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Des défis du Nord au Sud

Frost heave behavior of unsaturated soils under low overburden pressure and its estimation

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ABSTRACT
This study proposes two kinds of estimation methods for the frost heave ratio of unsaturated frost-susceptible soils under low overburden pressure such as subgrade soils at the pavement structure in cold regions. One is the modified Takashi's equation in contemplation of matric suction of soils under low overburden pressure. The other is the simple frost heave model which evaluates the effects of initial water content, Bishop's effective stress and water absorption during freezing on the frost heave ratio. In addition, the applicability and the usefulness of both methods were discussed based on the results of frost susceptibility tests. As the results, it was revealed that the estimation methods proposed in this study have an excellent applicability to the precise prediction for the frost-heave phenomenon of unsaturated subsurface ground in cold regions.

RÉSUMÉ
Cette étude propose deux types de méthodes d'estimation de la proportion de soulèvement dû au gel de sols insaturés susceptibles de geler dans des conditions de faible pression de surcharge tels que les sols de fondations des structures de chaussée dans les régions froides. L'une de ces méthodes est l'équation modifiée de Takashi qui considère la succion matricielle des sols dans des conditions de faible pression de surcharge. L'autre méthode est le modèle simple de soulèvement par le gel qui évalue les effets de la quantité d'eau contenue initialement, la contrainte effective de Bishop et l'absorption d'eau pendant le gel sur la proportion de soulèvement dû au gel. En outre, l'applicabilité et l'utilité des deux méthodes ont été discutées en se basant sur les résultats des tests de susceptibilité au gel. En conclusion, les résultats ont révélé que les méthodes d'estimation proposées dans le cadre de cette étude présentent une excellente applicabilité pour la prédiction précise du phénomène de soulèvement dû au gel dans le sous-sol insaturé des régions froides.

1 INTRODUCTION

In cold regions, freeze-thaw action induces various geotechnical disasters. For example, numerous cracks are generated at road pavements by the frost heave phenomenon. For mitigation of geohazards, it is important to investigate the freeze-thaw behavior of soil grounds. However, several aspects of the mechanism of frost heave and the thaw behavior of geomaterials are still unclear because these are interactively influenced by several nonlinear factors depending on the in-situ conditions (e.g., Miller 1978, Takagi 1980). In Japan, the mechanism of water absorption to the freezing front of soils, especially under the low overburden pressure observed at the subsurface layer in the unsaturated condition, has not yet been clarified, even though the frost heave ratio can be estimated by a well-known experimental equation "Takashi's equation" at a certain overburden pressure over almost 10 kPa (Takashi et al. 1974).

This study is aimed at examining the influence of nonlinear factors such as the overburden pressure, freezing velocity, degree of saturation, and water supply system on the freezing behavior of soils in terms of the frost heave ratio and temperature changes in specimens during testing. Additionally, this study proposes two kinds of estimation methods for the frost heave ratio of unsaturated frost-susceptible soils such as subgrade soils at pavements in cold regions under low overburden pressure. One is the modified Takashi's equation in consideration of the matric suction of soils under low overburden pressure. The other is a simple frost heave model that evaluates the effects of the initial water content, Bishop's effective stress, and water absorption during freezing on the frost heave ratio.

To this end, we first performed a series of frost heave tests on a frost-susceptible geomaterial under different test conditions, which are considered as the factors that strongly influence the frost heave amount of soils (Michalowski 1993, Konrad and Nixon 1994, Hermansson and Guthrie 2005). Furthermore, we performed a water retention test of the frost-susceptible geomaterial to examine the water retentivity and strength characteristics of the soil in the unsaturated condition. Based on the test

