Effect evaluation of freeze-thaw action on hydro-mechanical behavior of unsaturated granular materials

Effet évaluation de l'action gel-dégel sur le comportement hydro-mécanique des matériaux granulaires insaturés

T. Ishikawa, S. Miura & T. Tokoro
Hokkaido University, Sapporo, Japan

ABSTRACT
This paper proposes new testing methods for evaluating the effects of freeze-thaw action on the deformation-strength characteristics and water retention-permeability characteristics of granular materials in unsaturated conditions. A triaxial and a permeability apparatus, which have a cooling system to control the temperature of the soil specimen, were developed in order to examine the hydro-mechanical behavior of unsaturated soils subjected to freeze-thaw sequence similar to that experienced by in-site soil in cold regions. Results indicate that the proposed testing methods with the newly developed test apparatuses are highly useful in the evaluation of the effects of the freeze-thaw action on the hydro-mechanical behavior of unsaturated soils.

RÉSUMÉ
Cette article propose de nouvelles méthodes d'essai pour évaluer les effets de l'action gel-dégel sur les caractéristiques de déformation-résistance mécanique et rétention hydrique-perméabilité des matériaux granulaires insaturés. Un Appareil triaxial et un appareil de perméabilité, qui ont un système de refroidissement pour contrôler la température de l'échantillon de sol, ont été développés afin d'examiner le comportement hydro-mécanique des sols insaturés soumis aux cycles gel-dégel semblable à des sols en place dans les régions froides. Les résultats indiquent que les méthodes d'essai proposées avec les nouveaux appareils développés sont fortement utiles dans l'évaluation des effets de l'action gel-dégel sur le comportement hydro-mécanique des sols insaturés.

Keywords : unsaturated soils, triaxial test, permeability test, freezing and thawing, slope failure

1 INTRODUCTION

In cold regions, natural disasters such as slope failures at cut slope often occur in snow-melting season. The slope failure at subsurface layers in cold regions is deemed to be caused by the increase in degree of saturation from snow-melting and/or the change in deformation-strength characteristics of soil resulting from freeze-thaw action. Hence, it is indispensable to examine the influence of the freeze-thaw action of pore fluid on the hydro-mechanical behavior of unsaturated soil ground for establishing a precise predictive method of natural disasters in cold regions.

Until now, a number of experimental studies have been made mainly on the deformation-strength behavior of frost-heaving in geomaterials, such as clays and silts, in saturated condition (Aoyama et al. 1979, Ono et al. 2003). Besides, Ishikawa et al. (2008) has recently examined the behavior of volcanic coarse-grained soils exposed to the freeze-thaw action, which however, lacks the frost heave characteristics. These researches indicate that the freeze-thaw action has strong influence on the mechanical characteristics of geomaterials in saturated condition regardless of frost-heave characteristics of the soils. However, the synthetic studies on the hydro-mechanical characteristics of unsaturated soils subjected to freeze-thaw action have hardly been seen to date, except Nishimura et al. (1990, 1993).

The objective of this study is to develop testing methods for evaluating the effects of freeze-thaw action on the hydro-mechanical characteristics of granular materials at unsaturated condition. In this paper, two new test apparatuses, which can simulate the freeze-thaw sequence in real foundations, were developed and the influences of freeze-thaw action on the deformation-strength properties, water retention curves and coefficient of permeability were examined for a crushable volcanic coarse-grained soils at unsaturated condition.

2 TEST APPARATUS

2.1 *Freeze-thawing triaxial test apparatus*

A schematic diagram of a newly developed freeze-thawing triaxial apparatus for unsaturated soils is shown in Figure 1. The apparatus has a cooling system to control the temperature of the cap and pedestal. So, any temperature difference between cap and pedestal can be arbitrarily set to the triaxial specimen. Since the specimen is covered with an acrylic cylindrical cell for frost heave simulation during freezing and thawing and a lateral displacement of the specimen is constrained by the cell, one-dimensional frost heave can be replicated in the specimen. The apparatus can thus apply a freeze-thaw sequence to a triaxial specimen as experienced by in-situ soils in cold regions.

On the back of freeze-thaw process, a monotonic loading triaxial compression test and a water retention test can be performed for coarse-grained soils under various degrees of saturation and loading conditions. The apparatus can control pore air pressure (u_a) and pore water pressure (u_w) separately. Pore water pressure is applied to a specimen through a hydrophilic acrylic copolymer membrane filter (Versapore membrane filter, Air Entry Value (AEV) = 110 kPa) attached to the pedestal and the pore air pressure is applied through a hydrophobic polyflon filter attached to the cap. In addition, axial load can be applied to the specimen by strain control method with a direct drive motor (DDM).

