Geohazard at volcanic soil slope in cold regions and its influencing factors

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ABSTRACT

This study examines the mechanism of the geohazards occurred at a volcanic soil slope in cold regions and its influencing factors in consideration of the effects of freeze-thaw actions on the physical properties, the water retention-permeability characteristics, and the deformation-strength characteristics of volcanic soils from the viewpoint of both experimental study and analytical study. To this end, we performed the long-term field measurement, model tests, laboratory element tests, and numerical simulations by taking volcanic soil slope subjected to freeze-thaw actions. As the results, this study revealed that there is a difference in the slope failure mechanism between cold region and warm-temperate region, and that freeze-thaw actions seriously influence thermo-hydro-mechanical behaviour of crushable volcanic coarse-grained soil slope under unsaturated condition even if the soil is a non-frost-susceptible geomaterial. Furthermore, this study clarified the mechanism, the endogenous factors, and the exogenous factors of the slope failure for volcanic soil ground in Hokkaido in comparison with the slope failure in warm-temperate regions.

Keywords: cold regions, slope failure, freeze-thaw action, volcanic soils, thermo-hydro-mechanical behavior

1 INTRODUCTION

Much of Japan is covered by volcanic soils, which have been produced since the quaternary period due to volcanic activity. Even in Hokkaido, a cold and snowy island in northern Japan, volcanic soils are widely distributed over 40% of the total area. Volcanic soils are known to show different behaviour from that of clay or sand, and have been the subject of much research, as they have caused complicated geotechnical engineering problems (Miura and Yagi 2003). Volcanic soil deposits possess diverse inherent properties that depend on the various modes of deposition and the conditions of the depositional environment, which are mostly dominated by the local geology, the local topography, and the local climatic conditions. From a geotechnical engineering point of view, the most distinctive feature of the volcanic coarse-grained soils in Hokkaido is the tendency for particle breakage, which leads to a degradation in static and dynamic deformation-strength characteristics (Miura et al. 1996a; Miura et al. 1996b; Yagi and Miura 2004). Especially, crushing of the particles of Hokkaido's volcanic coarse-grained soils can be observed even under relatively low stress levels, i.e., the subsurface layer subjected to freeze-thaw action with snowfall.

On the other hand, in snowy cold regions like Hokkaido, with a drop in air temperature during the winter season a surface layer of soil slopes freezes from the ground surface, and with a rise in air temperature during the spring season the frozen soils conversely thaw from ground surface. This freeze-thaw action also affects the seepage flow inside soil slope because the frozen soil layer is impermeable. As a matter of fact, in Hokkaido, geohazards such as slope failure at cut slope or landslide at natural slope are often occurred in snow-melting season. For example, according to the data for the last 14 years, the slope failure occupies 62 % of total number of the causes for the urgent inspections at the national roads in Hokkaido, and among it the slope failure at thawing season occupies 26 %. Therefore, the prediction of slope failure at thawing season is indispensable for the disaster prevention measures in Hokkaido.

This subsurface failure is deemed to be caused by an increase in the degree of saturation arising from the melting of snow and/or the degradation in the mechanical characteristics of the soils caused by freeze-thaw actions. For example, the growth of ice lenses within frost-susceptible soils and their subsequent hollowing with thawing may weaken the structure of the soil skeleton, owing to the formation of local cracks and a reduction in soil density (Qi et al. 2006). Likewise, for volcanic coarse-grained soils, which have multifarious physical properties and display

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complex mechanical behaviour, the particle breakage caused by the freezing of pore water may result in a degradation of the physical properties and the mechanical characteristics. Furthermore, since freeze-thaw action may cause the degradation of the physical properties in case of volcanic coarse-grained soils, it also alters the water retention-permeability characteristics. Accordingly, it is imperative to establish a precise predictive method for slope failure in Hokkaido to examine the influence of freeze-thaw action on the deformation-strength characteristics and the water retention-permeability characteristics of soils, irrespective of their frost susceptibility, and to identify endogenous and exogenous factors affecting slope failure in the snow-melting season.

This paper reviews and summarizes previous researches on the mechanism of the geohazard occurred at a volcanic soil slope in cold regions and its influencing factors in consideration of the effects of freeze-thaw actions on the physical properties, the water retention-permeability characteristics, and the deformation-strength characteristics of volcanic soils from the viewpoint of both experimental study and analytical study. To this end, Chapter 2 discusses the mechanical behaviour of the soil slope during freezing and thawing based on the results of the long-term field measurement of soil slope in Hokkaido and full-scale and small-scale model tests of soil slopes subjected to freeze-thaw actions. Chapter 3 discusses the change in the physical properties, the water retention-permeability characteristics, and the deformation-strength characteristics of fragmental volcanic coarse-grained soils caused by freeze-thaw actions from the viewpoint of particle crushability based on the results of various types of laboratory element tests under saturated and unsaturated conditions. Chapter 4 discusses the applicability of numerical simulations, which can consider the interactions among thermal analysis, seepage analysis, and deformation analysis, to the failure mechanism analysis of volcanic soil slope subjected to freeze-thaw actions from the viewpoint of the frost heave phenomenon and the change in material properties due to freeze-thaw. Finally, Chapter 5 discusses the mechanism of the slope failure at volcanic soil grounds in Hokkaido, and its influencing factors from the viewpoints of endogenous factors and exogenous factors by comparing the mechanism of slope failure in temperate regions with that in cold regions.

2 BEHAVIOUR OF SOIL SLOPE DURING FREEZING AND THAWING

2.1 Concept of slope behaviour during freeze-thaw

In the past, a number of field studies and laboratory model tests have been conducted to understand soil mass movement, namely “solifluction,” observed at frost-heaving and thawing soil slope composed of high frost-susceptible soils. According to the past researches (e.g. Harris and Davies 2000; Matsuoka 2001), the solifluction process is commonly estimated as follows. When a surface layer of the soil slope freezes from the ground surface with a drop in air temperature, frost heave of the soil caused by ice segregation develops in the direction perpendicular to slope surface. Afterwards, when the frozen soil thaws from ground surface downward with a rise in air temperature, the melting of ice lens within the soil bring excess meltwater into the soil. Since the frost-heaved subsurface layer has a high void ratio, high water content, low shear strength in the early stages of soil thawing, it subsides in the nearly vertical direction as the overburden pressure increases by degrees with the thawed layer thickening. Thaw settlement reflects closure of voids left by ice lens in the soil, and as the results the strength gradually increases with the increase in the density in comparison with before thawing. Finally, when the strength becomes equal to the downslope gravitational shear stress, the soil mass movement converges. Thus, the solifluction which induces shear deformation parallel to slope surface is progressively developed by cyclic freeze-thaw actions at subsurface layer of soil slope.

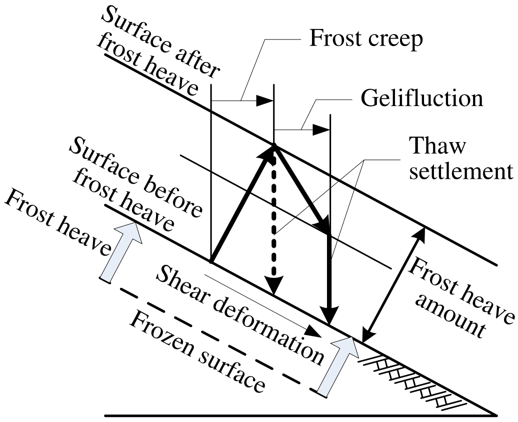


Fig. 1. Solifluction composed of “frost creep” and “gelifluction”.

According to Harris and Davies (2000), the surface displacement during soil freezing and thawing is composed of “frost creep” and “gelifluction” as shown in Figure 1. The frost creep is an effect of frost heave that causes soil mass movement down slope when frozen soil thaws and subsides with closing ice lens voids due to gravity. The gelifluction is a form of soil mass movement such that thawing soils waterlogged by the seasonal freeze-thaw action slip down a slope by gravity like a liquid. They describes that the gelifluction can occur only in the uppermost few decimeters of soil slope and at greater depths thawing settlement is mainly associated with frost creep. Moreover, Harris et al. (1995, 1997, 2000) demonstrated that the surface displacement was strongly correlated with slope angle which determines shear stress and soil characteristics such as frost susceptibility, permeability and stress-strain relationships in the thawing soils, since

Table 1. Physical properties of sample in field measurement.

ρ_s (g/cm^3)	ρ_d (g/cm^3)	ρ_t (g/cm^3)	w (%)	w_L (%)	w_P (%)	e
2.650	1.670	2.030	21.7	28.6	17.7	0.587

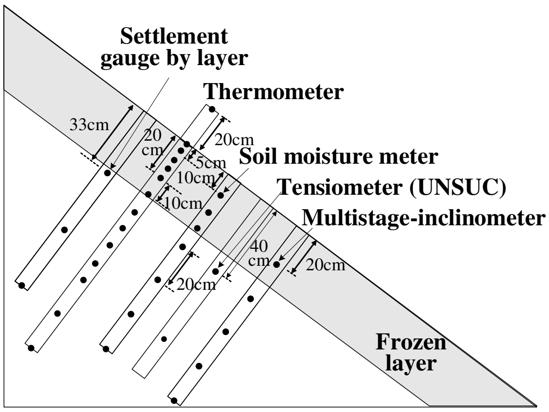


Fig. 2. Arrangement of measuring devices in field measurement.

they affect frost heave/thaw settlement. Therefore, it is essential for the precise understanding of the mechanical behaviour of soil slope during freezing and thawing to take into account thaw softening of the soil before and after freeze-thaw sufficient to cause solifluction.

2.2 Field measurement

Long-term field monitoring on an actual cut slope, which was composed of a volcanic cohesive soil (Table 1), was conducted beside national highway route 274 at Biman, Tokachi Shimizu-town in order to examine the behaviour of soil slope subjected to freeze-thaw and rainfall. Note that a slope failure due to the increase in the degree of saturation caused by rainfall and snowmelt was occurred at a cut slope near the measurement site in the thawing season of two years ago from the start of field measurement. The slope height is 23 m, and the slope angle is 34°. According to the results of frost heave tests, the soil exhibits high frost-susceptibility. A long term behaviour of the slope has been monitored with thermometers, soil moisture meters, tensiometers, settlement gauge by layer and multistage- inclinometer for temperature, water content, pore water pressure (PWP), displacement by layer respectively as shown in Figure 2. These monitoring instruments were installed from surface up to 1.2 m deep. The monitoring period is from November 12, 2007 to November 13, 2009. Note that the at the AMeDAS (Automated Meteorological Data Acquisition System) observation point closest to the field monitoring site, the 5-year average freezing index (F) in 2002–2006 is 494.2 °C·days and the average maximum snow depth is 0.86m. Here, the freezing index is defined as the number of cumulative degree-days during freezing season.

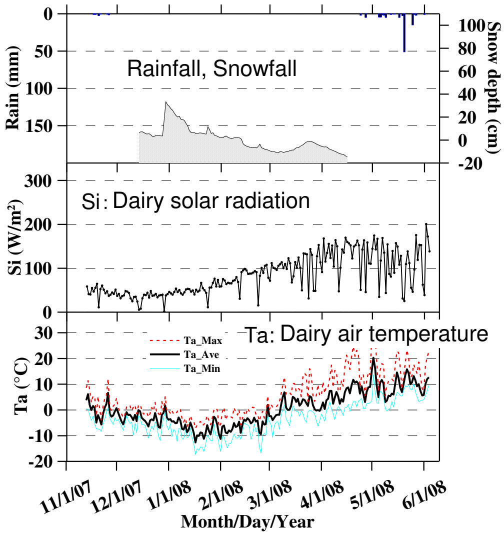


Fig. 3. Weather conditions during field measurement.

