Effects of Freeze-Thaw History on Deformation-Strength Properties and Permeability of Fine-Grained Soil

Effets de l'historique du gel-dégel sur les propriétés de résistance à la déformation et de perméabilité des sols à grains fins

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ABSTRACT: In cold and snowy areas, surface soils on slopes often move downward especially in early spring. Its moving caused by repeated freeze-thaw cycles. If we properly evaluate slope stabilities and carry out effective slope protection works, we should understand variations of strengths, stiffnesses, permeabilities, and so on in the cycles. By the way, it is known that repeated freeze-thaw cycles make ice lenses within surface soil. They spread parallel to ground surface so they are arranged parallel to shear stress on the slope. In this study we carried out frost heave tests that obtained changes of the void ratio and permeability in the cycle of freezing and thawing, direct box shear tests that obtained strength-deformation characteristics in the cycles, and the bender element tests that also obtained velocities of shear waves with vertical and horizontal propagation in the cycles. Then we conclude that the formation of ice lenses made parallel to shear stress is important for mechanical properties of surface soils.

RÉSUMÉ : Dans les régions froides et enneigées, les sols de surface sur les pentes se déplacent souvent vers le bas, en particulier au début du printemps. L'évaluation correcte de la stabilité des pentes et la réalisation de travaux de protection des pentes efficaces devraient nous permettre de comprendre les variations de forces, rigidités, perméabilités, et ainsi de suite au cours des cycles. Dans cette étude, nous avons effectué des tests de soulèvement par le gel qui nous ont permis d'obtenir les variations de l'indice de vide et de la perméabilité dans le cycle de gel et de dégel, des essais de cisaillement direct à la boîte qui nous ont donné les propriétés de résistance à la déformation au cours des cycles et des tests par élément fléchissant qui nous ont également donné les vitesses des ondes de cisaillement avec la propagation verticale et horizontale au cours des cycles. Nous avons alors conclu que la formation de lentilles de glace parallèles à la contrainte de cisaillement joue un rôle important dans les propriétés mécaniques des sols de surface.

KEYWORDS: frost heave, freezing and thawing test, permeability, strength-deformation characteristics, elastic shear modulus

1 INTRODUCTION

Surface soil of natural and artificial slopes in cold and snowy areas, such as Hokkaido (the northernmost island of Japan), moves downwards in early spring due to the cycle of freezing and thawing (e.g. Ueno et al. 2010). A mechanism of this phenomenon is conceptually shown in Figure 1. In winter, ice lenses formed around freezing fronts within the soil on a slope, then ice lenses grow, causing frost heave. In spring, ice lenses thaw with increasing water contents of soil as temperature rise, then soil begins to move or flow downwards by gravity. Slopes often fail by snowmelt and rainwater. To evaluate slope stability and select effective slope protection work, we should obtain variations of strength, stiffness and permeability in the cycle of freezing and thawing. As shown in Figure1, most of directions of ice lenses are parallel to shear stress. However, there are few studies focusing the directionality of ice lens.

In this study, we pursued changes of the void ratio and permeability in the cycle of freezing and thawing, covered soil samples with various densities. To use soil samples containing ice lenses, we developed a new method of the direct box shear test, enabled to measure deformation-strength properties, and a new method of the freezing and thawing test to measure velocities of shear waves with vertical and horizontal propagation, enabled to measure elastic shear moduli and analyze anisotropic structures.

