Experimental study on the permeability change of fine-grained soil by freeze-thaw effect

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ABSTRACT:
Permeability increase of fine-grained soils caused by freeze-thaw effect is a well known phenomenon. It has been believed that it was caused by scar of ice lens and shrinkage cracks in thawed soils. However, the current research revealed that the effect of ice les might be extremely small in the normally consolidated clays. These results were obtained by a one-dimensional freeze-thaw test where the direction of permeability measurement was at right angles to the ice lens. In this study, the experimental device to measure permeability of the ice lens direction was introduced. The conventional consolidation and falling heads permeability tests with this device enables evaluation of permeability of both ice lens and its right angle directions.
The tests results revealed that the permeability of fine-grained soil varies within the certain relation between the void ratio and permeability independent of freezing method. But, permeability of freeze-thawed did not increase over a certain pressure. Moreover, it was suggested that after thawing permeability increases regardless of direction and development of the ice lens.

KEY WORDS: Permeability, ice lens, freeze-thaw test, consolidation

1. INTRODUCTION

Frozen earth wall method was adopted in demolition of nuclear reactor of Fukushima Daiichi Nuclear Power Station. In the construction, frozen soil wall of approximately 2m in thickness, approximately 30m in depth and 1,500m in total extension is installed as it surrounds the No.1-4 nuclear reactors for the purpose of shielding the nuclear reactor building from the surrounding underground ground water. The volume of frozen soil for the wall is approximately 70,000m^3, and its operation period is approximately seven years until prevention of water leaking from the building is completed. Compared with the conventional artificial ground freezing, its scale and operation period is outstanding while degradation of its water shielding function by power supply trouble is considered as a problem. For stable operation, it is necessary to understand the water flow toward inside of the wall in the case that some or all of the frozen soil wall's functions are lost.

On the other hand, it has been known that coefficient of permeability increases remarkably after freeze-thaw of frost susceptible fine-gained soils. Therefore, when mudrock part of the frozen earth wall thaws, ground water flow that is greater than assumed is generated on the surface of the frozen soil impermeable wall, and it promotes thawing as a result. It is concerned that if the coefficient of permeability increases after thawing compared with that before freezing. Therefore, for stable operation of the frozen soil impermeable wall, it is necessary to understand if the coefficient of permeability of the ground returns to the value of the unfrozen soil when frozen soil thawed, or how much it increases if it does. Further, it is necessary to clarify the mechanism of it. Chamberlain et al. (1979) and Benson & Othman (1993) reported that the coefficient of permeability had increased by one to two digits after freeze-thaw of the fine-gained soil. Moreover, they concluded that it was caused by the scar of ice lens (IL) occurred in the heat flow right angle direction during the frost heave process. The other study reported that both the coefficient of permeability and void ratio had decreased after freeze-thaw of the low compacted fine-gained soils (Nakamura et al., 2011).

On the other hand, Ito et al. reported after freeze-thawed that the coefficient of permeability increases by 5-10 times despite that void ratio decreases in normally consolidated fine-gained soil (Hirose et al., 2000, Ito et al., 2005, Tamazaki et al., 2008, Ito et al., 2012). Furthermore, they insisted that in freeze-thaw tests with Kanto loam and Fujimori clay, the increase in coefficient of permeability after thawing is governed only by overburden pressure regardless of cooling rate and temperature gradient. The above results suggest that the increase in coefficient of permeability in freeze-thaw soil is not influenced by the effect of IL and the shrinkage crack.