2.2 *Freeze-thawing permeability test apparatus*

A schematic diagram of a newly developed freeze-thawing permeability apparatus for unsaturated soils is shown in Figure 2. The apparatus is an improved permeability test apparatus with air pressure chambers proposed by Ingersoll (1981), Uno et al. (1990) and Abe (1994), and it can perform constant head permeability tests for unsaturated soils by steady-state method.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-833

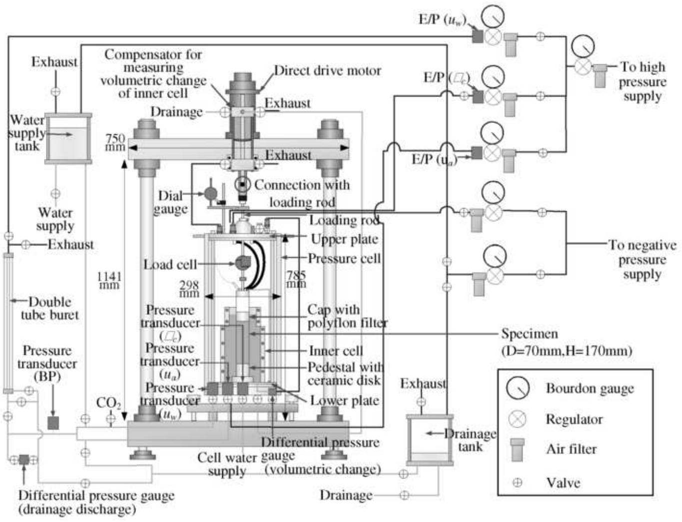

Figure 1. Freeze-thawing triaxial test apparatus.

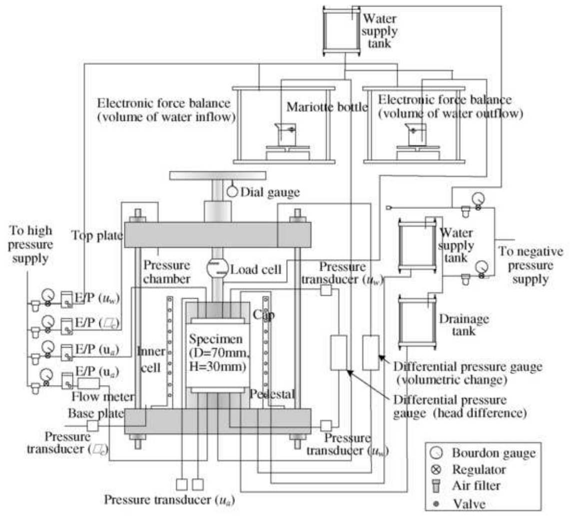

Figure 2. Freeze-thawing permeability test apparatus.

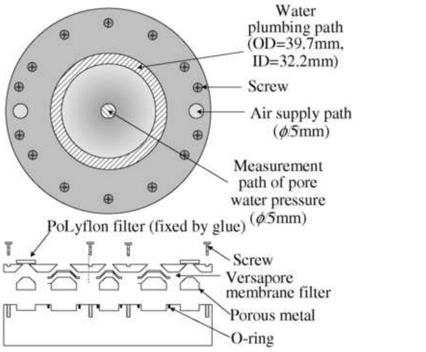

Figure 3. Structural design of cap and pedestal.

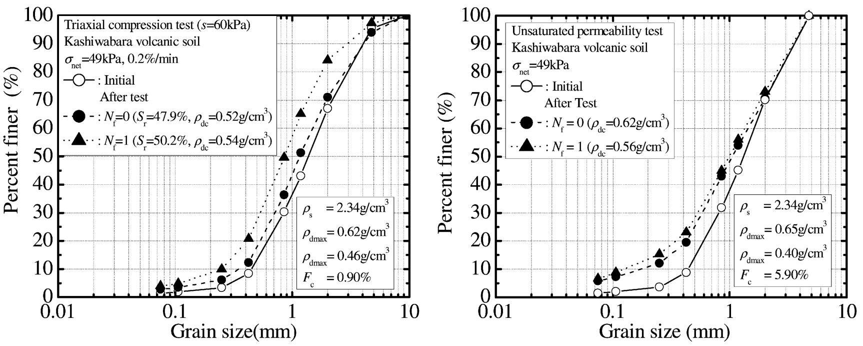

Figure 4. Grain size distribution of samples.