2 TEST APPARATUSES AND SPECIMENS

Three types of test apparatus were used in this study. The first is a frost heave test apparatus according to JGS 0172-2009: Test

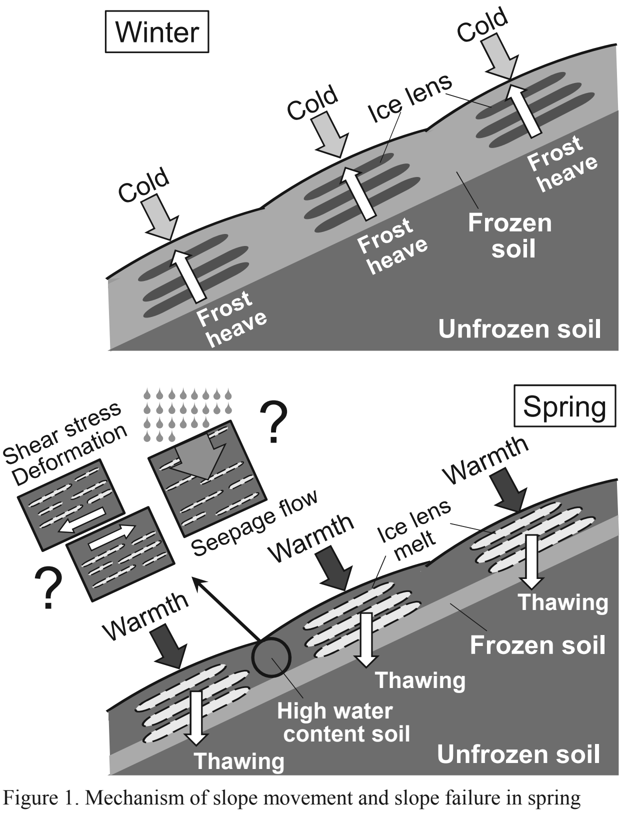

Figure 1. Mechanism of slope movement and slope failure in spring

method for frost susceptibility of soils, which uses specimens in a disk form 10 cm in diameter and 5 cm in thickness and is capable of falling head permeability tests using a burette before and after a freeze-thaw cycle (designated hereinafter as the frost heave test apparatus capable of permeability tests). The second is a frost heave test apparatus equipped with bender elements (BEs) for measuring the velocity of shear waves propagating in the specimen before and after a freeze-thaw cycle (designated hereinafter as the frost heave test apparatus equipped with BEs). As shown schematically in Figure 2a, two pairs of BEs are provided, in the upper and lower plates and in the mold, respectively. The BE pair in the cooling plates measures the velocity $(V_s)_{vh}$ of the shear wave that oscillates horizontally and propagates vertically, while the BE pair in the mold measures the velocity $(V_s)_{hh}$ of the share wave that oscillates and propagates horizontally (Kawaguchi et al. 2001, Yamashita and Suzuki 2001). The BE pair in the mold was removed in freeze-thaw tests to avoid any damage by freezing, and mounted again after thawing for BE tests. The third apparatus is a direct box shear test apparatus that permits freeze-thaw test in the shear box (designated hereinafter as the temperature-controllable direct box shear apparatus). The shear box is schematically represented in Figure 2b. The specimen is a disk 6 cm in diameter and 4 cm in thickness. A coolant is circulated in the piston and pedestal for temperature control. The shear box, or the circumferential surface of the specimen, is thermally insulated by a two-centimeter-thick acrylic resin layer. A rubber sheet, 0.3 mm in thickness, is placed between the upper and lower halves of the shear box during freeze-thaw tests to prevent water leakage, and is removed for shear tests to leave a 0.2mm clearance between the box halves.

Figure 3 shows grain size distribution curves for the two frost-susceptible fine-grain soils used in this study. One is weathered volcanic ash obtained at Kitami City, Hokkaido (sample V) which was used in the tests using the two frost heave test apparatus. The test specimens were prepared by compacting the volcanic ash sample conditioned to be slightly drier than with the optimum water content. The other, used in the temperature-controllable direct box shear tester, is a mixture of clay commercially available in dry powder and silt at a ratio of 1:1 by weight, which was made to a slurry at twice the liquid limit and then consolidated one-dimensionally to a vertical stress σ_v= 100 kPa (sample CL, w_L = 38%, I_P = 19).