The purpose of this study is to clarify the extent of change in coefficient of permeability after the freeze-thaw of mudrock or overconsolidated soils which are concerned for frozen soil impermeable wall and its mechanism. The image of groundwater flow through the thawed frozen earth wall is assumed as shown in Figure 1. In the early period of thawing of the frozen soil impermeable wall, the following two cases are to be concerned; the case of the ground water that flows between frozen pipes, which is of the IL direction, and the case of overall thawing, which is of the IL orthogonal direction. Moreover, considering the frozen pipes direction, the ground water that flows along the frozen soil wall is of the IL direction. In this report, the authors clarify difference between the coefficient of permeability in the IL direction and that in the IL orthogonal direction and its mechanism. Therefore, in order to examine the change in coefficient of permeability in the IL orthogonal direction, a freeze-thaw permeability test with a one-dimensional freeze-thaw experimental device shown in Figure 2 was conducted. Furthermore, a horizontal displacement restraining freeze-thaw permeability test shown in Figure 3 was conducted to examine the ground water in the IL direction, which occurs when part of the actual frozen soil wall thaws. Furthermore, in order to investigate factor of the increase in coefficient of permeability of the freeze-thaw soil, a consolidation permeability test was performed with samples obtained from the two kinds of freeze-thaw tests based on the standard consolidation test.

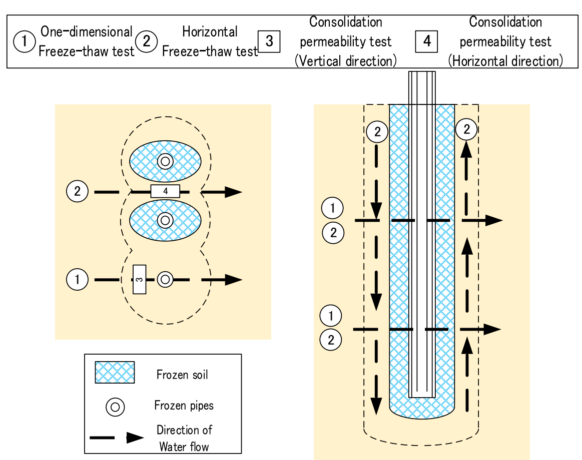

Figure 1 Image of groundwater flow through the thawing frozen earth wall

2. EXPERIMENTAL PROCEDURE

2.1 Soil material

Table 1 shows physical properties of the sample soil which is Fujimori clay filtered with a 425μm sieve. It was adjusted at the water content 1.3 times greater than the liquid limit and preloaded at P=500kN/m^2.

2.2 One-dimensional freeze-thaw permeability test

A 1-D freeze-thaw permeability test was performed with the apparatus shown in Figure 2. For the test, the lower and upper plates are set as a low-temperature side (Tc) and high-temperature side (Tw), respectively, and the soil was freeze-thawed from the lower to the upper direction. In addition, water supply and drainage was conducted from the upper plate during freeze-thaw. The buret was connected to the lower plate before and after the freeze-thaw, and a falling head permeability test was performed from the lower to the upper directions. Figure 4 shows temporal variation of the temperature of the upper and lower plates. A 24-hour falling head permeability test was performed at Tw, Tc = +5 ℃ before the test. Next, the temperature was lowered with the temperature difference between Tw and Tc as 5 ℃ and cooling rate as dT/dt = 0.2 ℃/h. When Tc reached -0.8 ℃, ice nucleus was formed. Next, Tc and Tw was lowered to -6 ℃ and -1 ℃, respectively. Tc and Tw was then lowered to -10 ℃ and maintained for 6 hours. Table 2 shows test conditions. In order to examine the effect of the overburden pressure p, C22 and C23 were conducted under p=100kN/m^2 and 190kN/m^2, respectively. Furthermore, to examine the effect of the pre-consolidation, the pre-consolidation load P of 300kN/m^{2}and 150kN/m^2 was given to C24 and C25, respectively, with the overburden pressure p=100kN/m^2 as a constant value. After the freeze-thaw test, samples for consolidation were taken out in each of the IL direction (horizontal direction) and IL orthogonal direction (vertical direction) as shown in Figure 5 and a consolidation permeability test was conducted.

