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Experimental estimation of permeability of freeze-thawed soils in artificial ground freezing

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Abstract

Permeability increase of freeze-thawed soil is a well-known phenomenon. Many of researches have been conducted to clarify the mechanism of permeability of freeze-thawed soils and to estimate it with simple 1-D freeze-thaw test systems. However, it was quite doubtful whether permeability of freeze-thawed soils of AGF could be estimated directly from such a simple 1-D test.

Purpose of this study is to propose an estimation procedure of permeability of freeze-thawed soil after artificial ground freezing work. Two types of experiments were conducted for this purpose. One was the 1-D freeze-thaw permeability test in which all of the freezing, loading and permeability measurements were conducted for vertical direction. The other was the horizontal displacement restrained horizontal freeze-thaw vertical permeability test (H test) in which freezing was conducted for horizontal direction while the loading and permeability measurements were for vertical. From these tests, two sets of permeability of freeze-thawed soils were obtained directly by a falling head permeability test. Moreover, water content distribution of the specimens were measured and converted into void ratio. Permeability of freeze-thawed soil of the H test was estimated based on void ratio distribution of the specimen and the relationship between permeability and void ratio from the 1-D test. Finally, the estimated and measured permeability were compared.

Test results revealed that the permeability at H test can be estimated from the distribution of void ratio and that from the 1-D test, while two sets of permeability of freeze-thawed soils greatly differ from each other. It is considered that permeability increase of freeze-thawed soils is caused by deflection of void ratio distribution generated after freeze-thaw and the void ratio grows greater in the colder side and lower in the warmer side. As the result, overall permeability of freeze-thawed soils at H test became greater than that of the 1-D test.

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1. Introduction

In seasonally frozen ground, the ground is lifted up by frost heave, causing cracks on the road. The frost heave generates the ice lens (IL) and shrinkage crack (SC) in the soil, and it has been believed that IL is particularly likely to occur in silty soil. Vinson et al. [1] investigated on the factors affecting frost heave susceptibility on coarse-grained soils, and argued that the factors other than particle size must be considered into account in determining frost heave susceptibility. Akagawa et al. [2] examined frost susceptibility of the welded tuff, and confirmed that IL was generated under the condition of both the slow cooling rate and water supply. Although a number of researches have been conducted on factors affecting frost susceptibility, they haven't been completely understood. The significant increase in permeability of freeze-thawed soil is a well known phenomenon, and it has been believed that the increase was by one to two orders of magnitude for the permeability because of soil structure change due to freeze-thaw effect. In addition, Dumais et al. [6] showed that the increase of permeability after thawing was correlated with the median particle diameter of the fine fraction.

In a natural state, ground freezing is occurred in the vertical direction while overburden pressure acts in the same

direction. However, in the Artificial Ground Freezing method (AGF), ground freezing is occurred in the horizontal direction by freezing pipes installed in the ground while the overburden pressure acts in the vertical direction. In AGF, over-consolidated deep underground soil is subjected to freeze-thaw action. In the case that IL and SC occur in over-consolidated soil, unexpected groundwater flow may occur in the impermeable layer due to the trace of IL and SC remaining after thawing, which is a concerned issue.

Some experimental studies were conducted to develop a method for predicting a permeability change of over consolidated soil caused by freeze thaw effect with AGF. Permeability change in the case that frozen soil partially thawed was examined by the horizontal displacement restrained freezethaw permeability test (H test) shown in Fig. 1. Permeability when the frozen soil completely thawed was examined by the 1-D freeze-thaw test shown in Fig.2. Ito et al. [7] reported that permeability of thawed soil was not affected by the freezing condition which dominates amount of IL. Also, it was reported that permeability of unfrozen and freeze-thawed soil was expressed by two sets of relation for the void ratio and permeability [8]. Both the permeability and void ratio increased remarkably in freeze-thaw cycles under small overburden pressure, and the void ratio distribution of H test remarkably increased on the low temperature side [9,10]. Although a unique correlation between the void ratio and the permeability was recognized, a method to predict permeability of freeze-thawed soil from void ratio distribution has not been proposed.

2. Purpose

The purpose of this study is to develop a method to predict permeability change in freeze-thawed soil. Particularly, the







Fig.2 One-dimensional freeze-thaw permeability test.

followings were examined.

(1) Influence of the degree of pre-consolidation and overburden pressure on the permeability were examined to identify the factors of increase in permeability by freeze-thaw.

(2) In order to prove the applicability of the proposed prediction method, the computed permeability from the void ratio distribution of H tests was compared with the one obtained from the falling head permeability test.

3. Test Method

3.1 Soil material

Table 1 shows physical properties of Fujinomori clay filtered with a 425µm sieve. It was adjusted at the water content that is 1.3 times greater than the LL. Consolidation of slurry to the test condition was performed at several stages. Next, a specimen with 10cm in diameter was trimmed to 5cm height in the 1-D test. In the H test, a specimen with 8cm in width and 7cm in depth was trimmed to 8cm height.