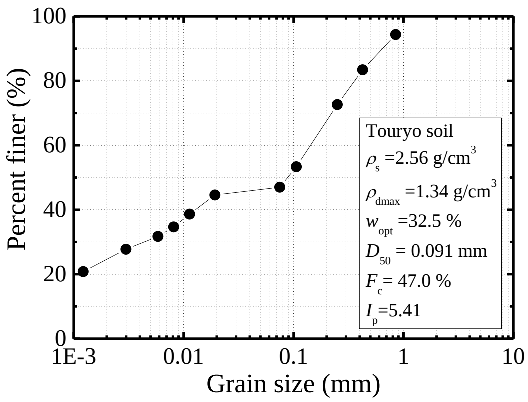

Figure 1. Physical properties of Touryo volcanic soil

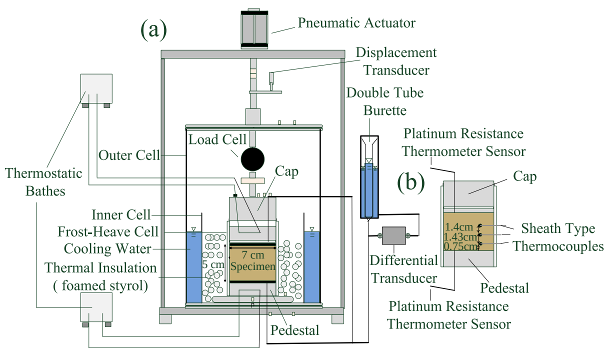

Figure 2. Frost heave test apparatus (a: general view, b: temperature measurement of specimen)

results, we discussed the influences of the test conditions on the frost heave amount and thermal properties of geomaterials. Next, we discussed the applicability and usefulness of both estimation methods by comparing the results of the frost susceptibility tests with the estimation results of the proposed methods.

2 FROST HEAVE BEHAVIOR OF GEOMATERIAL

2.1 Test Material and Test Apparatus

In this study, we used a frost-susceptible volcanic fine-grained soil "Touryo soil" as a test sample. Figure 1 shows the physical properties and grain size distribution curves of the test sample. Touryo volcanic soil (T-soil) is a weathered volcanic cohesive soil, which was sampled in Kitami, Hokkaido, Japan. T-soil shows high frost-susceptibility (Nakamura et al. 2010).

Figure 2 shows a schematic diagram of the apparatus for the frost heave tests. The apparatus has two thermostatic baths to separately control the temperatures (*T*) of the cap and pedestal by circulating antifreeze liquid at a specified constant temperature. Here, the temperatures were measured by embedded platinum resistance thermometer sensors. Therefore, any temperature difference between the cap and the pedestal could be arbitrarily set for a specimen. Moreover, the temperature of the specimen was maintained constant by circulating cold water at 2 °C through an opening between

Table 1. Experimental conditions and test results

Water supply system	σ_a	u	S_{r0}	s	ξ	U	U_h	$\Delta V_w/V$
	kPa	°C/h	%	kPa	%	mm/h	mm/h	
open	2.5	0.2	86.0	9.2	73.7	0.63	0.73	0.557
open	2.5	0.4	73.4	26.4	21.4	2.22	0.67	0.171
open	2.5	0.8	65.4	51.4	23.7	2.84	0.95	0.184
open	5.0	0.2	81.7	13.6	55.8	0.77	0.69	0.423
open	10.0	0.2	76.1	21.3	53.0	0.64	0.64	0.415
open	10.0	0.4	69.0	37.6	27.8	1.62	0.63	0.133
open	10.0	0.8	70.0	34.6	15.8	3.62	0.89	0.123
open	50.0	0.2	81.0	14.4	25.9	0.98	0.34	0.229
open	100.0	0.2	92.7	3.8	16.9	0.64	0.17	0.144
open	200.0	0.2	82.7	12.5	3.3	1.07	0.03	0.034
close	2.5	0.2	82.5	12.7	15.1	2.28	0.64	0
close	5.0	0.2	78.9	17.1	15.7	2.44	0.56	0
close	10.0	0.2	76.6	20.5	14.4	2.73	0.53	0

an inner cell and a pressure cell and by packing thermal insulating materials between the frost-heave cell and the inner cell. Moreover, the apparatus could apply overburden pressure (σ_a) in the range of 0–130 kPa by using an electropneumatic actuator. Additionally, three sheath-type thermocouples were inserted into the specimen through the frost-heave cell to examine the thermal distribution over time during the test. These thermocouples were located at heights of 0.75 cm, 2.18 cm, and 3.58 cm from the specimen bottom. Then, the inflow and outflow of the water volume from the specimen were measured by a differential transducer connected to a double tube burette.

