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The on-site remediation of contaminated fine-grained soil based on the effect of permeability change after freezing and thawing

Conversion à pied d'oeuvre de sol à grains fins basée sur l'effet du changement de perméabilité après gel et dégel

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ABSTRACT
In many cases, washing contaminated ground is very difficult. One major reason is the low permeability of fine-grained soils. In order to overcome such a problem, it was proposed to utilize the phenomenon of permeability which increases after freezing and thawing. A series of semi-full scale experiments have been carried out to investigate the feasibility of the method to an on-site remediation project. The major experimental results are as follows: 1) Permeability of fine-grained soil increased after freeze-thaw treatment. In this experiment, the soil's permeability increased 20 to 100 times. 2) It was observed in the specimen after the experiment that sodium chloride aqueous solution was pushed from the central part to the side direction of the specimen. In comparison with the unfrozen specimen, the frozen-thawed specimen was almost perfectly washed. 3) The washing efficiency of the frozen and thawed case was about 7 to 10 times greater than the non-frozen case.

RÉSUMÉ
Dans de nombreux cas, la terre contaminée est très difficile à laver. L'une des principales raisons est la faible perméabilité des sols à grains fins. Afin de remédier à ce problème, il a été proposé d'exploiter le phénomène de perméabilité qui augmente dans les sols à grains fins, après congélation puis dégel. Une série d'expériences à semi-pleine échelle a été réalisée pour apprécier la possibilité d'utiliser cette méthode pour un projet de conversion à pied d'oeuvre. Les principaux résultats expérimentaux sont les suivants : 1) La perméabilité des sols à grains fins augmente après un traitement de gel-dégel. Dans cette expérience, la perméabilité du sol a augmenté de 20 à 100 fois. 2) A la fin de l'expérience, on observe dans le spécimen que la solution aqueuse de chlorure de sodium a migré de la partie centrale vers la direction latérale du spécimen. En comparaison avec le spécimen non gelé, le spécimen gelé-décongelé a été presque parfaitement lavé. 3) L'efficacité du lavage dans le cas du gel-dégel a été d'environ 7 à 10 fois meilleure que dans le cas non gelé.

1 INTRODUCTION

It is difficult to wash and remove pollutant confined in cohesive soil by conventional methods such as the pump and treat method, etc. This reason is due to the low permeability of cohesive soil. In addition, negative pressure such as by a vacuum may become a cause of the clogging in soil's voids resulting in lower permeability. In order to solve this problem, the freezing and thawing method was proposed. When fine-grained soil is freezing, numerous ice lenses generate aggregated structures. After thawing the soil, a large part of newly generated structures remains in the soil resulting in an increase in permeability of the soil as shown in Fig. 1.

Based on such a phenomenon, it was proposed that the freeze-thaw effect can be applied to contaminated fine-grained soils as a pretreatment before washing by a conventional remediation method.

An image of the remediation method of contaminated fine-grained soil based on this effect is shown in Fig. 2. In this method, a group of temperature control pipes and water supply pipes are installed in the contaminated area at a predetermined interval. At first, the coolant is circulated in the temperature control pipes to freeze the contaminated ground. After it is confirmed that the pre-determined part of the ground is frozen, the ground is thawed with the warm water circulating inside the temperature control pipe. At this time, the water conduction pipes are set to supply and collect water by applying pressure on one side. The cracks generated by the ice lenses, etc. in the freezing stage are expected to remain in the thawing stage, which results in increasing permeability in the ground. Polluted water from the contaminated ground is removed from another set of water conduction pipes.

The purpose of this paper is to introduce the preliminary test results and the model experiment in order to examine the applicability of the proposed method.