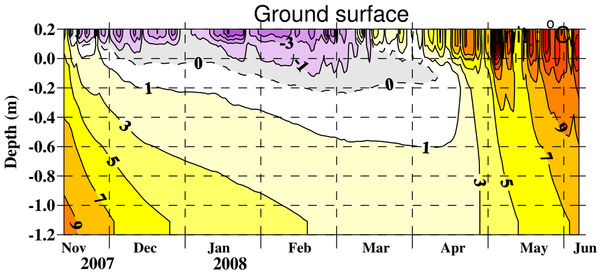


Fig. 4. Depth-directional distribution of ground temperature.

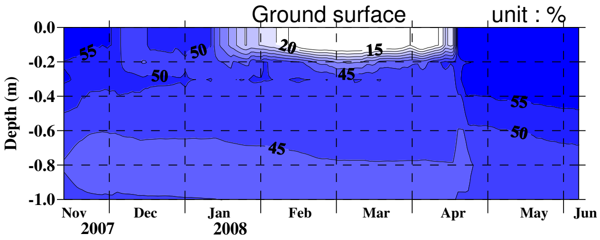


Fig. 5. Depth-directional distribution of volumetric water content.

Figure 3 shows an example of the temporal transitions in daily mean air temperature, daily solar radiation, daily precipitation, and daily snowfall at the field monitoring site. The average daily temperature remains below 0 °C during roughly three months from early December to early March, and from mid-March it rises over 0 °C. Figure 4 shows the spatial temporal contour of the depth-directional distribution of ground temperature based on the measurement data by thermometers. When air temperature drops to 0 °C or below, the 0 °C isotherm may penetrate deep into the soil ground. Afterwards, when the frozen soil thaws from ground surface downward with a rise in air temperature, a thin frozen soil layer can be observed inside subsurface layer for a short period like one week or so.

On the other hand, Figure 5 shows the spatial temporal contour of the depth-directional distribution of volumetric water content based on the measurement data by soil moisture meters. There is a tendency for the water content to decrease rapidly after middle January in 2008, when the frost-penetration depth increased dramatically. This is due to functional features of the

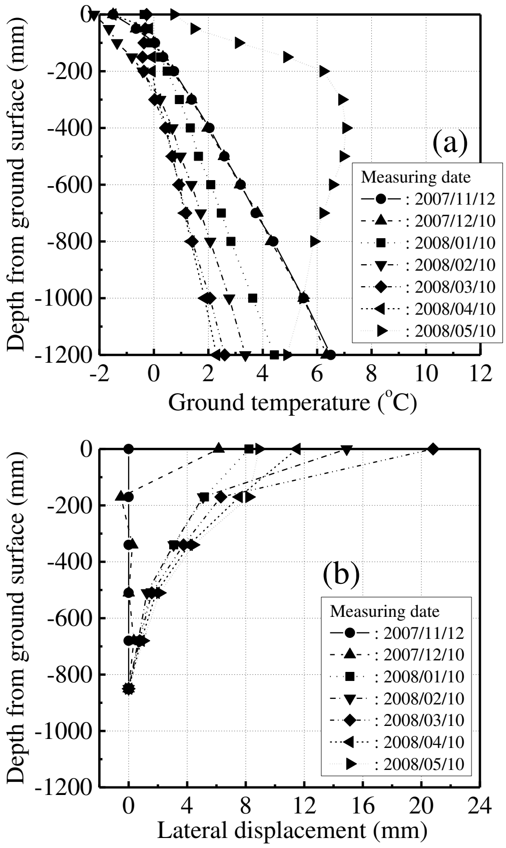


Fig. 6. Depth-directional distribution (a: ground temperature, b: lateral displacement).

soil moisture meter used in the measurement. Besides, water content at subsurface layer after thawing increases as compared with that before freezing. This indicates that there is a close relationship between the freeze-thaw history and the seasonal fluctuation in water content of soil ground.

In addition, in order to examine the solifluction behaviour of frost-susceptible soil slope at thawing season, this study measures the depth-directional distribution of lateral displacement parallel to the slope surface by using a multistage-inclinometer. Here, a multistage-inclinometer is newly developed five connected rigid rods with a strain gauge at each joint, which can measure the rotational angle of two adjacent rods every 20 cm (Figure 2). In the field measurement, the multistage-inclinometer was buried under the soil ground in the direction perpendicular to slope surface. Figure 6 shows the temporal transition in the depth-directional distribution of lateral displacement parallel to the slope surface along with the transition of ground temperatures from autumn to spring. In this study, the lateral displacement toward a lower place of the slope is given a positive sign. When the 0 °C isotherm gradually penetrates deep into the soil ground with time passing, the lateral displacement increases along with the growth of ice lens due to frost heave though it seems strange. The reason is considered to be because the multistage-inclinometer was not set perpendicular to the slope surface and/or the frost heave occurred nonuniformly in the soil ground. Afterwards, even if the frozen soil thaws from ground surface downward with a rise in air temperature, freeze-thaw of the soil slope causes the residual displacement parallel to the slope surface at a subsurface layer where frost heave occurs. Accordingly, the shear deformation is progressively developed at the subsurface layer by cyclic freeze-thaw actions. This indicates that the multistage-inclinometer is highly useful in the examination of the solifluction behavior of frost-heaved soil slope at thawing season, and that for the precise prediction of subsurface failure, it is important to examine the influences of cyclic freeze-thaw actions on the thermo-hydro-mechanical behavior of frost-susceptible soil grounds in detail.

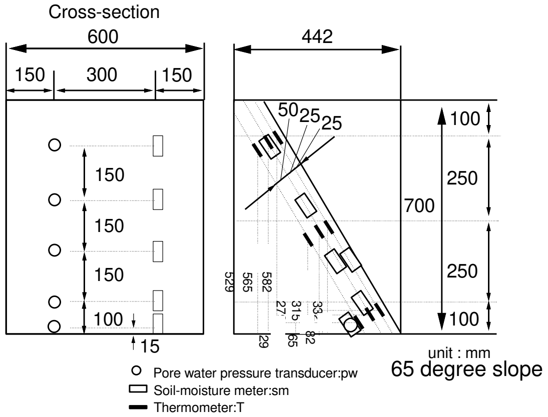
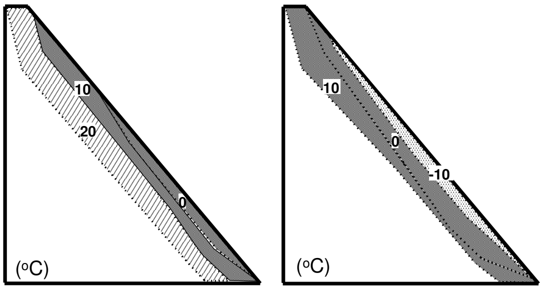


Fig. 7. Model slope and setting positions of measuring devices.

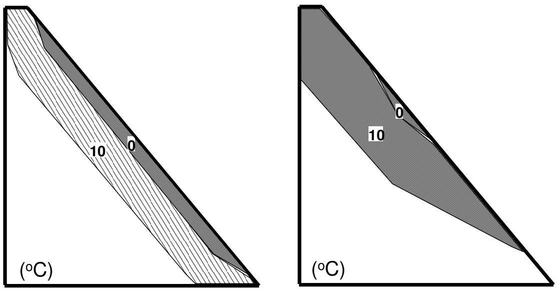
2.3 Small-scale model tests

Kawamura et al. (2009) examined the deformation behaviour of soil slope, which was composed of a volcanic coarse-grained soil, during freezing and thawing and during a rainfall test. Figure 7 depicts the shape of model slope and the setting positions of measuring devices used in a freeze-thawing test. A model slope was constructed by pluviating into air so as to be the desired density (ρ_d = 0.45 g/cm^3, and its variation in density is within 5 %). Initial water content (w_0) of the model slope after construction was equal to around 50 %. Thereafter, the slope surface was carefully cut to the desired slope angle of 65^o (relative to the horizontal) using a straight edge so as to free from disturbance of the surface. In the rainfall test with freeze-thaw actions, the surface of slope was made to freeze up by dry ice during 8 hours and was basically thawed in the room temperature of 20 °C during 9 hours. In their research, the above-mentioned series of freezing and thawing operations was defined as 1 freeze-thaw process cycle (N_f). Subsequently, a rainfall test with the rainfall intensities of 60 and 100mm/hr, which were accurately simulated by using several types of spray-nozzles, was conducted. During the test, the changes in deformation behaviour, degree of saturation



10,800sec.(180min.) 28,800sec.(480min.)

(a) During freezing



43,200sec.(720min.) 61,200sec.(1020min.)

(b) During thawing

Fig. 8. Contour maps of ground temperature inside model slope.

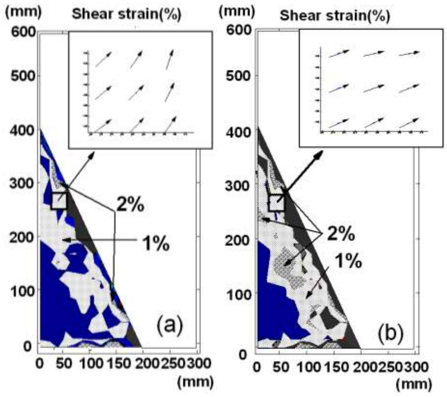


Fig. 9. Contour maps of increment in shear strain inside model slope with strain vectors (a: after freezing, b: after thawing).

and ground temperature were monitored by using digital video cameras, soil moisture sensors and thermocouple sensors, respectively. In particular, the deformation behaviour was estimated by the particle image velocimetry (PIV) analysis (White et al. 2003).

Figures 8 show the contour maps of ground temperature inside the model slope subjected to freeze-thaw action for four different elapsed times (*t*). From these figures, it is recognized that a frozen soil layer parallel to the ground surface is formed at the subsurface layer of the model slope in freezing process and the 0 °C isotherm gradually gets deeper with the passage of time during temperature drop. In this case, the frost penetration depth was about 80 mm from the slope surface. Figures 9 show contour maps of the increment in shear strain inside the model slope from the beginning of the test to two different elapsed times (*t*) of 8 hours in freezing process and 16 hours in thawing process, respectively. It also shows typical examples for the strain vectors during the same period of time at the slope surface. The shear strain is developed at the subsurface layer of the model slope by freezing, and strain vectors in freezing process are approximately perpendicular to the slope surface. While, it can be observed in Figure 9b that the shear strain at the area suffered from freeze-thaw action remains there even after thaw. In this case, from the measurement of frost heave amount and density, it is revealed that the frost heave amount of the model slope was about 5 mm, and the difference in the density between unfrozen and frozen parts of the sample caused by freeze-thaw action can be also confirmed. Besides, some cracks were observed at the boundary between unfrozen and frozen soil layers. These results indicate that the freeze-thaw action brings about the change in the soil skeleton structure at the frost-heaved subsurface layer even in case of low frost-susceptible volcanic coarse-grained soils. However, since the thawing soil was under unsaturated condition of the degree of saturation after thaw being roughly 26 %, the gelifluction shown in Figure 1 was considered to hardly occur in the volcanic coarse-grained soil and then thawing settlement observed in the model slope may originate mainly in frost creep accompanied by vertical settlement.