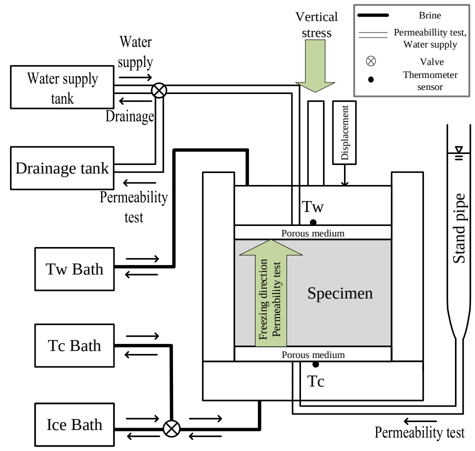

Figure 2 One-dimensional freeze-thaw permeability test

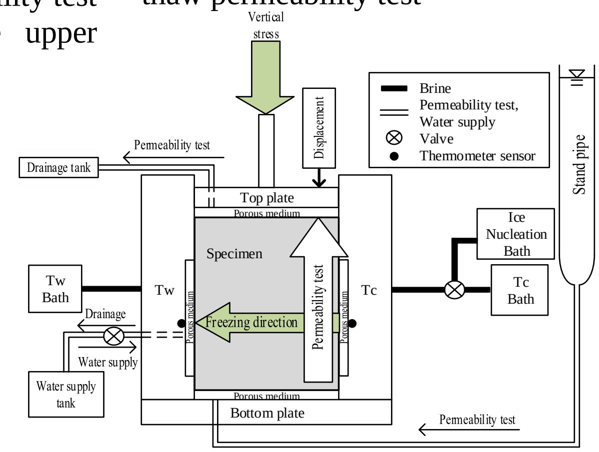

Figure 3 Horizontal displacement restraining freeze-thaw and vertical permeability test

Table 1 Properties of Fujinomori clay

ρ_s g/cm³	w_L %	w_P %	Gradation Sand %	Gradation Silt %	Gradation Clay %
2.674	41.4	23.0	9.4	59.1	31.5

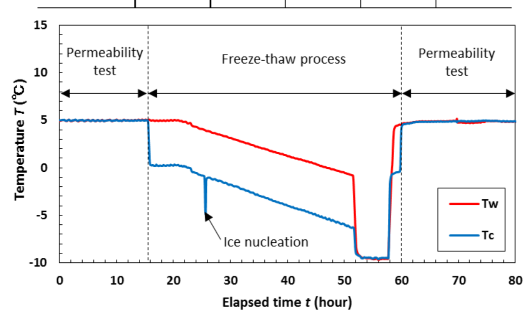

Figure 4 Freezing temperature during horizontal freeze-thaw test(K22)

2.3 Horizontal displacement restraining freeze-thaw and vertical permeability test

A Horizontal displacement restraining freeze-thaw and vertical permeability test was

performed with the apparatus shown in Figure 3 based on the test conditions shown in Table 2.
In the test, one side was set as a lower temperature side (Tc) and the other side as (Tw), and the soil was freeze-thawed horizontally from the Tc side to the Tw side. The water supply and drainage was carried out from the Tw side. A falling head permeability test was performed in the vertical direction with the buret connected to the lower side before and after the freeze-thaw process. The temperature change of Tw and Tc during the test was same as that shown in Figure 4. To examine the effect of overburden pressure *p*, constant pre-consolidation load *P* was given to K30, K21, K22, and p=50kN/m^2, 100kN/m^2 and 200kN/m^2. After the test, samples were taken out in the IL direction (vertical direction) as shown in Figure 6, and a consolidation permeability test was performed.

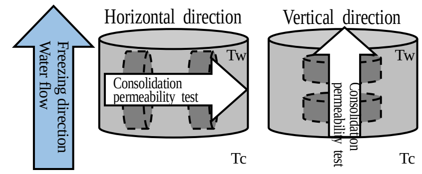

Figure 5 Sampling of specimen for consolidation permeability test

Table 2 Test Condition

Test method	Test No.	Pre-consolidation pressure P kN/m^2	overburden pressure p kN/m^2	dT/dx ℃/cm
Horizontal freeze-thaw	K21	500	100	0.625
	K22	500	200	0.625
	K30	500	50	0.625
1-D freeze-thaw	C22	500	100	0.714
	C23	500	190	0.714
	C24	300	100	0.714
	C25	150	100	0.714