2 PROCEDURE OF THE MODEL EXPERIMENT

A series of experiments are being conducted using the test equipment shown in Fig. 3. This test system is able to carry out

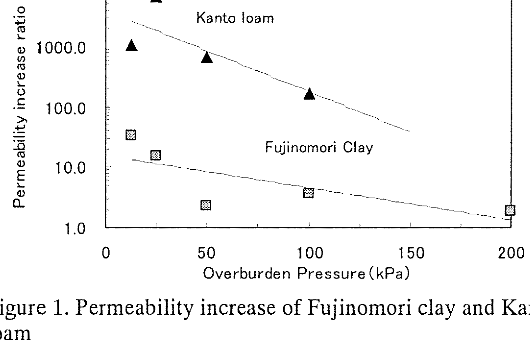
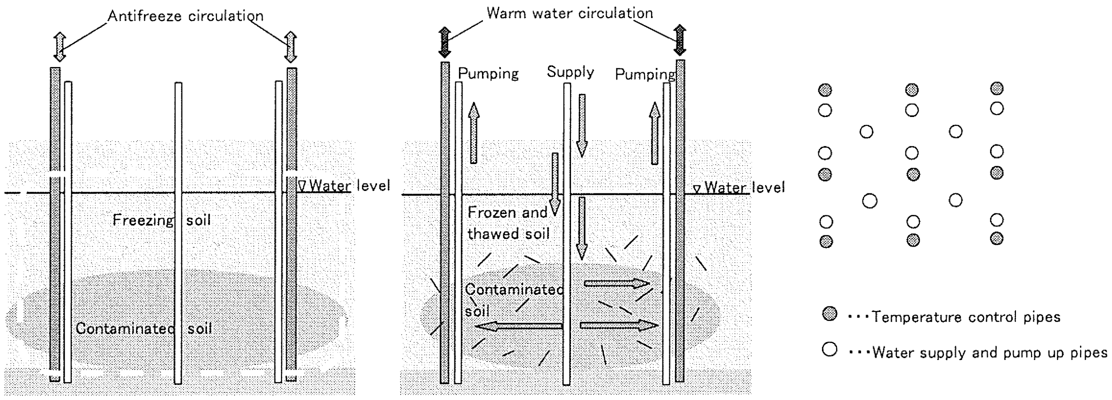


Figure 1. Permeability increase of Fujinomori clay and Kanto loam



(1) Freezing (2) Thawing and washing (3) Plain view

Figure 2. Concept of the on-site remediation method using soil's freezing and thawing effect

the freezing and thawing of the cylindrical tank-shaped specimen that is prepared in the test tank. The four temperature control plates placed outside of the tank cool the specimen from the tank wall to the center direction by circulating temperature-controlled anti-freeze in them. The plates also heat the frozen specimen by circulating warm water in them.

The center pipe is used to supply water to the specimen center. This is a steel pipe of 34 mm outer diameter, and the ϕ =2mm hole is placed in 2 rows on the surface of the pipe in 15mm intervals. The four plastic board drains are placed inside the tank wall for drainage purposes. The plastic board drain is a commercially available product of 4mm thickness for soft ground improvement. In the experiment, four pieces of 5cm × 45cm were cut from the original drain material. A constant water head is applied to the specimen through the center pipe and negative pressure is applied through the four drains by a vacuum pump.

The sample soil for the experiment is Fujinomori Clay (ρ_s: 2.662g/cm^3, LL: 57.2%, PL: 27.0%) passing through a 425μm screen sieve. A 2% sodium chloride aqueous solution was added to the sample soil as a pollutant. The sodium chloride solution of about 70% water content was added to the sample soil to make the slurry and was left for half a day. Then the slurry was mixed for 30 minutes and de-aeration was carried out after that. Next the slurry sample soil was put into a tank of 60cm inner diameter at 55cm from the bottom as shown in Fig.4. Finally, the sample soil was consolidated at 30kPa loaded weight by allowing drainage through the center pipe and the four drains.