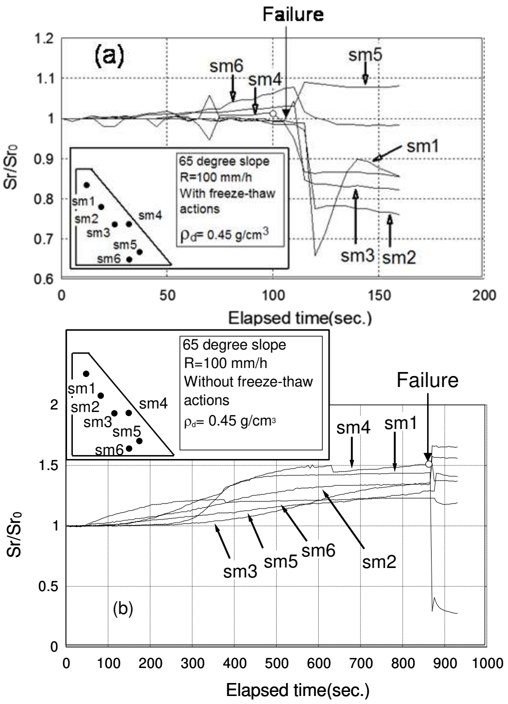


Fig. 10. Change in degree of saturation during freezing and thawing (a: with freeze-thaw, b: without freeze-thaw).

Figure 10 compares the changes in the normalized degree of saturation (S_r/S_{r0}) over time during a rainfall test, which were obtained from small-scale model tests with and without freeze-thaw action. Here, the S_r/S_{r0} is

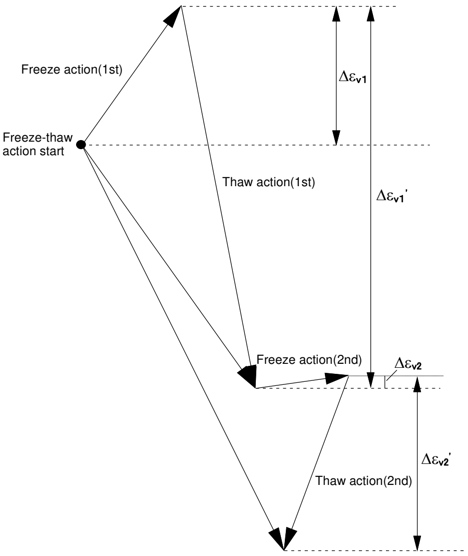


Fig. 11. Strain vector diagram at slope surface during 2 cycles of freeze-thaw action.

obtained by dividing the degree of saturation (S_r) at a given time by the initial degree of saturation (S_{r0}). The degrees of saturation in both tests are gradually increasing with the increase of rainfall, but suddenly decreasing after slope failure. From the results, it can be pointed out that one of the causes of slope failure is the increase in degree of saturation. In particular, there is a possibility that the thawing process has an influence on the failure mechanism because the degree of saturation in the frozen soil layer suddenly increases from low condition to high condition during thawing. Whereas, there are some differences in the elapsed time until failure and degree of saturation depending on freeze-thaw history. For example, the elapsed time (t = 105 sec) in the test with freeze-thaw action is 9 times faster than that (t = 876 sec) in the test without freeze-thaw action, and degree of saturation (S_r = 26.6 %) in the former test is lower than that in the latter test (S_r = 26.6 %). Moreover, from the comparison of the shapes of failed slope, it is revealed that the depth of slip surface of the slope subjected to freeze-thaw action becomes shallow as compared with that without freeze-thaw action. These indicate that the freeze-thaw action seriously affects the occurrence and mechanism of slope failure.

Figures 11 depicts the schematic of the typical change in strain vectors at the slope surface through 2 freeze-thaw process cycle (N_f). Note that Ishikawa et al. (2008) indicated that the secant shear modulus of a volcanic coarse-grained soil decreases with the increment in N_f irrespective of effective confining pressures (σ_c') and its reduction ratio converges at around N_f = 2. At the first cycle, the deformation at the subsurface layer of model slope develops mainly in the direction perpendicular to slope surface in case of temperature drop, and then the frozen soil subsides in the nearly vertical direction while thawing in case of temperature rise. On the other hand, at the second cycle, the directions of deformation behaviour during both freezing and thawing change downward as compared with the direction at the first cycle, since the first freeze-thaw action may form loose soil structure and decrease the shear strength as compared with those before freeze-thawing. An upward vertical strain at the slope surface caused by frost heave becomes smaller with increasing N_f. Accordingly, from the connection diagram of strain vectors, it can be recognized that though a subsurface layer of model slope upheaves in a direction normal to the slope surface during temperature drop and subsides in the nearly vertical direction during temperature rise, such deformation behaviour of soil slope varies depending on the freeze-thaw history, and the effect of freeze-thaw action is remarkably significant at the first cycle. These results qualitatively agree well with past experimental researches on cyclic frost-heave tests of clay and silt (Eigenbrod 1996, Hui and Ping 2009).

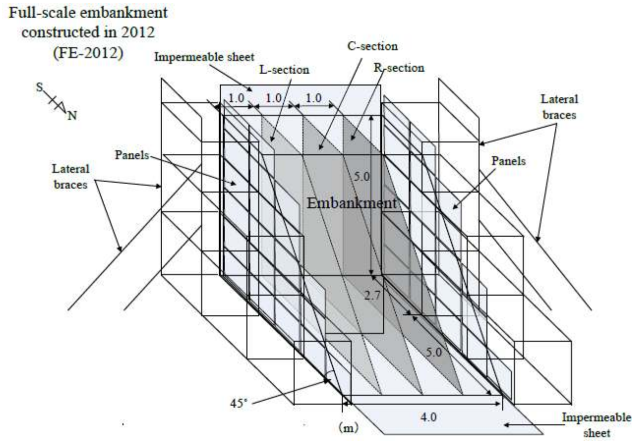


Fig. 12. Geometry of model embankment along with installed monitoring instruments.

2.4 Full-scale model test

Matsumura (2014) performed long-term measurement on the behaviour of a model embankment constructed using a coarse-grained volcanic soil at Sapporo in order to examine the failure mechanism of the embankment slope subjected to freeze-thaw and rainfall. The slope has a height of 5 m, 7.7 m in length, 4 m in width and a slope angle of 45° as given in Figure 12. A long-term behaviour of the slope has been monitored with thermometers, soil moisture sensors and tensiometers for temperature, water content and pore water pressure (PWP) respectively as shown in Figure 13. These measurement instruments were installed at every 0.2 m depth from surface up to 1.5 m deep. The monitoring commenced on November 9, 2012. During the initial day, the slope had a dry density of 0.98 g/cm^3 to 1.06 g/cm^3 with a corresponding water content (w) ranging from 41.2 % to 43.5 %. Furthermore, in order to induce the slope failure through excess water, a constant amount of water (1 m^3/day) has been supplied

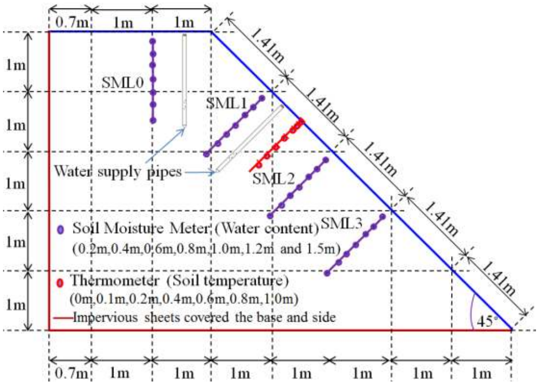


Fig. 13. Installed monitoring instruments in cross sections.

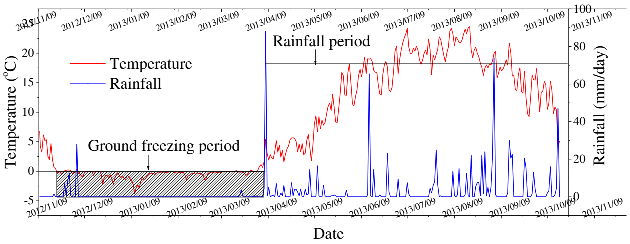


Fig. 14. Temperature and rainfall in full-scale model test.

to the slope using a water tank and water supply pipes. The water has been supplied to the slope using water supply pipes installed in different sections.

The measured temperature and rainfall data for the entire monitoring period is given in Figure 14. From the measurement of ground temperatures at different depths, it was estimated that the frost penetration depth would be 0.2m. Figure 15 shows the fluctuation of water content at different depths from the day of slope construction until failure. Note that the depth of slip surface ranges from 0.6 m to 0.8 m. From Figure 15, it can be observed that the water content tends to decrease for initial 150 day of time. The decreasing water content describes the freezing phenomenon. Due to penetration of freezing isotherm into the soil ground the water content of the soil reduces as the water concealed in the soil particles starts to form ice. Meanwhile, when the ground temperature increases more than zero, the frozen water in the soil particles starts melting, which results in increase in overall water content of the slope. Furthermore, the rainfall infiltration adds more amount of increase in water content. For example, after the end of freezing period, there was a heavy rainfall around 09-04-2013 and the corresponding temperature on that day is above 0°C (Figure 14). This rainfall should eventually increase the water content of the slope as observed from Figure 15. Starting that day the water content of the slope gradually increases whenever there was rainfall. From this observation, it is clear that increase in water content of the slope is more rigorous during the thawing period due to snowmelt and rainfall infiltration.

The failure of the slope has been observed on October 17, 2013 as shown in Figure 16. It is evident that the local failure was progressively induced from the area of high water content. The maximum value of water content in the failed slope was 55 %. Considering the results, it is concluded that the slope failure can be predicted if the changes in water content of the slope are estimated by field monitoring.

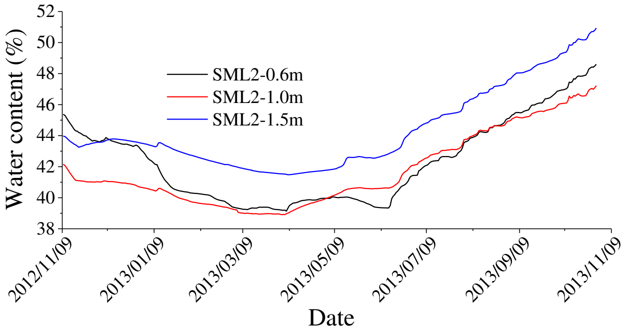


Fig. 15. Typical changes in water content in full-scale model test.

Fig. 16. Slope failure observed at October 17, 2013.