3 RESULTS AND DISCUSSION

3.1 *Void ratio and coefficient of permeability*

Falling head permeability tests were performed before and after the freeze-thaw tests using the frost heave test apparatus in order to study effects of freeze-thaw cycles on the void ratio *e* and the coefficient of permeability *k*. Sixteen specimens were prepared using a rammer and a mold at three levels of compaction energy: 126, 284, and 550 kJ/m^3 (Nakamura et al. 2011). The vertical stress was σ_v=10 kPa for all the tests. Six of the specimens underwent three freeze-thaw cycles and *k* was measured before and after each cycle. The frost heave test method specified in the JGS 0172-2009 standard was used. In the thawing tests, the specimen was dewatered through the top and bottom surfaces held at 5°C, and then saturated again.

Figure 4 shows the rate of frost heave U_h (mm/h) and frost heave ratio ξ (%) of the specimen as functions of void ratio *e* at the beginning of freezing. A greater *e* means more pore water and lower tensile strength, which might suggest easier ice lens formation. Actually, however, both U_h and ξ are lower at higher *e* at the beginning of freezing, presumably because of inhibition of continuity of the unfreezable water needed for frost heave (Nakamura et al. 2011). The results of the three consecutive freeze-thaw cycles, indicated by the points connected with lines, show that the repeated cycles lead to convergence to fairly constant values of U_h and ξ.

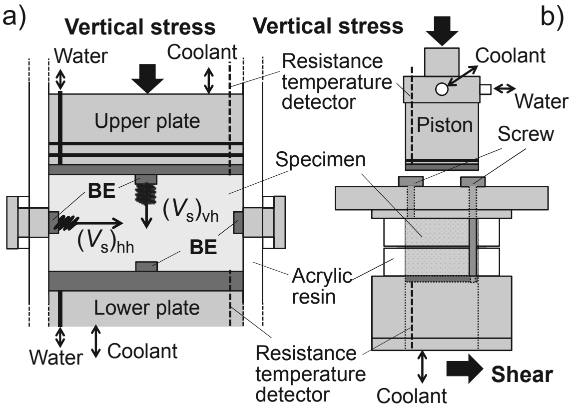

Figure 2. Test apparatus diagrams (a): frost heave apparatus equipped with BEs, b): temperature-controllable direct box shear apparatus)

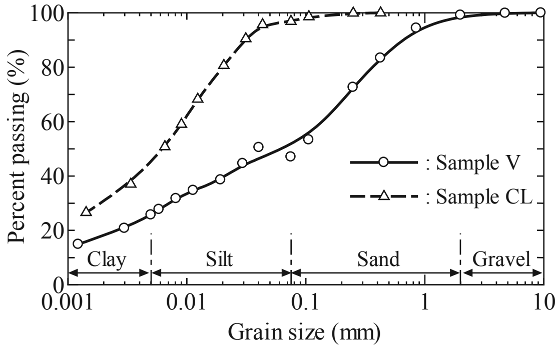

Figure 3. Grain size distribution of samples used in the tests

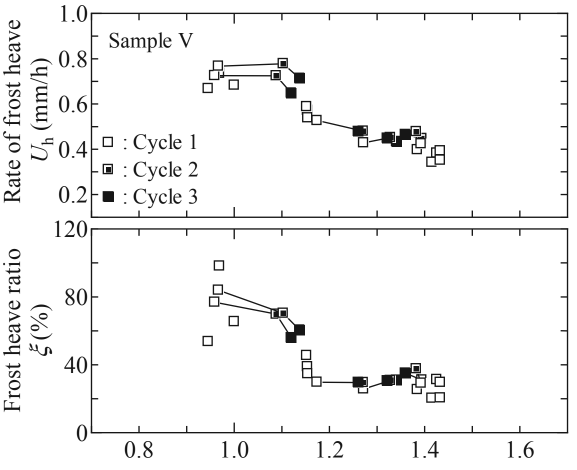

Figure 4. U_h and ξ as functions of *e* at the beginning of freezing

Figure 5 represents changes in the void ratio *e* and coefficient of permeability *k* of the specimen through the freeze-thaw cycles. The data for each specimen are connected by lines. As observed in Figure 4, the freeze-thaw cycles decrease greater initial *e* values and increase smaller initial *e* values, eventually leading to convergence to a relatively limited range of *e* values between 1.1 and 1.3. Ono et al.(2003) reported that freeze-thaw history decreases *e* of clay at a normally consolidated state and increases *e* of clay with a larger over consolidation ratio. This observation is in agreement with the present results assuming that higher compaction energies on the specimen result in over consolidation in terms of the specimen's mechanical