3.2 One-dimensional freeze-thaw and permeability test

Fig. 2 shows a one-dimensional freeze-thaw permeability test system (1-D test). This test system consists of an acrylic cylinder and upper and lower plates. For the test, the upper and lower plates are set as a high-temperature

side (Tw) and low-temperature side (Tc), and a test specimen was frozen from the lower to upper sides, and water was supplied and drained from upper the plate during freezing process. Fig. 3 shows the temperatures of Tc and Tw in the experiment. The temperature was lowered with cooling rate as $dT/dt = 0.2 \,^{\circ}C/h$ unt il Tc and Tw reached $-6 \,^{\circ}C$ and $-1 \,^{\circ}C$ respectively. After that, Tc and Tw were lowered to $-10 \,^{\circ}C$ and maintained for 6 hours to freeze the entire specimen. This test system allows to conduct a falling head permeability test by connecting the lower plate and burette, and draining water from the upper plate. A falling head permeability test was performed from the lower to upper directions before and after freeze-thaw process.

Table 2 shows test conditions for examining the effects of the overburden pressure p and pre-consolidation pressure P. In order to investigate the effect of overburden pressure p, in C22 and C23 $P = 500 \text{ kN/m}^2$ was kept while different p was applied. Also to see the influence of pre-consolidation pressure, in C22 and C24 and C25 different P was applied, while $p = 100 \text{kN/m}^2$ was kept. After freeze-thaw process, the specimens of C24 and C25 were divided into several portions respectively from Tc to Tw, and water content was measured to calculate the void ratio.

3.3 Horizontal displacement restrained horizontal freeze-thaw and vertical permeability test

Fig.1 shows a horizontal displacement restrained freeze-thaw and vertical permeability test system (H test). This test system consists of the cooling plates on the left and right sides, acrylic plates with a thickness of 5cm on the front and rear sides, and upper and lower temperature control plates made of vinyl

Table 1 Properties of soil used in this study.





Fig.3 Temperature condition during freeze-thaw test.

Table 2 Test Condition.

Test method	Test No.	Consolidation	Overburden	Temperature
		pressure	pressure	gradient
		P	р	dT/dx
		kN/m ²	kN/m ²	°C/cm
1-D freeze-thaw	C22	500	100	0.714
	C23	500	190	0.714
	C24	300	100	0.714
	C25	150	100	0.714
Horizontal freeze-thaw	K21	500	100	0.625
	K22	500	200	0.625
	K25	300	50	0.625
	K30	500	50	0.625

Cooling rate dT/dt : 0.2 °C/h , Lowest temperature T : -10 °C, Freeze-thaw cycles n : 1, Water supply : Open chloride. In the test, the temperatures of the lower temperature side (Tc) and higher temperature side (Tw) were controlled respectively. The specimen was frozen horizontally from the Tc to Tw sides. In freeze-thaw process, water was supplied and drained from the Tw side. During the test, the temperature of the cooling plate was controlled as shown in Fig. 3. An overburden pressure was applied from the upper plate during freeze-thaw test. A falling head permeability test was performed in the vertical direction before and after freeze-thaw process with the burette connected to the lower plate, and drained from the upper plate.

Table 2 shows test conditions. In order to examine the effect of the test (overburden) pressure p, the same preconsolidation pressure $P = 500 \text{ kN/m}^2$ was applied to K21, K22 and K30 while changing the test pressure. In order

to investigate of the pre-consolidation pressure, the same overburden pressure $p = 50 \text{ kN/m}^2$ was applied to K25 and K30 while changing pre-consolidation pressure. The specimen was divided into several equal portions from Tc to Tw after the H test. The water contents of these portions were measured to estimate the void ratio.

4. Result

4.1 One-dimensional freeze-thaw test

(1) Frost heave

Fig. 4 shows the frost heave over elapsed time. Total frost heave is the smallest at C23 with the greatest overburden pressure. After thawed, C25 with smaller pre-consolidation pressure and C23 were compressed more than before frozen. The displacement in the thawing of both C22 and C24 returned almost to the level before freezing.

(2) Void ratio and permeability obtained in the 1-D test

Fig. 5 shows relationship between void ratio e and permeability k. Permeability k_u is obtained from freeze-thaw test of unfrozen soil, and permeability k_t is obtained from the freeze-thawed specimen. In C22 and C24, the void ratio of freeze-thawed soil does not changed greatly from the unfrozen soil, and in C23 and C25, the void ratio decreases. In both experiments, k_t increased more than k_u . In C22, C24 and C25 with $p = 100 \text{ kN/m}^2$, it is recognized that the void ratio after thawing is converged to approximately e = 0.85 and $k_t = 1.0 \times 10^{-8} \text{ m/s}$ even with different pre-consolidation pressure. The relationship between the void ratio and permeability of freeze-thawed soil is different from that of unfrozen soil. This relationship of freeze-thawed soil can be expressed by relational expression (1) in Fig. 5.