3 BEHAVIOUR OF VOLCANIC SOILS SUBJECTED TO FREEZE-THAWING

3.1 Review on previous researches

Up to now, a large number of experimental studies have been conducted on the mechanical behaviour of high frost-susceptible geomaterials, such as clay and silt (Aoyama et al. 1977 & 1979, Nishimura et al. 1990, Ono and Wada 2003, Kawaguchi et al. 2013). For example, Aoyama et al. (1979) showed that in an overconsolidated cohesive soil with a high silt content, freeze-thaw action under undrained conditions causes the cohesion to decrease, but the internal friction angle does not change. Aoyama et al. (1977) also demonstrated a striking reduction in the unconfined compressive strength due to freeze-thaw sequences depending on the water content of the specimen and the number of freeze-thaw cycles. The reduction was shown to be due to factors such as lower density and the development of microcracks inside the specimen. Ono and Wada (2003) reported a series of undrained triaxial tests on saturated cohesive soils exposed to freeze-thaw sequences. For normally consolidated clay,

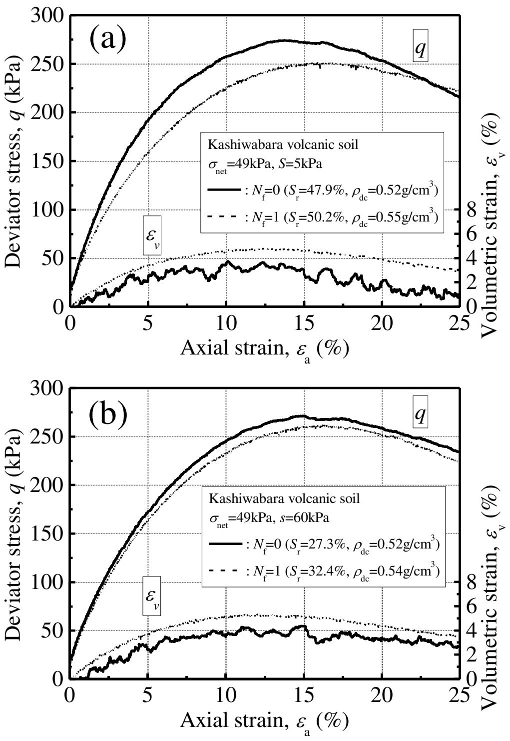


Fig. 17. Results of freeze-thawing triaxial compression tests (a: *s* = 5 kPa, b: *s* = 60 kPa).

the strength increased, showing a behaviour similar to that of overconsolidated clay. For clay with a high overconsolidation ratio, the degree of overconsolidation decreased. This indicates that the effect of freeze-thaw action on the shear behaviour of clay depends on its overconsolidation ratio. These researches indicate that the freeze-thaw action has strong influences on the deformation-strength characteristics of the soils. On the other hand, studies on freeze-thaw in non-frost-susceptible geomaterials, such as cohesionless soils, have mainly been conducted for the purpose of increasing the reliability of freezing sampling. Goto (1993) revealed that when a non-frost-susceptible geomaterial is frozen under drained conditions and beyond a certain confining pressure, the liquefaction strength and shear modulus of the thawed samples under a small strain are approximately the same as those prior to freezing. It can be seen from these studies that the effect of the freeze-thaw action is a popular area of research, resulting in various findings. However, little attention has been paid to non-frost-susceptible crushable geomaterials, such as the volcanic coarse-grained soils spread across Hokkaido.

3.2 Deformation-strength characteristics of freeze-thawed volcanic coarse-grained soils

Ishikawa et al. (2010) developed a new triaxial apparatus that can simulate freeze-thaw sequences similar to those experienced by in-situ soils in cold regions before triaxial compression tests, and discussed the influence of the freeze-thaw action on the mechanical behaviour of unsaturated volcanic coarse-grained soils, wherein significant particle crushing takes place during the loading processes, by performing a series of freeze-thawing triaxial compression tests on volcanic coarse-grained soils under different freeze-thaw histories and different degrees of saturation.

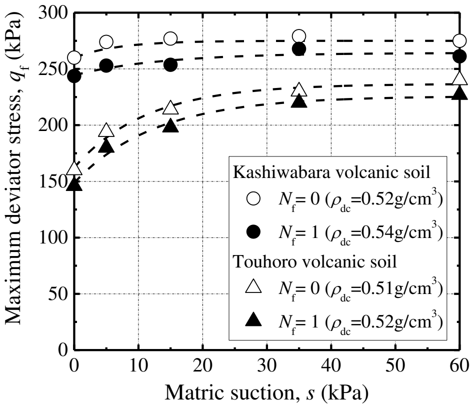


Fig. 18. Influence of freeze-thaw action on peak shear strength.

Figure 17 shows typical relationships of freeze-thawed specimens (number of freeze-thaw process cycles, $N_f = 1$) and non-freeze-thawed specimens ($N_f = 0$) between axial deviator stress (q), volumetric strain (ε_v), and axial strain (ε_a), which were obtained from consolidated drained (CD) tests under different matric suction (s). The volcanic coarse-grained soil exhibits peak strength at an axial strain of about 15 %, regardless of freeze-thaw histories. For plots with the same matric suction (s), the peak strength of the freeze-thawed specimen drops as compared with that of the non-freeze-thawed specimen, despite the fact that the increase in the density was caused by freeze-thawing. Moreover, a tendency of the specimen volume easy to contract in freeze-thawed specimens is observed. These results indicate that the freeze-thaw action has a serious influence on the deformation-strength characteristics of a volcanic coarse-grained soil, even if the soil lacks in frost heave characteristics. Figure 18 shows the relationships between the peak shear strength (q_f) and the matric suction (s) obtained from the test results on volcanic coarse-grained soils under different freeze-thaw histories. For plots with the same matric suction, the peak shear strength of a freeze-thawed specimen is smaller than that of the non-freeze-thawed specimen irrespective of matric suction or degree of saturation. Meanwhile, regardless of the freeze-thaw history, the peak shear strength decreases with decreasing matric suction. However, the influence of the water content on the peak shear strength of the crushable volcanic coarse-grained soils is insignificant in comparison with the influence of the freeze-thaw action. Note that the above-mentioned trends are not changed by the difference in a soil type.

The degradation in the deformation-strength

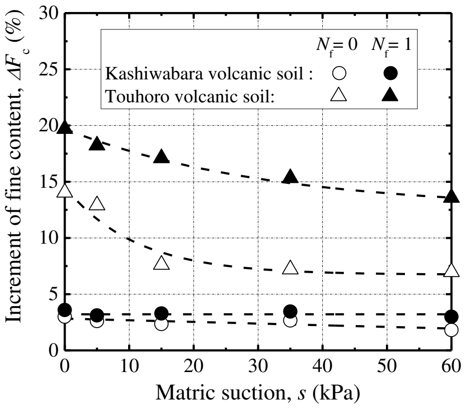


Fig. 19. Influence of freeze-thaw action on particle breakage.

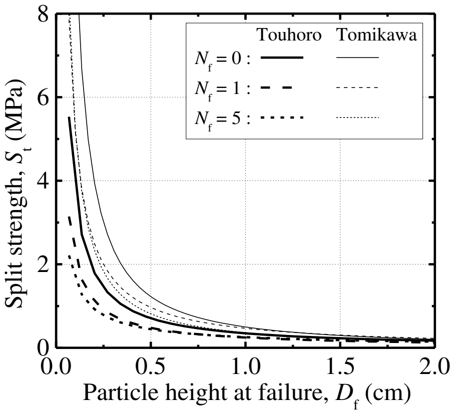


Fig. 20. Influence of freeze-thaw on single-particle hardness.

characteristics of saturated volcanic coarse-grained soils has to do with the increase in the fine content arising from freeze-thaw action because cyclic freeze-thaw action may seriously influence the rate of particle breakage (Ishikawa and Miura 2011). Figure 19 shows the relationships of freeze-thawed and non-freeze-thawed specimens between the increment of fine content (ΔF_c) through a test and the matric suction (s). It illustrates that particle breakage of both volcanic soils becomes more pronounced by the freeze-thaw action. The figure also shows a consistent increasing tendency of particle breakage with decreasing matric suction, which indicates that specimens with high water content are crushed to a greater extent than dry specimens. The tendency similar to the above-mentioned results can be observed in the relationships of peak shear strength to matric suction as shown in Figure 18. Accordingly, the particle breakage, mainly the particle breakage caused by freeze-thaw, is closely related to the decrease in peak shear strength of volcanic coarse-grained soils, under unsaturated conditions. In addition, as indicated from the results of single particle crushing tests in Figure 20, the freeze-thaw action weakens the single-particle hardness of volcanic coarse-grained soils, although the degree of weakening varies from one particle to another, and the embrittlement of the soil particles increases the proportion of particles broken during loading due to the freeze-thaw. Therefore, it can be supposed that one of the reasons why the freeze-thaw action reduces the shear strength of volcanic coarse-grained soils is that the soil particles become fragile through the freeze-thaw action, causing an increased overall particle breakage during the freeze-thaw triaxial compression tests, and thus, a further reduction in strength.

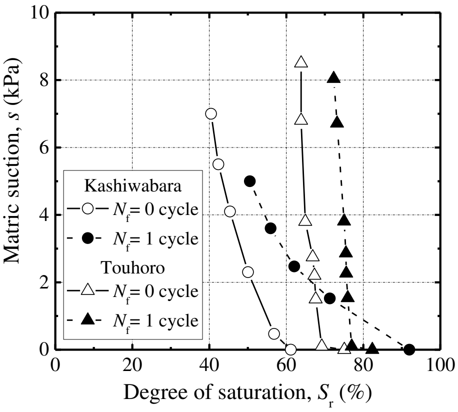


Fig. 21. Influence of freeze-thaw action on SWCCs.

From these results, it was revealed that the cyclic freeze-thaw action induce severe particle breakage during freeze-thawing and shearing in crushable volcanic coarse-grained soils, thereby decreasing the shear strength and deformation modulus of the soil. Therefore, the freeze and thaw of pore fluid is a point to be specially considered in evaluating the risk of surface failure at soil slopes in cold regions, regardless of frost heave characteristics of soil.

3.3 Water retention-permeability characteristics of freeze-thawed volcanic coarse-grained soils

Ishikawa et al. (2010) developed a new permeability apparatus for unsaturated soils that could be used to reproduce a freeze-thaw sequence to a cylindrical specimen, as experienced by in-situ soils in cold regions before a permeability test, and discussed the influence of the freeze-thaw action on the infiltration behaviour of unsaturated volcanic coarse-grained soils, wherein significant particle crushing takes place under low stress level, by performing a series of freeze-thawing water retention tests and freeze-thawing permeability tests along a drying process on two types of volcanic coarse-grained soils under different freeze-thaw histories and different degrees of saturation.

Figure 21 shows typical soil-water characteristic curves (SWCCs) for a freeze-thawed ($N_f = 1$) and non-freeze-thawed specimens ($N_f = 0$). For the plots with the same degree of saturation (S_r) in Figure 21, the matric suction (s), namely the water retentivity of a freeze-thawed specimen rises as compared with that of the non-freeze-thawed ones despite the fact that the latter has higher density than the former. However, the shape of the SWCCs with unclear air-entry values are almost unchanged, regardless of soil types. The reason

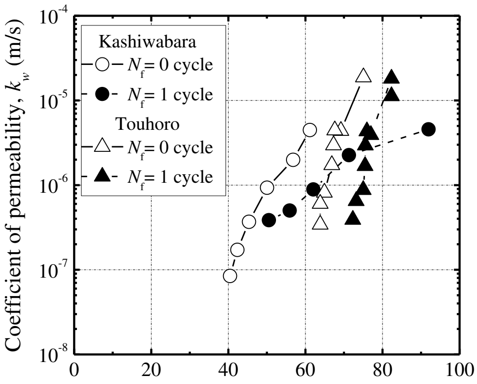


Fig. 22. Influence of freeze-thaw action on permeability.

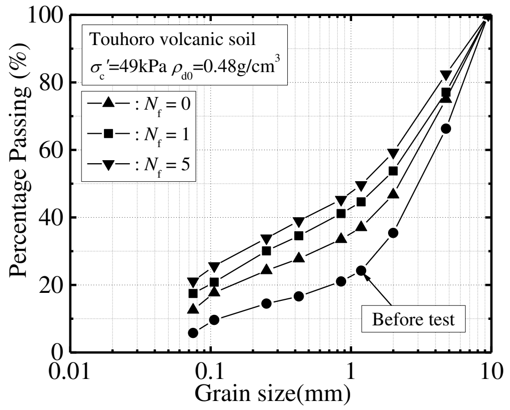


Fig. 23. Change in grain size distribution after freeze-thawing triaxial compression tests.

seems to be due to the grain refining of crushable volcanic coarse-grained soils mainly caused by freeze-thaw, which ultimately results in a gradual increase in the water retentivity of the soil. This tendency agrees well with a past research which reports the variation of the SWCC arising from the change in grain size distribution (Fredlund et al. 1997).