Cooling ratio dT/dt : 0.2℃/h , Lowest temperature : -10℃, Freeze-thaw cycles n : 1, Water supply : Open

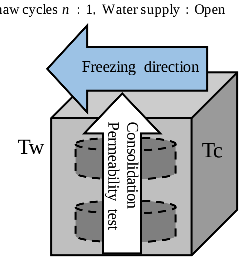

Figure 6 Sampling of specimen for consolidation permeability test after Horizontal freeze-thaw test

2.4 Consolidation Permeability test

The consolidation permeability test is a test for which standard consolidation test and falling head permeability test are combined. The overburden pressure was given progressively from 9.8 to 1256kN/m^2 with the load increment ratio as 1.
Initial load was given that is smaller by one step from the overburden pressure at the time of freeze-thaw. For the load above the overburden pressure, a 24-hour permeability test was performed after performing 24 hours consolidation at each load step. In order to evaluate the coefficient of the permeability, a permeability test was performed with the paste adjusted and degassed at water content that was 1.3 times greater than the liquid limit, for which load was given progressively from 9.8 to 1256kN/m^2.

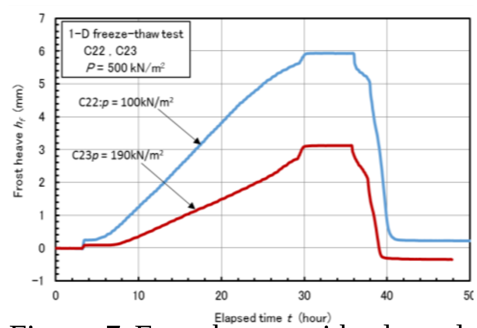

Figure 7 Frost heave with elapsed time (1-D test)

3. TEST RESULT

3.1 1-D freeze-thaw test

(1) Frost-heave and water supply

Figure 7 shows the frost heave with elapsed time. The total frost-heave is greater in C22(p=100kN/m^2), to which smaller overburden pressure was given, than in C23(p=190kN/m^2). The frost-heave increased in the process in which the temperature fell at the cooling rate of 0.2 ℃/h and then stopped increasing when the upper and lower plates' temperature Tw and Tc fell rapidly to -10 ℃. The displacement turns to settlement at the time of thawing, and both of them finally returned to the level before freezing. Figure 8 shows the water supply with elapsed time. Similar to the frost-heave, the water supply is greater in C22, to which smaller overburden pressure was given, than in C23. The water supply becomes constant when the temperature Tw fell to 0 ℃.

Moreover, the water was drained at the time of thawing, the water supply increased in C22 than in the initial stage, and was slightly lower in C23 than that before freezing. Figure 9 shows sample in the test. In the freezing process, the hair-crack-shaped IL grows up horizontally.

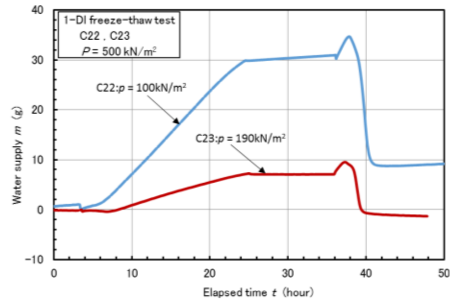

Figure 8 Water supply with elapsed time (1-D test)

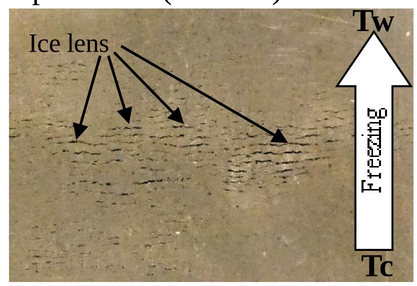

Figure 9 The hair crack to occur in the frozen soil

(2) Void ratio and coefficient of permeability obtained from 1-D freeze-thaw test

Figure 10 shows relationship between void ratio and coefficient of permeability.