One of the key features of the apparatus is the structural design of the cap and pedestal as shown in Figure 3. In order to reduce the total testing time, versapore membrane filters of AEV = 60 kPa and 200 kPa were respectively adopted in a water plumbing path and in a measurement path of pore water pressure, instead of using a ceramic plate. On the other hand, a polyflon filter was employed in air supply paths for controlling the pore air pressure. Other key features include the ability to perform water retention tests simultaneously with permeability tests for unsaturated soils by measuring the volume of water inflow and outflow with two electronic force balances installed inside the pressurized chambers. Here, the water supply provides a constant hydraulic head by means of Mariotte bottles in beakers mounted on electronic force balances. Besides, the apparatus resembles the above-mentioned triaxial apparatus in that one-dimensional frost heave observed at in-situ soils in cold regions can be replicated in the specimen just before permeability tests.

3 METHODOLOGY

3.1 *Soil specimens*

3.1.1 *Soil sample*

A test material was taken from a natural deposit of volcanic coarse-grained soil in the island of Hokkaido. Belonging primarily to Shikotsu primary tephra deposited by the eruption of Shikotsu caldera 31,000 – 34,000 years ago, Kashiwabara volcanic soil was extracted from approximately 1.5 m under ground level (lower than freezing depth). Physical properties and a grain-size distribution curve of Kashiwabara volcanic soil used in triaxial compression tests and permeability tests are shown in Figure 4, respectively. Kashiwabara volcanic soil has low values of both the dry densities (ρ_{dmax}, ρ_{dmin}) because its constituent particles are very porous on account of having large number of intra-particle voids. Furthermore, past studies (Miura et al. 1996, Nakata & Miura 2007), have revealed that Kashiwabara volcanic soil shows remarkable particle crushability even under relatively low stress levels.

3.1.2 *Preparation of test specimens*

Preparation of test specimens was conducted as follows. Cylindrical specimens for triaxial compression tests and permeability tests, the initial size as shown in Figure 1 and Figure 2 respectively, were prepared by using the air pluviation method (Miura and Toki 1982). To ensure an experimental accuracy from the aspect ratio of the maximum particle size versus the specimen diameter, the grain size above 9.5 mm and 4.75 mm was screened out from the original soil while preparing the specimens for triaxial compression tests and permeability tests, respectively. The initial dry densities of specimens (ρ_{d0}) were adjusted so that the dry density after consolidation (ρ_{dc}) becomes 0.54 g/cm^3, equal to the in-situ dry density ($\rho_{din\text{-}situ}$ = 0.53~0.55 g/cm^3).

A freeze-thaw process was conducted as follows. First, an acrylic cylindrical cell was installed on a soil specimen enclosed in the rubber membrane, and de-aired water was added from the bottom end of the specimen until the degree of saturation reached 70% or over. The state of the specimen after water permeation is called as “quasi-saturation”, hereafter. Next, the specimen was one-dimensionally consolidated, to σ_a of 12.2 kPa by loading a weight on the top of the specimen. Subsequently, the specimen was frozen from the upper part and thawed from the lower part with the cooling system while allowing unfrozen water in the specimen to inflow and outflow through a water plumbing path of pedestal or a measurement path of pore water pressure. The temperature gradient through the specimen was maintained at 0.1 °C/mm in triaxial compression tests and 0.2 °C/mm in permeability tests, and the constant freezing and thawing velocity (U) was 1.6 °C/h.

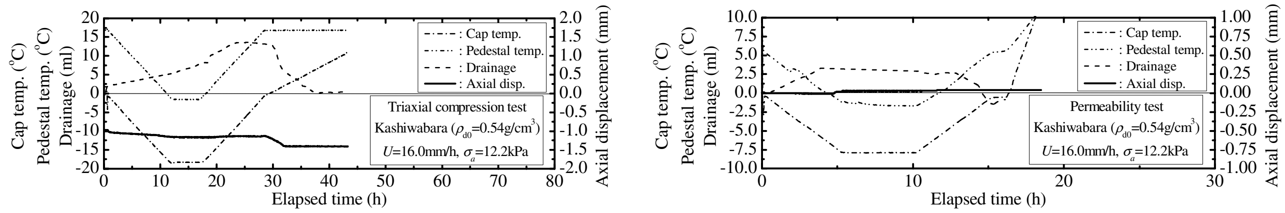

Figure 5. Comparison of frost heave behaviors between samples.