On the other hand, Figure 22 compares the relationships of the coefficient of permeability (k_w) to the degree of saturation (S_r), obtained from the same tests as Figure 21. The coefficient of permeability decreases inversely with the increase in the matric suction as expected. In addition, for the plots with the same degree of saturation (S_r), the coefficient of permeability (k_w) of the freeze-thawed specimen decreases as compared with that of the non-freeze-thawed one. The reason seems to be because of the grain refining of crushable volcanic coarse-grained soils caused by freeze-thawing as shown in Figure 23, which ultimately results in a gradual increase in the water retentivity and a gradual decrease in the permeability. These results indicate that the freeze-thaw action induces the increase in the fine content due to particle breakage at the fragmental volcanic soil ground, and thereby leads to the rise in the water retentivity and the degrade in the permeability. Therefore, the freeze-thaw action has a strong influence on the water retention-permeability characteristics of volcanic coarse-grained soils.

Table 2. Results of frost heave tests on volcanic fine-grained soil.

Water supply	σ_a (kPa)	u (°C/h)	S_{r0} (%)	s (kPa)	ξ (%)	U (mm/h)	U_h (mm/h)	$\Delta V_w/V$
open	2.5	0.2	86.0	9.2	73.7	0.63	0.73	0.557
open	2.5	0.4	73.4	26.4	21.4	2.22	0.67	0.171
open	2.5	0.8	65.4	51.4	23.7	2.84	0.95	0.184
open	5.0	0.2	81.7	13.6	55.8	0.77	0.69	0.423
open	10.0	0.2	76.1	21.3	53.0	0.64	0.64	0.415
open	10.0	0.4	69.0	37.6	27.8	1.62	0.63	0.133
open	10.0	0.8	70.0	34.6	15.8	3.62	0.89	0.123
open	50.0	0.2	81.0	14.4	25.9	0.98	0.34	0.229
open	100.0	0.2	92.7	3.8	16.9	0.64	0.17	0.144
open	200.0	0.2	82.7	12.5	3.3	1.07	0.03	0.034
close	2.5	0.2	82.5	12.7	15.1	2.28	0.64	0
close	5.0	0.2	78.9	17.1	15.7	2.44	0.56	0
close	10.0	0.2	76.6	20.5	14.4	2.73	0.53	0

3.4 Frost heave characteristics of volcanic fine-grained soil

Ishikawa et al. (2015) examines the influence of nonlinear factors such as the overburden pressure, freezing velocity, degree of saturation, and water supply system on the frost heave behaviour of volcanic fine-grained soils, which are considered as the factors that strongly influence the frost heave amount of soils. To this end, we first performed a series of frost heave tests on a frost-susceptible geomaterial under different test conditions and performed a water retention test of the frost-susceptible geomaterial to examine the water retentivity characteristics of the soil in the unsaturated condition. Based on the test results, we discussed the influences of the test conditions on the frost heave amount of the volcanic fine-grained soil. Additionally, we proposed an estimation method for the frost heave amount of unsaturated subsurface soils under low overburden pressure, and discussed the applicability and usefulness of the proposed estimation method by comparing the results of the frost susceptibility tests with the estimation results.

Table 2 summarizes the results of frost heave tests on a volcanic fine-grained soil under different test conditions. Here, an open-system permits free intake and discharge of water during a test, whereas a close-system prohibits it. From Table 2, it is observed that the frost heave behaviour of this volcanic fine-grained soil strongly depends on the experimental conditions. For example, in the frost heave tests with open-system freezing, the low overburden pressure (σ_a), slow cooling rate (u), and high initial degree of saturation (S_{r0}) tend to increase the frost heave ratio (ξ), frost heave rate (U_h), and absorbed water volume during freezing (ΔV_w), which indicates the increase in the frost heave amount. However, in the frost heave tests with close-system freezing, the influence of the overburden pressure on the frost heave ratio is hardly noticeable. Furthermore, when comparing the test results under different cooling rates, it is found that slower cooling rate of 0.2 °C/h leads to a larger frost heave ratio than the other cooling rates, whereas the test results at cooling rates of 0.4 and 0.8 °C/h are almost identical irrespective of the overburden pressure. This indicates that the influence of experimental conditions such as overburden pressure on the frost heave behaviour can hardly be recognized in the frost heave tests at a fast cooling rate. Accordingly, insufficient water supply resulting from the fast cooling rate and close-system freezing results in the growth inhibition of the ice lens, regardless of the overburden pressure. In this case, the effects of the freezing velocity and water supply system on the frost heave behaviour are equivalent to that of the water volume absorbed to soils during freezing. Therefore, it seems reasonable to consider that three independent factors among all the experimental conditions (the overburden pressure, the initial degree of saturation, and the absorbed water volume during freezing) strongly affect the frost heave amount of a volcanic fine-grained soil.

To reproduce the frost heave phenomenon of soils under saturated and unsaturated conditions, based on the above-mentioned results and consideration, we proposed a simple frost heave model as given in Equation 1.

$$\varepsilon_f = \frac{\varepsilon_{f\,\max} S_{e0}}{\varsigma\left(\sigma'_a + p_s\right) + 1} + \zeta \frac{\Delta V_w}{V_0} \tag{1}$$

$$S_{e0} = \frac{S_{r0} - S_{rr}}{S_{rs} - S_{rr}} \tag{2}$$

where $\varepsilon_{f\max}$: maximum frost expansion strain of soil (constant parameter), S_{e0}: initial effective degree of saturation (Equation 2), σ'_a: the effective overburden pressure, p_s: suction stress ($p_s = S_{e0} \cdot s$), s: matric suction, $\Delta V_w / V_0$: water volume absorbed to a unit volume of soil from the surroundings per unit time, V_0: initial volume of soil, S_{r0}: initial degree of saturation, S_{rr}: residual degree of saturation, S_{rs}: maximum degree of saturation, and ς and ζ: constant parameters. Note that the frost expansion strain (ε_f) is closely related to the frost heave ratio (ξ) obtained from the frost heave tests of soils. In Equation 1, a simple frost heave model can predict the frost expansion strain (ε_f), which is generated by the frost heave of soils over the temperature range of 0 °C to the final freezing temperature of soil (T_f) at which the change in the unfrozen water content converges during a temperature drop in terms of the initial water content, Bishop's effective stress, and water absorption during freezing.

Figure 24 compares the actual frost heave ratio (ξ) measured in frost heave tests under various experimental conditions with that calculated by Equation 1. The comparison reveals that the plots estimated by Equation 1 show a narrow range of variation against the 1:1 line of the ratio of the estimated value to the measured one. This indicates that the simple frost heave model expressed in Equation 1 can well reproduce the dependency of the frost heave behaviour of the volcanic fine-grained soil on the overburden pressure, cooling rate, initial degree of saturation, and water supply system, irrespective of experimental conditions. This indicates greater applicability of the simple frost heave model to the frost heave behaviour estimation of geomaterials.

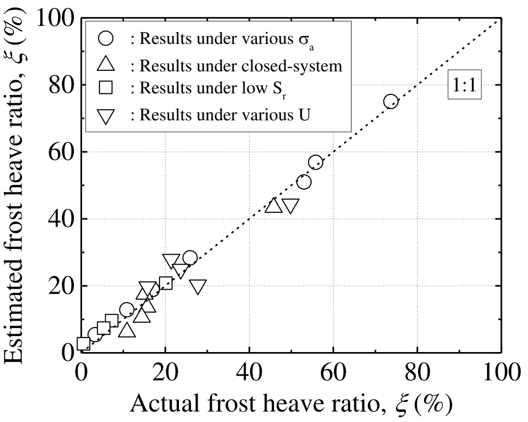


Fig. 24. Applicability of simple frost heave model.

4 MECHANISM OF VOLCANIC SOIL SLOPE FALILURE IN COLD REGEIONS

4.1 Review on previous researches

In general, a coupled hydro-mechanical analysis is employed for numerical simulations of rainfall-induced slope failure occurred in warm-temperate regions. However, as mentioned above, it is indispensable for the precise prediction of slope failure occurred in cold regions at snow-melting season to take into account the influence of freeze-thaw action on the mechanical behaviour of soil ground. Accordingly, it is more desirable for numerical models simulating slope failure induced by water infiltration due to rainfall and/or snowmelt to incorporate a thermal analysis, which can reproduce the freeze-thaw process of soil ground, into a conventional coupled hydro-mechanical analysis.

So far, some analytical studies have been made on the application of numerical simulations on the thermo-hydro-mechanical behaviour of geomaterials. For examples, Neaupane and Yamabe (2001) proposed a nonlinear elasto-plastic analysis by a two-dimensional finite element (FE) analysis which can depict the behaviour of rocks during freezing and thawing, and Kimoto et al. (2007) proposed a coupled thermo-hydro-mechanical (THM) FE analysis with the thermo-elasto-viscoplastic model which can simulate the thermal consolidation of heating water-saturated clay. Moreover, Nishimura et al. (2009) proposed a fully coupled THM FE analysis that simulates the behaviour of water-saturated soils during freezing and thawing, and demonstrates the performance of the numerical simulations in the in-situ pipeline frost heave tests. Zheng et al. (2014) proposed a simple frost heave model to assess the frost susceptibility of different soils using a few soil parameters, and demonstrates the applicability to a rational explanation of the pumping-enhanced frost heave mechanism in high-speed railway embankments.

In this way, most of THM simulations for soil ground focus on the design and evaluation of frost-heaved pipeline, transportation facilities, ground freezing method, and storage of liquefied natural gas (LNG) in underground chambers (Nishigaki et al. 1996, Ueda et al. 2007). In addition, Ishikawa et al. (2015) conducted numerical simulations for cut slope around a drain ditch on berm and pavement structure subjected to freeze-thaw actions with a coupled thermo-hydro-mechanical (THM) FE analysis (Ishikawa et al. 2014) in order to evaluate the interaction between frost-susceptible soil ground and structures during freeze-thawing. However, little attention has been given to the mechanical behaviour of frost-heaved soil slope during thawing, and the comprehensive studies on the mechanism of slope failure occurred in snow-melting season, which includes laboratory element test, laboratory model test, field measurement and numerical simulation, have hardly been seen to date. Therefore, the development of a numerical model that can simulate the thermo-hydro-mechanical behaviour of soil ground during freezing and thawing has been a subject of study for a long time in frost geotechnics.

4.2 Slope stability analysis

Subramanian et al. (2015) proposed an evaluation method for the stability of volcanic soil slopes considering the effects of coupled freeze-thaw and rainfall infiltration. They examined the variation in water content due to freeze-thaw action and rainfall infiltration of the volcanic soil slope model, which simulates the full-scale model slope shown in Section 2.4, by performing freeze-thaw and rainfall infiltration analyses. They also performed a slope stability analysis using the limit equilibrium method through coupling the water content of the slope with the shear strength theory for unsaturated soils (Bishop 1959; Fredlund et al. 1978) in order to obtain the safety factor of the slope during one year. Based on the comparison of the numerical results with the measured data, the advantages and shortcomings in simulating the freeze-thaw coupled rainfall slope failures using the proposed methodology were discussed.

The transitions of the safety factor and water content from the day of embankment construction until slope failure were estimated as given in Figure 25. During freezing period, the safety factor of the slope reduces initially and then maintained constant throughout the freezing term and again reduces due to rainfall and melting of ices then finally reduces less than 1.0 around the day of actual slope failure. A clear difference is observed between the safety factor for freeze-thaw and rainfall analysis and rainfall alone analysis demonstrating the effect of freeze-thaw actions on slope stability. Accordingly, the freeze-thaw and rainfall infiltration analysis proposed by Subramanian et al. (2015) is useful in order to analyze the fluctuation of the safety factor due to the change in water content (Figure 25b) throughout the period of freeze-thaw cycle and successive rainfall.