2.2 Test Procedures

2.2.1 Frost Heave Test

In conformance with the standard "Test method for frost susceptibility of soils" (JGS 0172-2003) of the Japanese Geotechnical Society, a series of frost heave tests were performed on T-soil. Table 1 summarizes the experimental conditions of all tests. The experimental conditions were changed in consideration of various factors that are thought to strongly influence the frost heave amount of soils based on previous studies (Michalowski 1993, Konrad and Nixon 1994, Hermansson and Guthrie 2005). In this study, the experimental conditions were determined with reference to in-situ environmental conditions such as the water content and stress state at the subsurface layers and the trend of air temperature in cold regions, which were obtained from a field measurement (Ishikawa et al. 2013). Moreover, the water supply system was changed to examine the effects of the ground water level and water supply source on the frost heave amount and thermal properties of geomaterials. Here, an opened-system permits free intake and discharge of water, whereas a closed-system prohibits it.

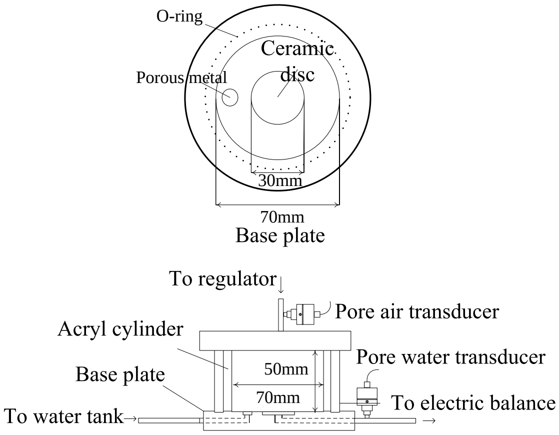

Figure 3. Water retention test apparatus

The frost heave test was conducted as follows. A cylindrical specimen (5 cm (height) × 7 cm (diameter)) was prepared by compacting the sample with the optimum water content with a cylindrical weight of about 3.65 kg, so as to attain the maximum dry density (ρ_d) of 1.34 g/cm^3 for comparison with previous test results. Here, the optimum water content of 32.5% was obtained by the test method for soil compaction using a rammer (JIS A 1210: 2009, A-a method). De-aired water was permeated into a specimen covered with an acrylic frost-heave cell from the bottom end of the specimen until the degree of saturation reached over 80%. Subsequently, the specimen was one-dimensionally consolidated by loading an intended overburden pressure on top of it. Simultaneously, the temperatures at both ends of the specimen were controlled at about 0 °C using the thermostatic baths. Then, the specimen was frozen from the lower part by decreasing the pedestal temperature at a given cooling rate (u) while maintaining that of the cap at 0 °C after a thermal shock in the same manner as done by Penner and Goodrich (1981) and Konrad (1989). Finally, the specimen was thawed from both ends by increasing the temperatures of the cap and pedestal to 5 °C.

2.2.2 Water Retention Test

In accordance with the standard "Test method for water retentivity of soils" (JGS 0151-2009) by the Japanese Geotechnical Society, a water retention test was performed on T-soil using a test apparatus (Figure 3), as follows. A cylindrical specimen (5 cm (height) × 7 cm (diameter)) was prepared in the same manner as that for the frost heave test. Subsequently, de-aired water was permeated into the specimen until it became capillary-saturated. After the specimen preparation, the pore air pressure (u_a) was gradually increased to obtain an unsaturated specimen while maintaining the pore water pressure (u_w) at atmospheric pressure, in order to determine the drying process of the soil-water characteristic curve (SWCC). During the water retention test, the volumetric change of the specimen caused by the application of matric suction (u_a-u_w) was hardly observed.