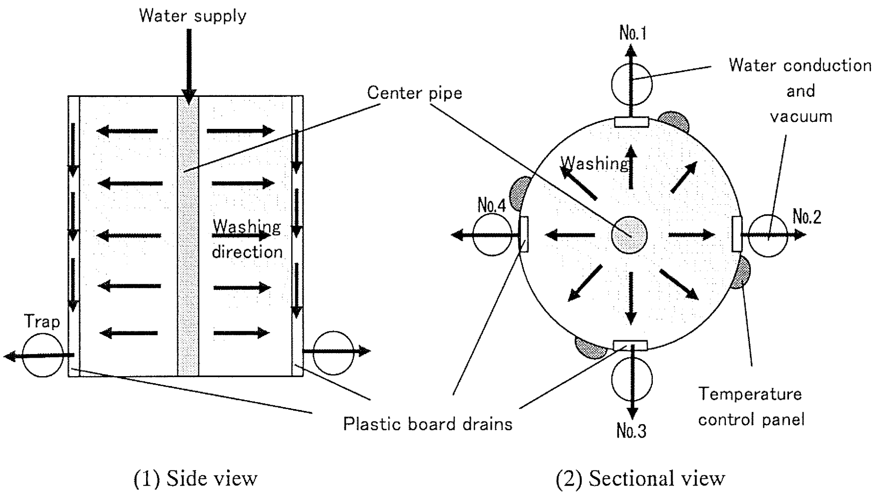
The freezing and thawing experiment condition is shown in Table 1. The overburden pressure was set to 20 kPa throughout the experiment. The water supply and drainage bulbs were always open during the entire experiment.

The freezing stage was started by initiating circulation of the anti-freeze through the four temperature control plates. In the freezing stage, the progress of the freezing front was monitored by the thermocouples installed at the tank bottom and middle planes. By confirming that the freezing plane had reached the tank center, the circulation of the cooled anti-freeze ceased.

The thawing stage was started by circulating warm water through the temperature control plates. At the same time, washing water was supplied from the center pipe with 80cm of water head. After 24 hours, -30kPa of negative pressure was applied by a vacuum pump through the four drainage pipes for another 48 hours. Finally, the negative pressure ceased and the washing water was applied from the outside, which was the reverse direction water supply from the drainage pipes to the center pipe direction with 80cm of water head for another 24.5 hours.

All discharged water was collected in the four bottles or vacuum traps and the amount of water and their sodium chloride concentration were monitored. Furthermore, the permeability of the specimen was calculated based on the theory of confined groundwater.

After the experiment, the specimen was dismantled, and the distribution of the water content and the sodium chloride concentration was examined. Three sets of samples from the upper step (h=40-45cm from the bottom level), middle step (h=25-



(1) Side view (2) Sectional view

Figure 3. Freeze-thaw experiment system

Table 1. Freeze-thaw experiment condition

Case		A	B
Freeze-thaw condition		Non-frozen	Frozen-thawed
Initial height	(cm)	46.7	46.6
Initial water content	(%)	54.2	55.9
Initial NaCl concentration	(%)	1.7	1.8
Freezing temperature	(℃)	—	-1→ -11→ -13
Freezing period	(hour)	—	257.0
Water head in washing period	(cm)	80	
Washing period (water head only)	(hour)	—	24
Vacuum applied in washing period	(kPa)	-30→ -50→ -70	-30
Washing time (water head and vacuum)	(hour)	48.0	48.0
Period of opposite direction washing (water head only)	(hour)	—	24.5

30cm) and lower step (h=5-10cm) were used. In the data shown in this paper, the sodium chloride concentration was estimated from the chloride ion concentration.

For comparison purposes, the non-frozen case (Case A) was compared to the frozen and thawed case (Case B). The list of the experiment condition is shown in Table 1.

3 EXPERIMENT RESULTS

The result of the non-frozen case will be introduced in Fig. 4.

3.1 *Non-frozen case (Case A)*

(1) *Amount of the discharged water*
The discharged water was collected from the four directions (No.1, 2, 3 and 4). The difference of the amount between them was about 2 times. The total of them was about 8.3 L.

(2) *Sodium chloride concentration in the discharged water*
The sodium chloride concentration in the discharged water is also measured from the discharged water. It seems that there is a reverse relationship between the amount of discharged water and the concentration of salt in it. For example, the salt concentration kept almost same the initial concentration in No. 1 and 3 whose discharged amount were relatively small. But, they decreased to the half value in No. 2 and 4 whose discharged amount was relatively large.