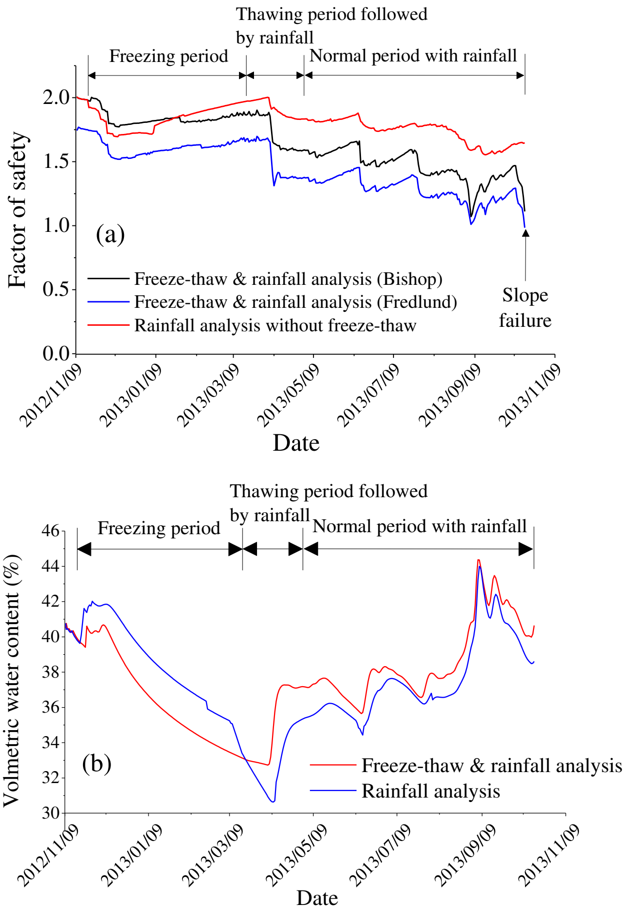


Fig. 25. Results of FE simulations for entire slope failure process. (a: safety factor, b: water content).

In general, the water content in soil during failure is more crucial to analyze the slope stability because the water content seriously influences the shear strength of unsaturated soils. Figure 26 compares the water content distribution at the day of failure obtained from the numerical analysis with the measured results. Though the water content variedly distributes all through the slope, it can be recognized that the maximum degree of saturation lies at the bottom of the slope. The physical slope model reaches a maximum degree of saturation up to 95% at the bottom part. Similar water content distribution has been obtained from numerical simulation. In numerical model the slope gets completely saturated at the bottom. This observation suggests that the water content distribution of the slope can be predicted for anticipated freeze-thaw cycles and rainfall infiltration using the method proposed by Subramanian et al. (2015). In addition, the estimated slip surface and factor of safety during the day of

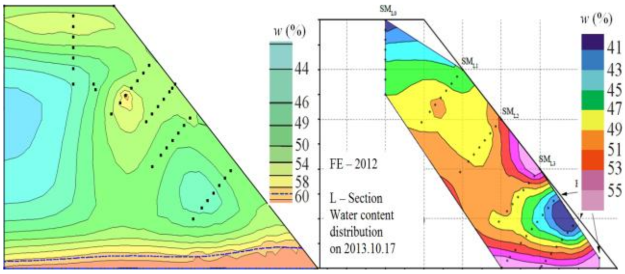


Fig. 26. Distribution of water content at the failure (left: FE analysis, right: physical slope).

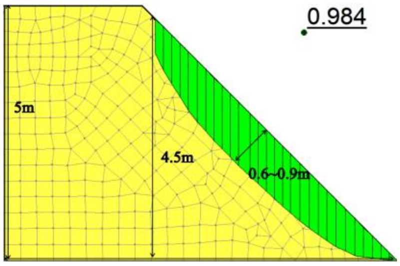


Fig. 27. Slip surface estimated by numerical analysis.

failure is given in Figure 27. The slip surface derived from the numerical analysis agrees well with the observed slip surface given in Figure 16. These results provide rational satisfaction and demonstrate the applicability of the analytical procedure. Therefore, it seems reasonable to conclude that if an agreeable prediction of the water content distribution is established, the stability of the slope subjected to freeze-thaw actions and rainfall infiltration can be evaluated by the simple limit equilibrium method considering the shear strength theory for unsaturated soils, which directly relates the water content distribution inside the slope to the stability.

4.3 Frost heave – thaw analysis

Ishikawa et al. (2008) performed a series of coupled thermo-mechanical (TM) FE analysis to examine the failure mechanism of volcanic soil slope suffered from freeze-thaw action at snow-melting season. This section presents a numerical simulation to reproduce the mechanical behaviour of frost-heaved soil slopes during freezing and thawing. A numerical simulation of the freeze-thawing test for model slope in Section 2.3 was conducted with the coupled TM FE analysis. Figure 28 shows the size, dimension and boundary condition of two-dimensional FE model under plane-strain condition, together with the element mesh which consists of four-node quadrilateral elements. A slope of FE model, which material is a volcanic coarse-grained soil, is the same size as that of the actual model test. Table 3 summarizes the input parameters of FE analysis. Note that the input parameters were set by referring to the experimental conditions of the actual model test, the results of various kinds of laboratory element tests for Kashiwabara volcanic soil under the experimental conditions similar to the model test, and the common values employed in past researches and the like.

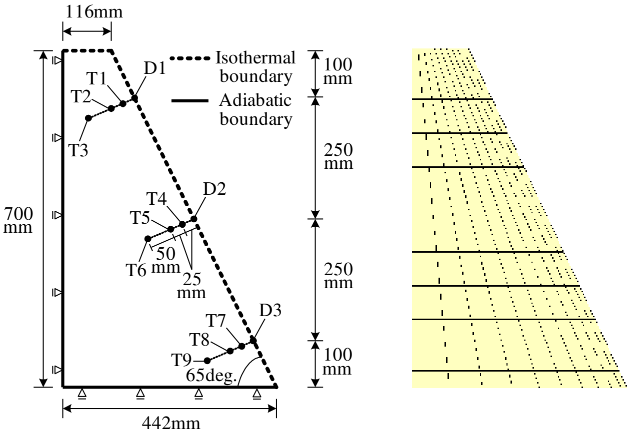


Fig. 28. Schematic diagram of two-dimensional FE model (left: size, dimension and boundary condition, right: element mesh).

Table 3. Input parameters of FE simulation.

Name of input parameter	Value
Dry density of soil ρ_d	0.45 g/cm^3
Water content w	50.0 %
Deformation modulus before freeze-thawing E_0	320.0 kPa
Poisson's ratio ν	0.30
Decreasing ratio of rigidity by freeze-thaw action b	0.90
Heat capacity at constant volume of soil C_s	1.26×10^{-6} J/m^{3}K
Thermal conductivity of soil λ	2.45×10^{3} J/mhK
Coefficient of thermal expansion of soil α_s	5.0×10^{-6} 1/K
Heat of solidification per unit volume of soil L_w	7.54×10^{7} J/m^3
Final freezing temperature T_f	-1.0 °C
Maximum frost expansion strain of soil ε_{fmax}	10.0 %
Maximum thaw contraction strain of soil ε_{tmax}	0.0 %

A FE simulation of freeze-thawing test for model slope was performed as follows. First, an initial temperature of 20 °C equal to the room temperature of laboratory was set to all elements under a prescribed thermal boundary condition, and the gravity force of 9.80 m/s^2 was applied to estimate the stress state of all elements. Here, the state of this FE model is called "the initial state". Next, for representing an installation of dry ices on the slope surface in the model test, the temperature of isothermal boundaries on the slope surface was dropped into -35 °C and kept constant for 8 hours. Finally, for simulating the thawing process of the frozen soil slope after removing dry ices, the temperature of isothermal boundaries was set at the room temperature and kept constant for 9 hours.

Figure 29 compares time histories of ground temperature (T) obtained from FE simulation for three measuring points (T4 to T6 in Figure 28) with those of the experimental results for the middle part of model slope. The FE simulation well reproduces the change of ground temperature with time during freeze-thaw, irrespective of position in the model slope. Figure 30 shows temperature distributions inside the soil slope of FE model at four different elapsed times (t). A frozen soil layer parallel to the slope surface was formed at the subsurface layer of FE model in freezing process, and it was gradually thickening with time during temperature

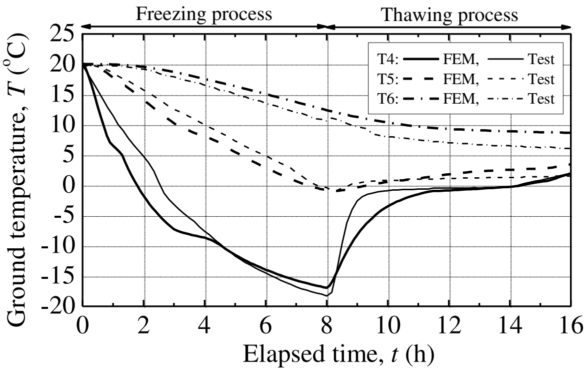


Fig. 29. Comparison in ground temperature between FE simulation and experimental results.

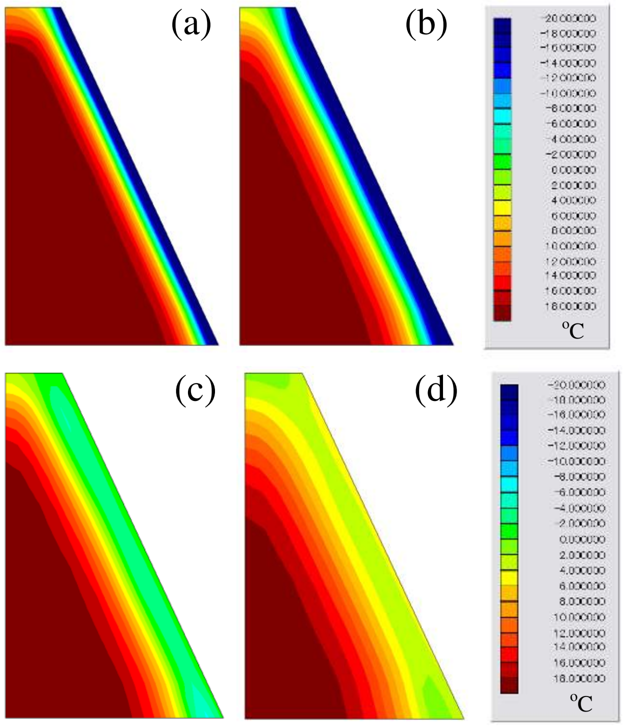


Fig. 30. Contour maps of ground temperature in FE simulation (a: at t = 3 hrs., b: at t = 8 hrs., c: at t = 10 hrs., d: at t = 17 hrs.).

drop. Whereas, though the frozen soil layer was gradually thawed from the slope surface during temperature rise, after a lapse of about 2 hours into thawing, a thin frozen soil layer parallel to the slope surface was observed inside the soil slope. The slope behavior of the FE model during thawing corresponds with the actual ground condition in thawing season as shown in Section 2.2.