Table 1. Conditions of direct box shear tests and changes in void ratio

Test	Freeze -thaw cycle	σ_v (kPa)	Void ratio, e	
			After consol. (before freezing)	Before shear (after thawing)
DBS1	Yes	12	0.97	1.00
DBS2			0.99	1.02
DBS3			1.01	1.05
DBS4	No		1.01	
DBS5	Yes	75	0.97	0.91
DBS6			0.96	0.92
DBS7	No		0.95	

characteristics. The coefficient of permeability k changes along with the changes in e, thus the change in k through the freeze-thaw cycles is considered to be strongly dependent on the changes in e. Similar to the above, k converges on about 5×10^{-8} m/s. These observations explain why k has been reported to be increased by freeze-thaw cycles by some investigators and to be decreased by others (Chamberlain et al. 1990, Starke 1989).

3.2 *Deformation and strength properties*

Table 1 summarizes the conditions and results of the tests (DBS 1-7) performed with the temperature-controllable direct shear box apparatus. Two levels of the vertical stress σ_v, 12 and 75 kPa, were used for loading and shear. Freezing and thawing tests were replicated several times under identical conditions. The temperatures of the top and bottom surfaces of the specimen were set to 4°C and 0°C, respectively and lowered at a rate of 0.2°C/h for freezing and increased at a rate of 0.4°C/h for thawing until the top surface reached 20°C. The constant-pressure direct box shear tests were performed at a rate of 0.02 mm/min with a 0.2 mm gap, or clearance, between the upper and lower halves of the shear box. Table 1 shows that freeze-thaw cycles increase e of the specimens with high over consolidation ratios (OCRs) (DBS 1-3) and decrease e of those with lower OCRs (DBS 5 and 6).

Figure 6 illustrates the shear stress τ and vertical displacement ΔH as functions of horizontal displacement δ in the constant-pressure direct box shear tests. The specimens that have not undergone a freeze-thaw cycle clearly show higher stiffness at the beginning of shear, and generally higher maximum shear stress τ_{max}. Both increase and decrease of the shear strength after freeze-thaw cycles have also been reported (Aoyama et al. 1985, Ogata et al. 1985). Triaxial test results have also shown that freeze-thaw cycles make high-OCR cohesive soil to some extent similar to normally consolidated soil whose shear strength decreases with increase in e and, in contrast, make normally consolidated soil to some extent similar to over consolidated soil whose strength increases with decrease in e (Ono et al. 2003). This study shows a similar tendency for the dilatancy characteristics. An exception is the test DBS 7, where τ_{max} is relatively high in spite of e higher than in DBS 5 or 6. This is presumably due to structurally weak zones in the specimen formed by melting of ice lenses as the shearing direction is almost parallel to the surface where ice lenses formed in the present experiments. This mechanism suggests that zones with very low shear strength may appear in the soil elements in a slope in snowmelt season. Similarly, variation in deformation-strength characteristics after freeze-thaw cycles can be explained by the existence of structurally weak zones in the specimens.