(3) Void ratio distribution in the 1-D test

Fig. 6 shows the void ratio distribution in the freeze-thawed specimen obtained from the 1-D test. The void ratio was slightly greater on the Tc side than on the Tw side. In C24 with larger pre-consolidation pressure, the void ratio of freeze-thawed soil increased on the Tc side more than that of unfrozen soil. It is recognized that the void ratio distribution of C25 approaches the same level as that of C24.

(4) Permeability distribution estimated from the void ratio distribution of 1-D test

Fig. 7 shows the permeability distribution obtained from the



Fig.7 Permeability distribution in the specimens (1-D test).

void ratio of the 1-D test. The estimated permeability k_t is obtained by substituting the void ratio into Equation (1). The values of k_t of both C24 and C25 were almost equal, and corresponded well with that of k_t .

4.2 Horizontal displacement restrained freeze-thaw vertical permeability test

(1) Vertical displacement

Fig. 8 shows the vertical displacement over elapsed time. In this test, freezing direction is horizontal while the displacement was allowed only in the vertical direction. In K22 with the greatest overburden pressure, vertical displacement h did not change significantly between unfrozen and freeze-thawed soil. In K21 and K25 and K30, it was shown that h increased in freeze-thawed soil.

(2) Void ratio and permeability

Fig. 9 shows relationship between void ratio and permeability. k_t increased greater than k_u . In K22, the void ratio of freeze-thawed soil was lower than that of unfrozen soil while on the other hand in K21, K25 and K30, the void of freeze-thawed soil was greater than that of unfrozen soil. In addition, k_t decreased with an increase of the overburden pressure.

(3) Void ratio distribution in the H test

Fig. 10 shows void ratio distribution in the freeze-thawed specimen obtained from the H test. According to K21, K22 and K30 with pre-consolidation pressure $P=500 \text{ kN/m}^2$, the void ratio on the Tc side increased more in the smaller overburden pressure p. On the Tw side, the void ratio of freeze-thawed soil did not changed so much and was kept around 0.8. As for K25 with the smallest pre-consolidation $P=300 \text{ kN/m}^2$ and overburden pressure $p=50 \text{ kN/m}^2$, the void ratio on the Tc side was increased remarkably.

(4) Permeability distribution estimated from the void ratio distribution of H test

Fig. 11 shows permeability distribution obtained from the void ratio distribution from the H test. The calculated permeability k_t ' is obtained by substituting the void ratio obtained from the H test into Equation (1). The distribution of k_t ' was similar to the void ratio distribution after thawing. Comparing the measured permeability k_t with k_t ', k_t shows the value close to k_t ' around Tc, which suggests that the permeability increased after thawing in the H test is strongly influenced by the increased void ratio on the Tc side.

Fig. 12 shows the relationship between the estimated and measured permeability. The measured permeability is obtained from the falling head permeability test after freeze-thaw process. The estimated permeability k_t '(CM) obtained from the 1-D test is computed by substituting the permeability calculated from the void ratio distribution into Equation (2) in Fig. 12. On the other hand, k_t '(KM) was computed by substituting the permeability calculated from the void ratio distribution into Equation (3) in Fig. 12. Both k_t '(CM) and k_t '(KM) present a good agreement with k_t .

Fig. 13 summarizes the relationship between the measured and computed void ratio vs permeability relationship in the 1-D





Fig.9 Relationship between the void ratio and permeability (H-test).



Fig.10 Void ratio distribution in the specimens (H-test).



Fig.11 Permeability distribution in the specimens (H-test).

and H tests. The permeability of frozen-thawed soil $k_t(K)$ is obtained from the H test, and $k_t(C)$ is obtained from the 1-D test. The relationship shows that there is a good agreement between the measured permeability $k_t(K)$ and the computed permeability $k_t'(KM)$ by the proposed method. Similarly $k_t'(CM)$ shows a good agreement with $k_t(C)$.

5. Conclusion

The conclusion of this study is summarized as follows.

(1) Changes in void ratio and permeability by freeze-thaw were strongly influenced by overburden pressure in the freezethaw test rather than pre-consolidation pressure which was related to the strength of soil, and it is recognized that void ratio and permeability decrease with an increase of overburden pressure.

(2) The void ratio of freeze-thawed soil became greater on the Tc side. In particular, in the H test, the void ratio on the Tc side remarkably increased with smaller overburden pressure.

(3) The permeability distribution was calculated from the void ratio distribution in the H test based on the relationship between the void ratio and permeability in the 1-D test.

(4) The estimated permeability calculated from the distribution of permeability was closed to the measured value, which suggests that the permeability of freeze-thawed soil in AGF can be evaluated by the estimated permeability calculated from both the void ratio and permeability distributions in the 1-D test.



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