ellesmere Island, Nunavut, Canada," *Canadian Geotechnical Journal*, vol. 37, no. 2, pp. 449–462, 2000.
- [14] S. Kawamura, S. Miura, T. Ishikawa, and H. Ino, "Failure mechanism of volcanic slope due to rainfall and freeze-thaw action," in *Proceedings of the International Symposium on Prediction and Simulation Methods for Geohazard Mitigation (IS-Kyoto '09)*, pp. 25–31, Japan, 2009.
- [15] S. Kawamura, S. Miura, T. Ishikawa, and S. Yokohama, "Rainfall-induced failure of unsaturated volcanic slope subjected to

- freeze-thaw action and its evaluation,” *Journal of Geotechnical Engineering*, vol. C-66, no. 3, pp. 577–594, 2010 (Japanese).
- [16] S. Kawamura, S. Miura, and T. Ishikawa, “Mechanical behavior of unsaturated volcanic slope due to rainfall and freeze-thaw actions,” in *Proceedings of the Experimental and Applied Modeling of Unsaturated Soils (GeoShanghai '10)*, pp. 152–158, Geotechnical Special Publications, ASCE, no. 202, 2010.
- [17] S. Kawamura, S. Miura, and S. Yokohama, “Rainfall-induced failure of volcanic slope with crushable particles subjected to freeze-thaw action,” in *Proceedings of the Advances in Geotechnical Engineering (GeoFrontiers '11)*, pp. 3597–3608, Geotechnical Special Publications, ASCE, no. 211, 2011.
- [18] M. Yamaki, S. Miura, and S. Yokohama, “Effect of freeze-thaw sequence on deformation properties of crushable volcanic soil,” *Journal of Geotechnical Engineering*, vol. C-65, no. 1, pp. 321–333, 2009 (Japanese).



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