(3) *Permeability of the specimen*
In Fig. 4(a), the permeability of the specimen computed from the amount of discharged water from the four directions is shown. The permeability was kept almost constant through the entire test period. The average of the four directions was about 1.1×10^{-6}cm/s.

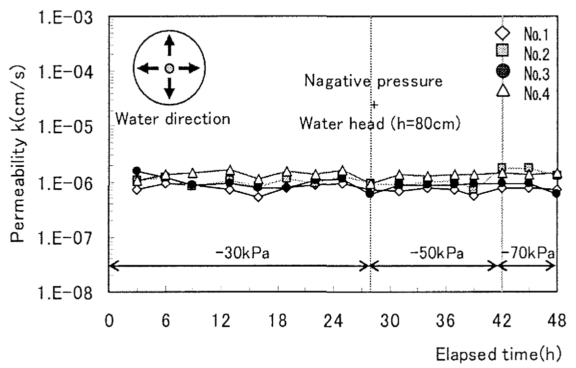
(4) *Distribution of sodium chloride remained in the specimen*
In Fig. 4(b), the sodium chloride distribution in the test specimen is shown. Except at the center and the wall side, the concentration was roughly constant and was close to the initial value. The percentage of the removed salt that is defined as the washing ratio was about 7 % from the specimen and 9 % from the discharged water.

3.2 *Frozen and thawed case (Case B)*

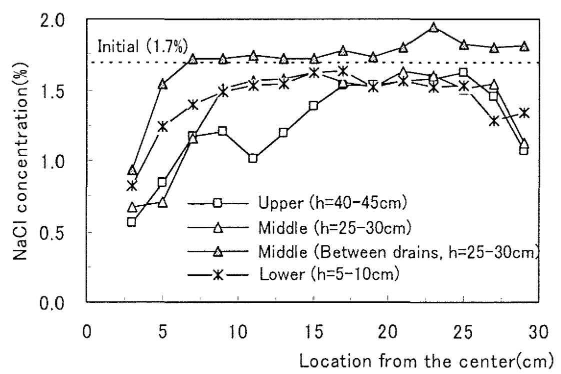
(1) *Amount of the discharged water*
The total amount of the discharged water in 48 hours after application of -30 kPa negative pressure is 170L which is 20 times greater than that of Case A in the same duration.

(2) *Sodium chloride concentration in the discharged water*
Before the application of negative pressure, the sodium chloride concentration was kept at almost the initial value of 1.8%. After application of -30 kPa negative pressure, it sharply dropped and stayed at about 0.1 to 0.3 % right before stopping the negative pressure. In the reverse water circulation stage, the concentration was almost zero in the reverse washing stage. It was inferred that the center portion of the specimen was perfectly washed at the end of application of the negative pressure.

(3) *Permeability of the specimen*
In Fig. 5(a), the permeability of the specimen computed from the amount of discharged water from the four directions is shown. The permeability showed its peak value right after application of the negative pressure. Then, the value decreased to

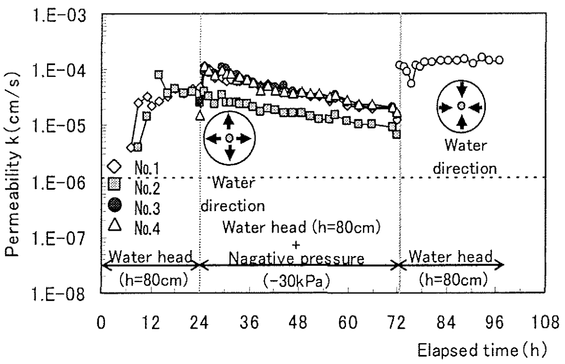


(a) The permeability of the specimen computed from the amount of discharged water from the four directions