The void ratio *e* decreases after thawing while the coefficient of permeability *k* increases for either of C22 and C23. The coefficient of permeability *kt* after freeze-thaw is greater than the coefficient of permeability *ku* before freeze by approximately 2-3 times. *kt* was greater in C22, to which smaller overburden pressure was given, than in C23. In the past study, it was reported that the increase ratio of the coefficient of permeability became 5-100 times greater when a sample of P=100kN/m^2 in Fujimori clay was freeze-thawed with less than p=100kN/m^2 and that the ratio tends to becomes small with an increase of the overburden pressure (Tamazaki et al., 2008). Considering the results together with those obtained from the present study, it is understood that the increase of *kt* becomes small with an increase of the pre-consolidation load *P* and overburden pressure *p*.

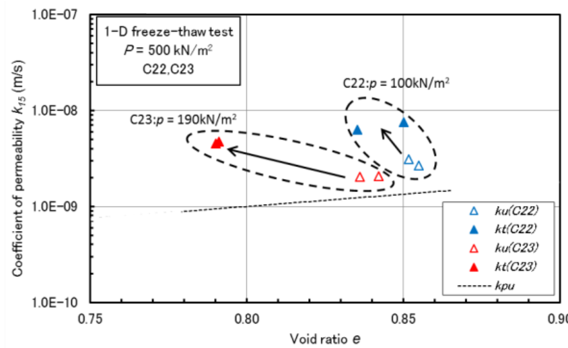

Figure 10 Relationship between the void ratio and coefficient of permeability (1-D test)

(3) Difference in coefficient of permeability for the IL and for the IL orthogonal directions

In order to examine the difference in coefficient of permeability for the IL direction and that for the IL orthogonal direction, the coefficient of permeability *kpu* obtained from the consolidation permeability test of an unfrozen sample and the coefficient of permeability *kpt* obtained from the consolidation permeability test with a sample obtained from a test piece after freeze-thaw are compared. Figure 11 shows relation between void ratio and coefficient of permeability obtained from the data shown in Figure 10 and the consolidation permeability test. No clear difference was seen in *kpt*(C) in the IL and the IL orthogonal directions of C22. The same tendency was seen in C23 and *kpt* is almost same in C23 and C22. Comparing *kpt*(C) and *kpu*, *kpt* is greater for the lower load, though they become almost same as the consolidation stage advances and the void ratio reaches around

0.70.

(4) Difference in coefficient of permeability after freeze-thaw obtained from 1-D freeze-thaw test and consolidation permeability test

Next, for the coefficient of permeability after freeze-thaw *kt* shown in Figure 11, the result of the 1-D freeze-thaw test and consolidation permeability test shows that *kt*(C) obtained from the 1-D freeze-thaw test is 5 times as great as the coefficient of permeability *kpt*(C) obtained from the consolidation permeability test. Moreover, coefficient of permeability of unfrozen sample obtained from the 1-D freeze-thaw test *ku*(C) almost equals that after freeze-thaw obtained from the consolidation permeability test *kpt*(C).

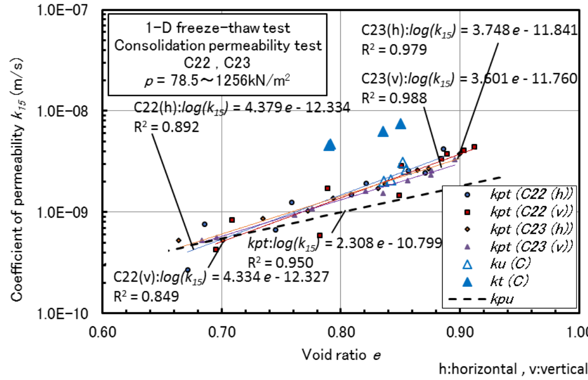

Figure 11 Relationship between the result of 1-D test and consolidation permeability test