3.2 *Testing methods*

3.2.1 *Triaxial compression tests for unsaturated soils*

Monotonic triaxial compression tests were conducted as follows. The quasi-saturated specimen was isotropically consolidated under a prescribed net normal stress ($\sigma_{net} = \sigma_c - u_a$) of 49.0 kPa in fully drained condition by applying a prescribed confining pressure (σ_c) of 249 kPa, pore air pressure (u_a) of 200 kPa and pore water pressure (u_w) of 200 kPa until there was no longer a tendency for the change in axial displacement or drainage volume. Subsequently, an unsaturated specimen under an intended matric suction ($s = u_a - u_w$) of 5 kPa or 60 kPa was produced by decreasing u_w gradually while keeping both σ_c and u_a constant. The degree of saturation (S_r) for the cases when s = 5kPa and s = 60kPa correspond to approximately 49% and 30%, respectively. Upon attaining an equilibrium condition, the specimen was sheared by applying an axial deviator stress (q) at a constant axial strain rate of 0.2 %/min under fully drained condition (CD test) while all other testing parameters were held constant. The axial compression was terminated after reaching an axial strain (ε_a) of about 25 %. In addition, ordinary triaxial tests were also performed under the similar experimental conditions but without the freeze-thaw process for comparison.

3.2.2 *Permeability tests for unsaturated soils and water retention tests*

Constant head permeability tests were commenced at a condition near saturation, where the matric suction was close to zero, and proceeded through a drying process in accordance with the following procedure. First, a quasi-saturated specimen was isotropically consolidated under a prescribed net normal stress (σ_{net}) of 49.0 kPa in fully drained condition by applying a prescribed confining pressure (σ_c) of 99 kPa, pore air pressure (u_a) of 50 kPa and pore water pressure (u_w) of 50 kPa until there is no longer a tendency for the change in axial displacement or drainage volume. Subsequently, the steady-state method for measuring the coefficient of permeability (k_w) was performed by applying a constant hydraulic head difference of about 1.0 cm between the pedestal and cap, while keeping σ_{net} constant. The constant hydraulic gradient (i) in the vertical direction produced one-dimensional steady-state seepage from pedestal to cap across the specimen. Steady-state seepage conditions were achieved when the inflow rate (ΔQ_{in}) of water to the specimen and the outflow rate (ΔQ_{out}) of water from the specimen were equal, as shown in Equation 1.

$$q = \Delta Q_{in} = \Delta Q_{out} \tag{1}$$

where q is the volume of water per unit time. Both ΔQ_{in} and ΔQ_{out} are computed by using the volume of water (Q) flowing across the specimen in a designated time period (t) by which is measured with electronic force balances. Note that the water supply and the drainage are given positive as the sign of ΔQ_{in} and ΔQ_{out}, respectively. The coefficient of permeability (k_w) can be computed as:

$$k_w = \frac{q}{iA} = \frac{q}{A} \cdot \frac{L}{\Delta h} \tag{2}$$

where i is the hydraulic gradient in the range of 0.4 to 0.9, A is the cross-sectional area of seepage path, L is the height of specimen, Δh is the head loss across the specimen and measured with a differential pressure gauge connected to both cap and pedestal. In order to measure the coefficient of permeability corresponding to a particular matric suction or water content, the above-mentioned experimental procedure could be repeated for different magnitudes of matric suction or water content by decreasing the applied pore water pressure in steps while maintaining both σ_c and u_a constant, i.e., while maintaining a constant σ_{net}. Moreover, the volume of water inflow and outflow during each increment of matric suction was measured with electronic force balances and were used in calculating the water contents of the specimen, thereby yielding the water retention curve and the coefficients of permeability from a single soil specimen.

4 RESULTS AND DISCUSSIONS

4.1 *Behavior of soil specimens during freeze-thaw process*

Figure 5 shows the relations in a freeze-thaw process between temperatures of cap (T_c) and pedestal (T_p), volume of drainage (v), axial displacement of cap (u) and elapsed time (t). Here, as the origin point of the axial displacement is designated to the point before loading, the consolidation settlement due to the overburden pressure of σ_a = 12.2 kPa is initially observed. In a triaxial compression test, though the frost heave can hardly be recognized, a small settlement is observed in the soil specimen after thawing. On the other hand, in a permeability test, a little frost heave can be observed in the soil specimen and remains after thawing. The results indicate that the freeze-thaw action causes an increase and decrease in the density of crushable volcanic coarse-grained soils. Note that the reason why the same soil expands or contracts by freeze-thawing is considered to be due to the difference in grain size distributions of soil samples employed in these tests.