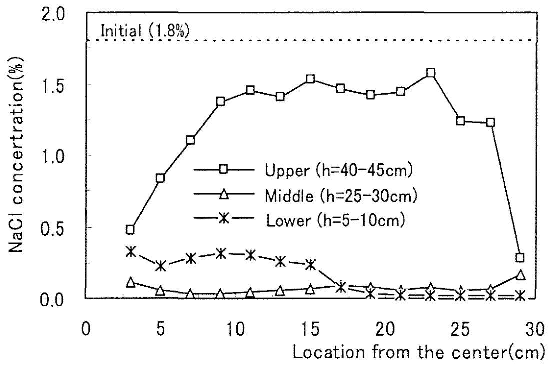


(b) Distribution of NaCl remained in the specimen

Figure 4. Non-frozen and thawed case (Case A)



(a) The permeability of the specimen computed from the amount of discharged water from four drains



(b) Distribution of NaCl remained in specimen (Direction to No.4 drain)

Figure 5. Frozen and thawed case (Case B)

one fifth of the maximum value. In comparison with Case A, the maximum value which is about 1.1×10^{-4}cm/s was 100 times greater than that of Case A. Overall, it can be said that the permeability of the frozen-thawed specimen was roughly 20 to 100 times greater.

In addition, it was confirmed that the deteriorated permeability at the end of the washing stage was recovered to the level of the maximum value by the reverse direction water supply.

(4) *Distribution of sodium chloride remained in the specimen*
In Fig. 5(b), the sodium chloride distribution in the test specimen after the freezing and thawing experiment is shown. The sample of the 3 sets from the upper step (h=40-45cm from the bottom level), middle step (h=25-30cm) and lower step (h=5-10cm) was collected and measured. In the middle and lower steps, in comparison with 1.8% initial concentration, the specimen was almost perfectly washed, especially the outer portion of the specimen. In the upper step, however, the degree of washing is significantly less than that in the middle and lower steps. This can be inferred from the monitored temperature record that about 10cm of the upper part of the specimen remained unfrozen in the cooling stage.

The percentage of the removed salt that is defined as the washing ratio was about 71 % from the specimen and 62 % from the discharged water.

3.3 *Comparison of the washing effect*

In Table 2, the washing ratios of the two experiments are shown. The effect of the freeze-thaw treatment is about 7 to 10 times greater than the non-frozen case when comparing the remained NaCl in the specimen and removed one in the discharged water. Moreover, the difference between them becomes about 16 times if the comparison is done in the middle and lower parts of the specimens where the effect of freezing can be directly compared with the non-frozen case.

3.4 *Observation of the specimen*

In observation of the specimen after the experiment, there were the regions where the clay changed from several mm to 1-2cm size particles. However, this structure was not seen in the upper surface of the specimen because the effect of heat flow from the top plate prevented the upper part of the specimen from freezing. In addition, the center portion of the specimen was consolidated because of the increasing pressure in the freezing stage.

Table 2. The washing ratio in the two experiments

(%)

Case		A		B		
		Non-frozen		Frozen and thawed		
	Steps	Direction to drains	Between drains	Direction to drains: Direction to No.2 drain	Direction to drains: Direction to No.4 drain	Between drains
Dismantled specimen	Upper step	17.5	–	32.5	32.6	19.8
	Middle step	12.1	0	90.6	95.6	94.4
	Lower step	11.7	–	95.6	94.6	93.1
	Average	13.8	0	72.9	74.3	69.1
		6.9		70.6		
Discharged water		9.3		62.3		

4 SUMMARY

The following became clear from the experiments introduced.
1) In this experiment, it was observed that the permeability increased about 100 times right after the freeze-thaw treatment. It fell to around 12 times afterwards with elapsing time. To increase the deteriorated permeability again, the reverse direction water supply may be effective.
2) The washing ratio of the frozen and thawed case was about 7 to 10 times greater than the non-frozen case. Especially in comparison of the middle and lower parts, it can be concluded that the effect of freeze-thaw is about 16 times greater in washing fine-grained soils than the non-frozen case.

The effect of freeze-thaw treatment for washing contaminated ground was confirmed, and the applicability of the freeze-thaw method for the on-site remediation of the contaminated ground was proven.

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