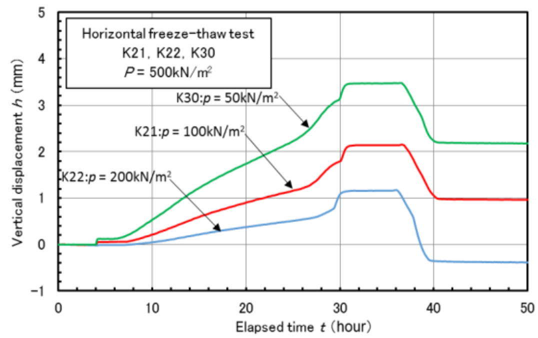

Figure 12 Vertical displacement with elapsed time (Horizontal freeze-thaw test)

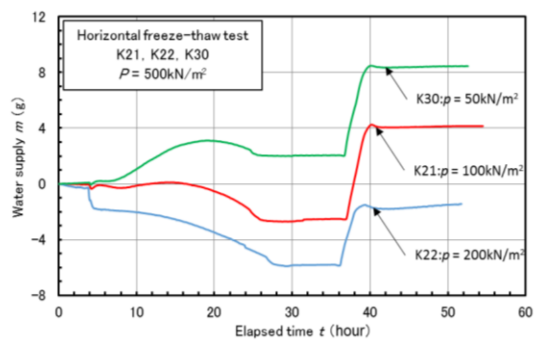

Figure 13 Water supply with elapsed time (Horizontal freeze-thaw test)

3.2 Horizontal displacement restraining freeze-thaw vertical permeability test

(1) Vertical displacement and water supply

Figure 12 shows the vertical displacement with elapsed time. In this test, freeze direction is horizontal while the displacement occurs only in the vertical direction. The maximum vertical displacement tended to be greater with smaller overburden pressure. Defrosting forcibly with Tw, Tc = +5 ℃ after freeze, for K22(p=200kN/m^2), greater overburden pressure, settlement was observed though it was not seen before freeze. Figure 13 shows water supply with elapsed time. For K30(p=50kN/m^2), smaller overburden pressure, water was supplied at the time of in freeze, though it was drained for K21(p=100kN/m^2) and K22. The displacement became great with an increase of overburden pressure.

(2) Void ratio and coefficient of permeability obtained from horizontal displacement restraining freeze-thaw vertical permeability test

Figure 14 shows relation between void ratio and coefficient of permeability. For K30 and K21 with small overburden pressure p, the void ratio after the freeze-thaw increased slightly compared with that before freeze though it slightly decreased for greater experimental load. The coefficient of permeability *kt*(K) after thawing rose by 5-10 times compared with coefficient of permeability *ku*(K) before freeze, and the void ratio did not almost change though the coefficient of permeability increased after the freeze-thaw.

(3) Result of consolidation permeability test

Figure 15 shows results of the consolidation permeability test of the IL direction.

The coefficient of permeability obtained from the consolidation permeability test of the freeze-thaw soil *kpt*(K) is much smaller than *kt*(K), and almost at the same level as that of unfrozen soil *kpu*.

(4) Factor of increased coefficient of permeability after freeze-thaw

Figure 16 shows relation between 1-D freeze-thaw test (C), horizontal displacement restraining freeze-thaw vertical permeability test (K) and consolidation permeability test of those freeze-thaw soils. The coefficient of permeability of unfrozen soil and freeze-thaw soil in the two freeze-thaw tests is distributed as relation of the void ratio *e* and coefficient of permeability *k* for two groups. In addition, in the freeze-thaw tests, the coefficient of permeability after the freeze-thaw tended to be slightly greater in the IL direction (K) than in the IL right angle direction (C). This is because the trace of the IL after the freeze-thaw were supposed remained because the displacement is restrained in the horizontal direction. In other words, the trace of the IL itself does not have a great influence on increase of the coefficient of permeability of the freeze-thaw soil.