3.3 *Elastic shear modulus*

Effects of freeze-thaw cycles on elastic shear modulus G and its anisotropy were studied using the frost heave test apparatus with BE on six specimens compacted to target densities by impacting a piston installed in the mold. BE tests were

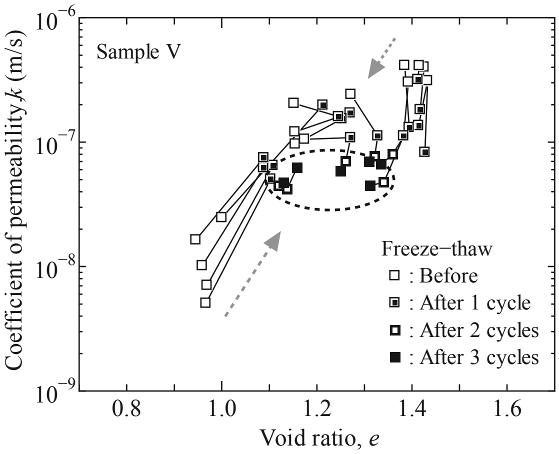

Figure 5. Changes in k and e by freeze-thaw cycles

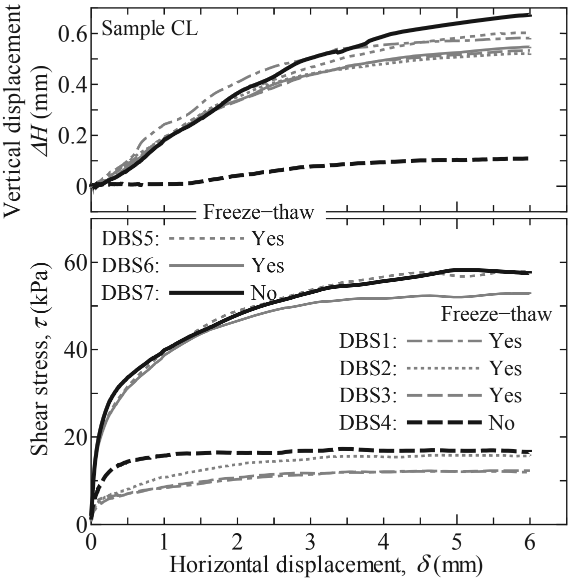

Figure 6. Difference in direct shear test results by freeze-thaw cycle

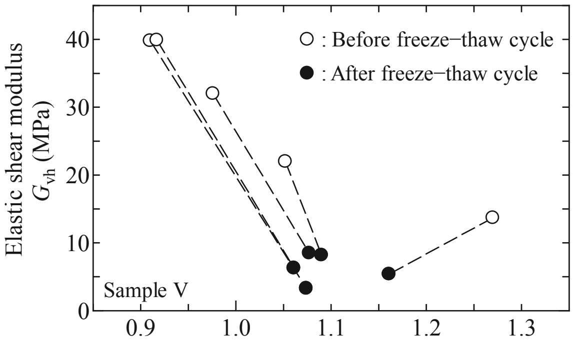

Figure 7. Changes in G_{vh} and e by freeze-thaw cycles

conducted under σ_v=10 kPa, and G_{vh} and G_{hh} of four specimens before and after freeze-thaw cycles were measured. The other two specimens underwent stepwise stress cycles (10 → freeze-thaw→10→20→40 kPa or 10→20→40→freeze-thaw→40→20 →10 kPa), during which G_{vh} and G_{hh} were measured.

Figure 7 shows changes in e and G_{vh} in freeze-thaw cycles at σ_v=10 kPa for five specimens. The void ratios clearly converge on the same range as in Figure 5; G_{vh} sharply decreases to lower than 10 MPa irrespective of the magnitude of *e* before freezing or increase/decrease in e after freeze-thaw cycles.

Figure 8 illustrates changes in G_{vh} and G_{hh} after freeze-thaw cycles. The decrease in G_{hh} is not so remarkable as that in G_{vh}, probably because the latter results from the velocity of the shear wave that traverses structurally weak zones formed by disappearance (melting) of ice lenses. The structural damages due to formation and disappearance of ice lenses are thus believed to greatly influence the deformation-strength properties of soil, in agreement with the results shown in Figure 6. The fact that G_{vh} is higher than G_{hh} before freezing may be due to σ_v acting on the specimen to a greater extent than the horizontal stress σ_h (Yamashita and Suzuki 2001, Roesler 1979).