Figure 31 shows the deformation behavior of FE model at freezing (t = 8 hours) and at thawing (t = 17 hours), respectively. The figure also shows typical examples for the displacement vectors of some nodes close to the slope surface. Here, a displacement vector is defined as the movement of a given node in FE model from the initial state to the given state during freeze-thawing. The finite element located in the frozen area near the slope surface tends to expand in freezing process and contract in thawing process, though the slight differences in the direction of frost heave and thaw settlement do exist among displacement vectors owing to the effects of boundary conditions. Consequently, the surface layer at the middle of the slope upheaves in a direction normal to the slope surface during temperature drop and subsides in the nearly vertical direction during temperature rise. This indicates that the freeze-thaw action causes the residual displacement parallel to the slope surface at a subsurface layer where frost heave occurs as mentioned in Section 2.2. Besides, Figures 32 show contour maps of the increment in shear strain inside the soil slope of FE model from the initial state to two different elapsed times (t). The shear strain was developed at the subsurface layer of FE model by freezing, and the shear strain remains there after the temperatures of all elements became over 0 °C. This development of shear strain seems to be caused by a tendency that the deformation in the vertical direction due to the gravity force during thawing becomes outstanding at the subsurface layer. These results qualitatively agree well with the results of the above-mentioned field measurement and small-scale model tests. Besides, it is worth noting that a conventional FE analysis without incorporating an algorithm which considers the frost heave behavior into the analytical procedure could not reproduce the above-mentioned slope behavior during freeze-thawing. Therefore, it seems reasonable to

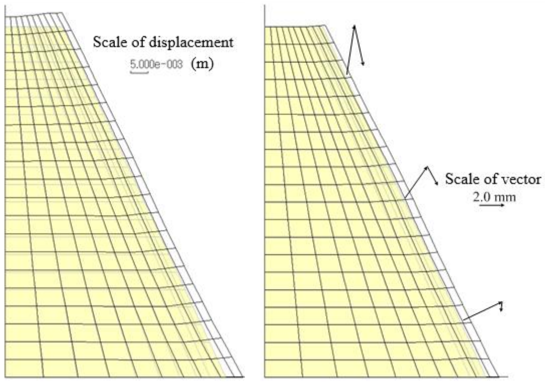


Fig. 31. Deformation behavior during freeze-thawing with displacement vectors (left: at t = 8 hrs., right: at t = 17 hrs.).

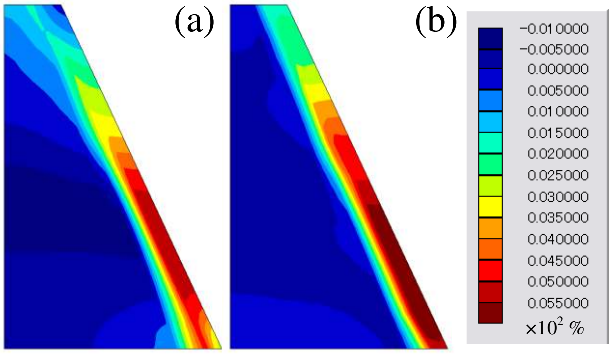


Fig. 32. Contour maps of increment in shear strain in FE simulation (a: at t = 8 hrs., b: at t = 17 hrs.).

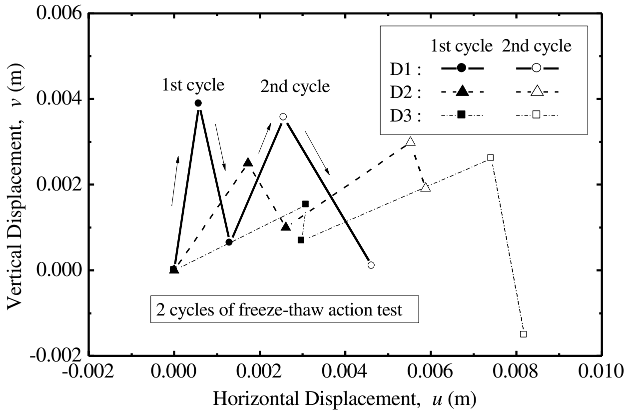


Fig. 33. Path taken by nodes at slope surface during 2 cycles of freeze-thaw action.

conclude that the coupled analysis presented in this study is an effective method to simulate the slope behavior of frost-susceptible soil ground during freezing and thawing.

In order to examine the applicability of a proposed FE simulation to the deformation behavior of soil slope during cyclic freeze-thawing, typical paths taken by three nodes on the slope surface (Figure 28) during 2 cycles of freeze-thaw action are shown in Figure 33. The deformation behavior of FE model at the second cycle is identical to that at the first cycle, though the slight differences in the direction of frost heave and thaw settlement between both cycles do exist. Comparing Figure 33 to Figure 11, the FE simulation has captured the distinctive features of the deformation behavior of soil slope during cyclic freeze-thawing in the actual model test. Therefore, it appears reasonable to conclude that the newly developed coupled FE analysis has a high applicability to the numerical simulation for repeated solifluction process observed at freeze-thawing soil slope.

5 INFLUENCING FACTORS ON VOLCANIC SOIL SLOPE FALILURE IN COLD REGEONS

5.1 Mechanism of slope failure in cold regions

Figure 34 shows three types of mechanisms for surface slope failure, which occurs at the untreated slope due to frost heaving and thawing observed in the snowy cold region. From the viewpoint of the mechanism, these slope failures have been divided into two main classes, namely slope failure at snow-melting season (from April to May) and slope failure at heavy rainfall during summer season (from August to September). Especially the former one could be further classified into the surface-flow type and the inside-erosion type. It should be noted that the mechanism of slope failure explained as following also fits for cut slope and embankment. Regardless of frost susceptibility, the slope failure may happen at the soil ground subjected to the freeze-thaw actions.

(a) Surface-flow type slope failure at thawing season

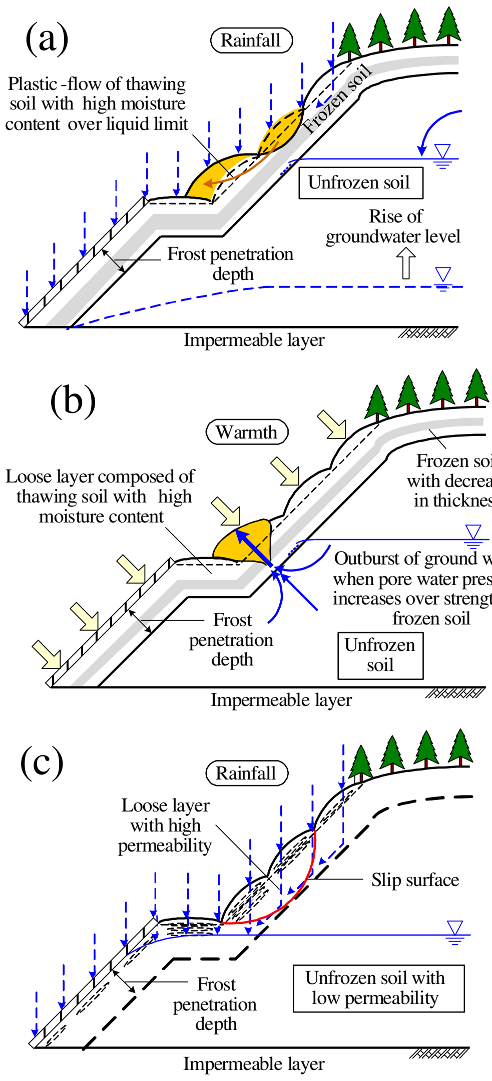


Fig. 34. Slope failure mechanism in cold regions (a: surface-flow type, b: inside-erosion type, c: rainfall-induced type).

In a frost-susceptible soil ground, the upper freeze-thawed subsurface layer (permeable layer) will be at a loose state due to cavitation caused by ice lens melting in the thawing season, though the hard frozen soil layer (impermeable layer) still exists at the deep part. Consequently, a two-layer structure, which consists of upper loose thawed soil layer and lower hard frozen soil layer, is generated. Besides, due to the snowmelt and the ice lens melting, the upper thawed surface soil tends to exhibit a high water content over liquid limit of the soil, which causes the subsurface failure readily than usual. In this case, the water infiltration arising from rainfall and snowmelt would trigger a surface failure regarding a boundary surface between the permeable layer and the impermeable layer of the two-layer structure as a slip surface.

(b) Inside-erosion type slope failure at thawing season

There is an impermeable frozen soil layer parallel to the slope surface formed during winter season.

When the water permeated from the backward of soil slope is supplied to the soil ground behind the frozen soil layer, the ground water level rises, thereby increasing pore water pressure as compared with that at the unfrozen soil ground. In this case, as the thickness of impermeable frozen soil layer decreases after frozen soil thawing during a rise in the air temperature in spring season, the weakest part of the thin frozen soil layer which cannot bear the increasing pore water pressure breaks partially. As a consequence, surface failure followed by inside erosion and piping is triggered by the outburst of ground water with high pore water pressure through the small hole of thin frozen soil layer.

(c) Rainfall-induced type slope failure at normal season

A two-layer structured ground with upper high permeable loose soil layer and bottom low permeable dense soil layer is formed as a result of lasted frost heave-thawing from winter to spring. The boundary of this two-layer structure can be identified in the soil slope shallower than the frost penetration depth, and it can exist even in the summer season after thawing season. Therefore, the rainfall infiltration into the soil slope causes the increase in the water content pressure mainly at the upper loose soil layer because of the difference in the permeability. As the result, the surface failure regarding the boundary surface of two-layer structure as a slip surface occurs readily as compared with soil slope without frost heaving. This type of slope failure is even larger in scale than the above-mentioned slope failure during snow-melting season.

5.2 Influencing factors of slope failure in cold regions

The reasons for surface slope failure on frost heaving-thawing received slope are explained as below (Figures 34 and 35). Although Figure 35a shows the state of slope in cold region from summer to autumn, the difference in slope failure mechanism between cold region and warm-temperate region is hardly recognized. However, in winter, soil ground freezes from the surface (Figure 35b) and thaws in spring (Figure 35c), which causes a difference in the slope failure mechanism (Figure 34). Following phenomena observed in soil ground subjected to freeze-thaw actions could be considered as primary factors for this difference.

- When the frost susceptibility of soils is different or the supply of underground water is different in case of the same soil, frost heaving amount variously alters. Such the difference in frost heaving amount makes the ground surface uneven.
- Frost heave is a phenomenon that ice lenses are formed at a frozen soil ground by suctioning water from unfrozen soil at the deep layer to the freezing fringe. Hence there are plenty of ice lenses distributed like vein through the ground. When the ice lens starts thawing as ground temperature rises in the early spring, soil ground shallower than frost penetration depth would be at a high water content state, thereby inducing the increase in the unit weight of soils and the decrease in the shear strength.

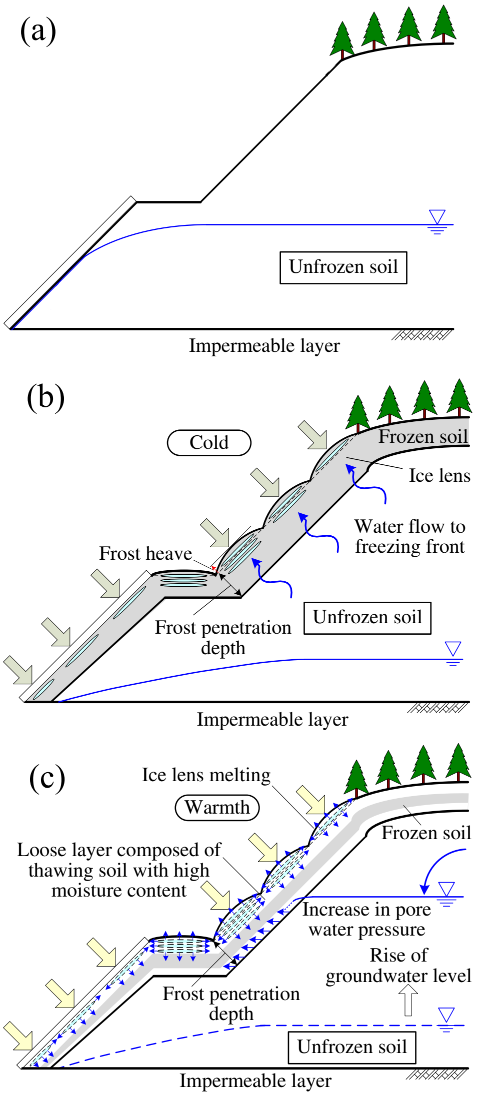


Fig. 35. Deformation of frost-susceptible soil slope through a year (a: from summer to autumn, b: in winter, c: in spring).