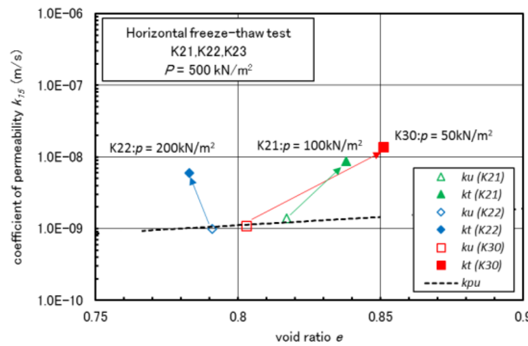

Figure 14 Relationship between the void ratio and coefficient of permeability (Horizontal freeze-thaw test)

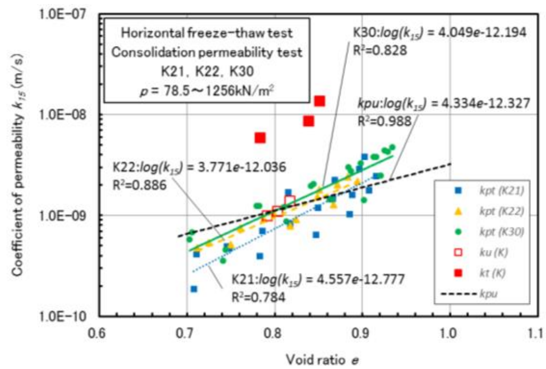

Figure 15 Relationship between the horizontal freeze-thaw test and consolidation permeability test

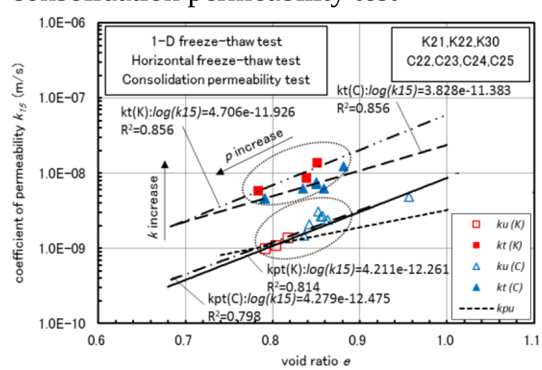

Figure 16 Relationship between the 1-D freeze-thaw test, horizontal freeze-thaw test and consolidation permeability test

Since, the freeze-thaw test was performed with the ramp-type freeze, it is unlikely that a shrinkage crack occurred. And that only the trace of the IL influenced coefficient of permeability of the freeze-thaw soil. However the effect of separation and rearrangement of soil particles by freezing of pore water may occur. In contrast, the result of the consolidation permeability test with a sample after the freeze-thaw test did not show significant difference between coefficient of permeability for the IL direction and IL right

angle direction. Both of them were just slightly greater than the coefficient of permeability of unfrozen soil.
However, it is not denied that the trace of IL and minute shrinkage crack by the frost heave, were lost during preparing consolidation test piece or initial loading.

4. CONCLUSION

The results of this study are summarized as follows.
(1) The results of the 1-D freeze-thaw test (IL orthogonal direction) and horizontal displacement restraining freeze-thaw vertical permeability test (IL direction) have revealed that the coefficient of permeability before and after the freeze-thaw can be expressed by two sets of the relation for its relation with the void ratio. Therefore, the coefficient of permeability before and after the freeze-thaw is predicted by void ratio.
(2) In the two sets of freeze-thaw tests, the coefficient of permeability after freeze-thaw *kt* was slightly greater in the IL direction (K) than in the IL orthogonal direction (C). This is considered that the displacement is restrained in the horizontal direction in the horizontal displacement restraining freeze-thaw vertical permeability test and the trace of the IL after the freeze-thaw easily remained.
(3) No clear difference was not seen between the coefficient of permeability *kpt* obtained from a consolidation permeability test of freeze-thaw soil and that obtained from a consolidation permeability test of the IL direction and the IL orthogonal direction. In addition, they were only slightly greater than the coefficient of permeability *ku* and *kpu* of unfrozen soil.
(4) It is not denied that the IL, and the trace of minute crack by the frost heave, is lost during the process of preparing consolidation test piece and initial loading.

5. REFERENCES

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