4.2 *Effects of freeze-thaw action on mechanical behavior*

Figure 6 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 CD tests under different matric suction (s). Kashiwabara volcanic soil exhibits peak strength at an axial strain of about 15%, very similar to the dense sand and over consolidated clay, regardless of freeze-thaw histories. For plots with the same matric suction (s), the peak strength of a freeze-thawed specimen drops as compared with that of the non freeze-thawed specimen irrespective of degree of saturation 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. The results indicate that the freeze-thaw action has a profound influence on the deformation-strength characteristics of a crushable volcanic coarse-grained soil, especially under low matric suction, that is high degree of saturation, even if the soil lacks in frost heave characteristics.

4.3 *Effects of freeze-thaw action on hydraulic behavior*

Figure 7 shows typical water retention curves of a freeze-thawed and non freeze-thawed specimens. Figure 8, on the other

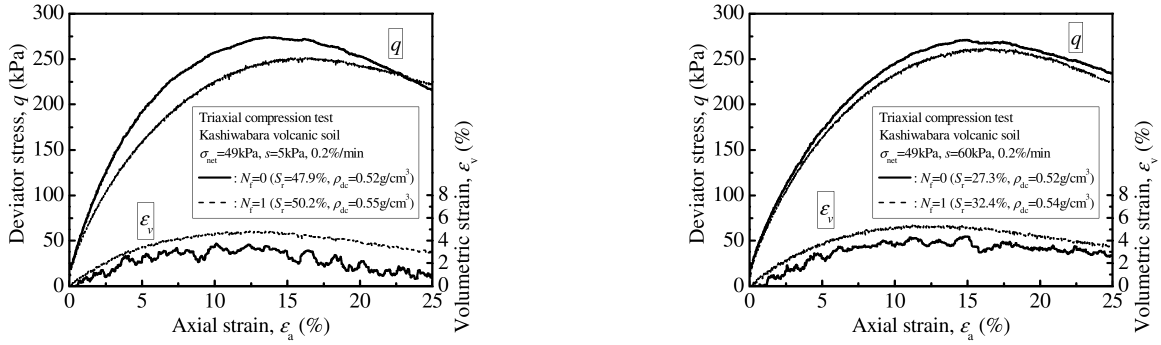

Figure 6. Comparison of triaxial compression test results.

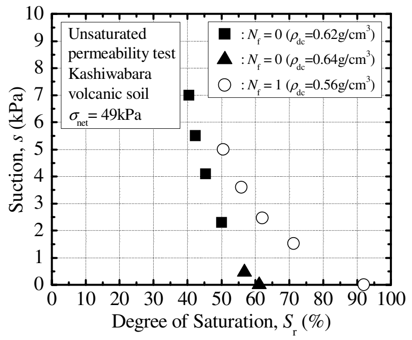

Figure 7. Comparison of water retention curves.

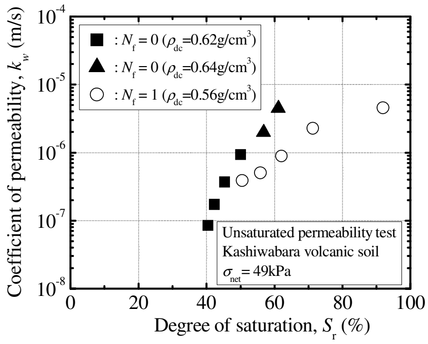

Figure 8. Comparison of coefficient of permeability.

hand shows typical sets of data for coefficient of permeability (k_w) versus degree of saturation (S_r) for these two specimen types. Measured results in these figures were obtained from permeability tests performed along a drying process. For the plots with the same degree of saturation (S_r) in Figure 7, 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. On the other hand, for the plots with the same degree of saturation (S_r) in Figure 8, the coefficient of permeability (k_w) of a freeze-thawed specimen decreases as compared with that of the non freeze-thawed ones. The reason seems to be because of the grain refining of Kashiwabara volcanic soil caused by freeze-thawing as shown in Figure 4, which ultimately results in a gradual increase in the water retentivity and a gradual decrease in the permeability. The results indicate that the freeze-thaw action also has a strong influence on the water retention-permeability characteristics of a crushable volcanic soil.

5 CONCLUSIONS

The following conclusions can be obtained;

- A freeze-thaw action has strong influence on the hydro-mechanical behavior of a crushable volcanic coarse-grained soil in unsaturated conditions even if the soil is a non frost-heaving geomaterial.
- Proposed testing methods with newly developed test apparatuses are highly useful in the evaluation of the effects of the freeze-thaw action on the hydro-mechanical behavior of unsaturated soils.

ACKNOWLEDGMENTS

This research was supported in part by Committee on Advanced Road Technology from Ministry of Land, Infrastructure, Transport and Tourism, Japan.

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