Moreover, an additional condition that a slope surface is not horizontal would induce some new phenomena as summarized below.

- Frost heave at a soil slope develops in the direction perpendicular to the slope surface, while frost heaved ground settles mainly in the vertical direction as mentioned in Section 2.1. As the result, a subsurface layer gradually becoming loose over time would be formed at the subsurface ground where the frost heave-thaw behaviour is repeatedly observed. According to past research (JGS

Table 4. Influencing factors of slope failure in cold regions.

Factor type		Factor name	In warm regions	In cold regions
Endogenous factors		Slope inclination	Affected	Affected
		Shear strength of soil	Affected	Affected
		Weathering velocity of soil and its stability	Affected	Affected
		Existence of slip surface and its formation	Affected	Affected
		Water catchment topography and ground water level	Affected	Affected
		Snowy cold climatic conditions	–	Seriously affected
		Frost susceptibility of soil	–	Seriously affected
Exogenous factors	Increase in sliding force	Shape change of slope	Affected	Affected
		Seismic motion	Affected	Affected
		Increase in unit weight of soil	Affected	Affected
	Decrease in shear resistance	Decrease in shear strength of soil	Affected	Affected
		Increase in pore water pressure	Affected	Affected
		Formation of loose soil layer due to frost heave	–	Seriously affected
		Change in physical properties of soil due to freeze-thaw	–	Seriously affected
		Change in mechanical properties of soil due to freeze-thaw	–	Seriously affected
		Formation of impermeable frozen soil layer	–	Seriously affected

Hokkaido branch 2004), it is reported that the thickness of above-mentioned loose soil layer in Hokkaido would be 25-50 cm on a cut slope facing north, 23-37 cm on a cut slope facing south, 40-58cm on an embankment facing north and 32-45 cm on an embankment facing south.

- When slope freezes from the surface and is covered by frozen soil with low permeability, the ground water level at the unfrozen soil ground behind the frozen soil layer would increase during thawing period of spring. In this case, while frozen soil layer gradually becomes thin due to thawing (Figure 35c), the inside-erosion type slope failure will occur. Especially, at the two-layer structured ground with upper high permeable loose thawed soil layer and lower impermeable frozen soil layer, the concentration of streamlines and the increase in seepage force observed at the upper part promotes the piping phenomenon and the inside erosion, thereby causing the progressive slope failure.
- Since an impermeable frozen soil layer parallel to the slope surface is formed at the deep subsurface part by thawing from the surface as the air temperature rises, a thawing soil which exhibits high fluidity and high water content is layered on the slippery frozen soil in early spring. For instance, in a muddy thawing soil layer with a water content even higher than the liquid limit, when a weak plane is formed at the discontinuous boundary of deformation-strength characteristics of soil such as the boundary between frozen soil layer and thawing soil layer, a surface-flow type slope failure during snow-melting season is likely to occur by the increase in the self-weight of soil and the decrease in the shear resistance of soil due to the rise of water content (Figure 34a).

When taking the above-mentioned influencing factors into consideration, the following information should be considered in order to precisely predict slope deformation in snowy cold regions caused by frost heave-thawing: a) which part of slope would freeze in winter, and how would the frost heave occur; b) how would the water content distribute in spring; c) how would deformation-strength and water retention-permeability characteristics of soils change through one year and so on.

5.3 Comparison to influencing factors in warm-temperate regions

By comparing the slope failure mechanism in cold regions with that in warm-temperate region, the endogenous factors and the exogenous factors of slope failure in cold regions can be summarized as given in Table 4. Note that there are two types of exogenous factors that produce the increase in the sliding force and the decrease in the shear resistance, respectively.

(a) Important factors for slope failure in warm-temperate regions are mainly summarized as follows:

[Endogenous factors]

- Slope inclination
- Shear strength of soil
- Weathering velocity of soil and its stability
- Existence of apparent and potential slip surface and its easiness for formation
- Water catchment topography and ground water level

[Exogenous factors]

- Shape change of slope due to erosion, excavation, and embankment
- Seismic motion
- Increase in unit weight of soil following increase in water content due to rainfall
- Decrease in shear strength of soil following increase in water content due to rainfall
- Increase in pore water pressure due to change in groundwater level and seepage flow, and rainfall

(b) Important factors for slope failure in cold regions are mainly summarized in addition to those in warm-temperate regions as follows:

[Endogenous factors]

- Snowy cold climatic conditions
- Frost susceptibility of soil

[Exogenous factors]

- Increase in unit weight of soil following increase in water content due to rainfall, snowmelt, and frost heave:
  Influx of snowmelt water and thawing of ice lenses would cause the increment in water content of soils, thereby inducing the increase in unit weight which increases the sliding force.
- Decrease in shear strength of soil following increase in water content due to frost heave, freeze-thaw, and snowmelt:
  Increment in water content caused by snowmelt and ice lens melting would induce decrease in matric suction, in other words, decrease in total cohesion of soil, which is directly related to the decrease in shear resistance as shown in Section 3.2.
- Changes in groundwater level and seepage flow, and increase in pore water pressure due to frost heave, freeze-thaw, and snowmelt:
  When an impermeable layer exists in soil slope, pore water pressure at the unfrozen soil ground behind the frozen soil layer will increase due to the rise of the ground water level as shown in Section 4.2. Furthermore, in soil ground where a loose soil structure has developed by freeze-thaw actions, streamlines are centralized due to high permeability of the soil, thereby increasing seepage force. These changes would influence the sliding force and shear resistance of soil.
- Formation of loose soil layer due to frost heave and freeze-thaw:
  Cavitation of ice lens inside frozen soil with thawing makes the soil skeleton loose, and in other words, causes the decrease in soil density, thereby inducing the decrease in shear strength of soil.
- Changes in physical properties due to frost heave and freeze-thaw:
  Physical properties of clay and silt subjected to freeze-thaw actions tend to become hydrophobic, to decrease the amount of drying shrinkage, and further to decline the liquid limit as well as the water retentivity. These changes would affect the sliding force and the shear resistance of soils.
- Change in deformation-strength and water retention-permeability characteristics due to frost heave and freeze-thaw:
  Although the effect of freeze-thaw history differs depending on overconsolidation ratio of clay (Section 3.1), it does affect deformation-strength and water retention-permeability characteristics of soils as show in Section 3.2 and 3.3. These changes would affect the sliding force and the shear resistance of soils.
- Formation of impermeable frozen soil layer due to frost heave and freeze-thaw:
  Since frozen soil layer can be considered as an impermeable layer, water content of soil ground shallower than frost penetration depth increases due to ice lens melting and rainfall, which would induces the increase in unit weight of soils and the decrease in the shear strength. Besides, since thawing soil, which exhibits high fluidity and high water content, exists over the slippery frozen soil layer, the slope failure regarding the boundary of two-layer structure as a potential slip surface would occur easily in thawing season as compared with usual.

In general, the factors which seriously affect stability of soil slope in warm-temperate regions are mainly the generation of pore water pressure, the decrease in shear strength of soil, and the increase in unit weight of soil (Kitamura and Sako 2010). In addition to these three influencing factors, the mechanism of slope failure in snowy cold regions is dominated by snowmelt, freeze-thaw actions, and frost susceptibility of soil. The combination of above-mentioned six influencing factors induces various types of geohazards observed at the soil slope in cold regions.

6 CONCLUSIONS

The main findings derived from this study are summarized as follows:

- Since slope failure at thawing season occupies 26 % of total number of the slope failures, the precise prediction of slope failure at thawing season is indispensable for the disaster prevention measures in Hokkaido.
- Freeze-thaw of soils triggers off some kinds of geohazards specific to cold regions like slope failure in snow-melting season. In this case, from the viewpoint of the mechanism, the slope failures in snow-melting season are divided into two types, namely surface-flow type and inside-erosion type.
- Subsurface layer of frost-susceptible soil slope upheaves in the direction normal to the slope surface during temperature drop, while frost heaved subsurface layer subsides in nearly vertical direction during temperature rise. As the result, freeze-thaw action causes residual displacement parallel to the slope surface and shear strain at the subsurface layer, which has a profound influence on slope failure in cold regions.
- Since there is a close relationship between the freeze-thaw history and the seasonal fluctuation in water content or the change in mechanical

characteristics of soils, it is necessary for the precise prediction of slope failure to examine the influence of freeze-thaw action on the hydro-mechanical behaviour of soil ground.

- Since freeze-thaw actions weaken the single particle hardness thereby becoming more fragile than before, the influences of freeze-thaw on hydro-mechanical behaviour of crushable volcanic coarse-grained soil in unsaturated condition should be considered carefully even if crushable volcanic coarse-grained soils without frost susceptibility.
- It is necessary for the precise prediction to evaluate the effects of freeze-thaw action on the occurrence and pattern of slope failure in cold region because the depth of slip surface of the slope subjected to freeze-thaw action becomes shallow and the occurrence of slope failure is advanced as compared with that without freeze-thaw history.
- Slope stability analysis which relates moisture content distribution to unsaturated shear strength is useful to analyze the stability of soil slope subjected to freeze-thaw and rainfall infiltration.
- It is necessary for the precise prediction to evaluate the influence of freeze-thaw action on the slope stability throughout a year because there is a clear difference in moisture content fluctuation between FE simulation with and the one without freeze-thaw.
- To reproduce the frost heave phenomenon of unsaturated soils which depends on overburden pressure, freezing rate, degree of saturation, and water intake ratio, this study proposed an experimental equation estimating the frost expansion strain.
- Coupled FE analysis where an algorithm considering the frost heave phenomenon is incorporated into the mathematical model is an effective method to simulate the frost heave-thaw behaviour of slope subjected to freeze-thaw action.
- Keeping in mind the difference in the slope failure mechanism between cold region and warm-temperate region, new six important factors (snowy cold climatic conditions, frost susceptibility of soil, formation of loose soil layer due to frost heave, change in physical property due to freeze-thaw, change in mechanical property due to freeze-thaw, formation of impermeable frozen soil layer) should be considered as the endogenous factors and the exogenous factors of slope failure in cold regions.
- In addition to three important influencing factors in warm-temperate region (the generation of pore water pressure, the decrease in shear strength of soil, and the increase in unit weight of soil), the combination of new six important influencing factors related to snowmelt, freeze-thaw actions, and frost susceptibility of soil should be considered to elucidate the mechanism of slope failure in snowy cold regions.

These findings indicate that when developing a theoretical model for predicting the mechanical behaviour of soil slopes in cold regions and evaluating the long-term stability, it is important to give a special consideration to the influencing factors specific to snowy cold regions clarified in this study. However, climate change due to global warming may increase slope failure at thawing season. Therefore, we need to continuously study new geotechnical hazards in snowy cold regions caused by climate change and its long-term hazard assessment by predicting climate change in Hokkaido in the near future.

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