Figure 9 represents changes in G_{vh} and *e* under stepwise stress cycles in the two tests mentioned above. The decrease in G_{vh} by freeze-thaw cycles under σ_v=40 kPa is smaller than in the other test because of a very small change in *e* during the cycle. While freeze-thaw cycles do not greatly influence the effect of σ_v on changes in G_{vh}, they lower G_{vh} to a considerably greater extent than do σ_v changes, and G_{vh} cannot be restored by loading or unloading in any of the tests. This suggests that structural damages in soil due to formation and disappearance of ice lenses are not readily restored

The results described above indicate that changes in the permeability of soil exposed to freeze-thaw cycles can be explained to in terms of changes in the void ratio *e*, but its deformation-strength property is not fully described in terms of changes in *e* because of effects of structural damages in the soil resulting from formation and disappearance of ice lenses.

4 CONCLUSIONS

i) U_h and ξ of compacted fine grain soil are lower for higher *e* before freezing, and converge to fairly constant values after freeze-thaw cycles.

ii) Changes in *k* follow those in *e* due to freeze-thaw cycles.

iii) The initial stiffness and τ_{max} in the constant pressure box shear tests were greater before freeze-thaw cycles irrespective of increase or decrease in *e* due to freeze-thaw cycles.

iv) Decrease in G_{vh} is considerable and greater than that in G_{hh} irrespective of *e* before freezing or increase/decrease in e due to freeze-thaw cycles.

v) Results of the box shear tests and BE tests suggest that structural damages resulting from formation and disappearance of ice lenses have marked influence on the deformation-strength properties of soil.

vi) Results of BE tests with different vertical stresses before and after freeze-thaw cycles suggest that structural damages resulting from formation and disappearance of ice lenses cannot be readily restored.

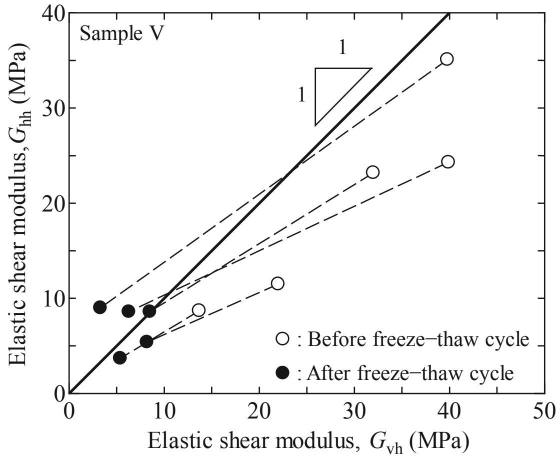

Figure 8. Changes in G_{vh} and G_{hh} by freeze-thaw cycles

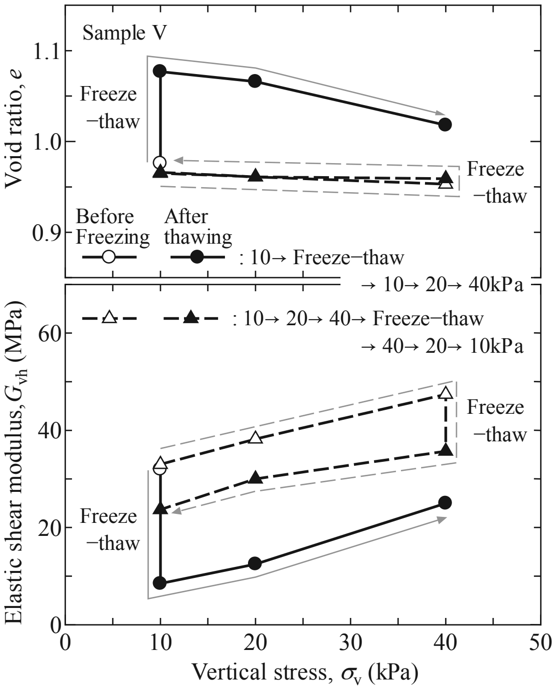

Figure 9. Difference in direct shear test results by freeze-thaw cycle

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