2.3 Results and Discussions

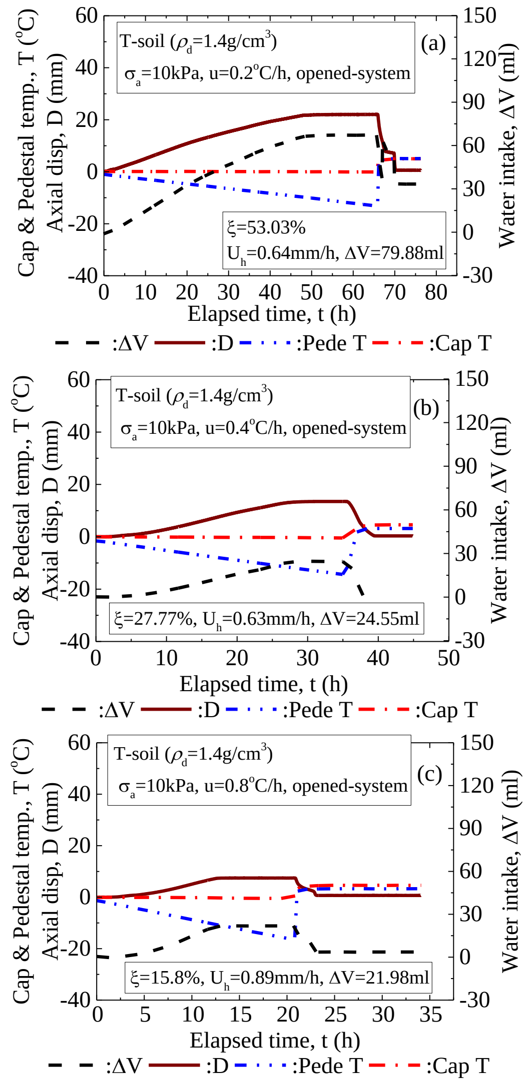

Figure 4. Results of frost heave tests on Touryo volcanic soil (a: u = 0.2 °C/h, b: u = 0.4 °C/h, c: u = 0.8 °C/h)

2.3.1 Frost Heave Test

Figure 4 depicts the freeze-thaw behavior obtained from frost heave tests with opened-system freezing under different cooling rates (u). In all parts of this figure, the x-axis represents the elapsed time (t) after thermal shock and the y-axis represents the axial displacement (D) and water-intake volume (ΔV, negative value means drainage), which were initialized to zero before thermal shock. Here, the freezing rate (U) and frost heave ratio (ξ) were respectively calculated as the ratio of the initial height of the specimen to the duration time of freezing and the ratio of a height increase to the initial height of the specimen. Table 1 also summarizes the results of all tests. From Figure 4, it is observed that the axial displacement increases and water is absorbed in the freezing process. Accordingly, the frost heave behavior can be observed in all the tests. From Table 1, it is observed that the frost heave behavior of T-soil strongly depends on the experimental conditions. For example, in the frost heave tests with opened-system freezing, the low

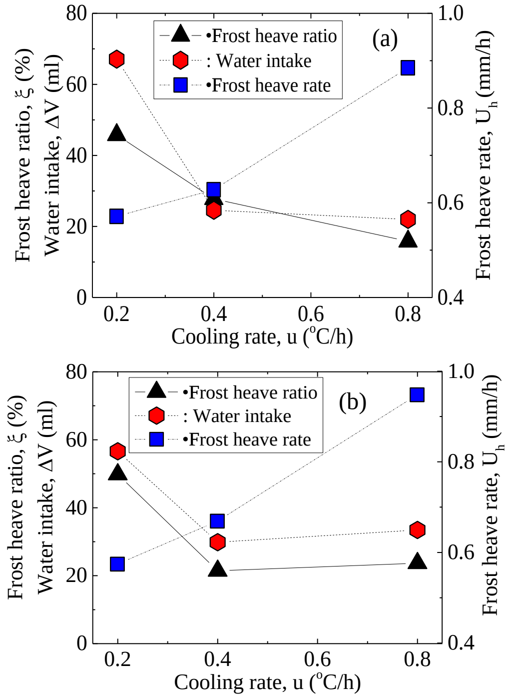

Figure 5. Influence of cooling rate on frost heave behavior (a: σ_a = 10 kPa, b: σ_a = 2.5 kPa)

overburden pressure, slow cooling rate, and high degree of saturation tend to increase the frost heave ratio (ξ), frost heave rate (U_h), and absorbed water volume during freezing (ΔV_w), which indicates the increase in the frost heave amount. Note that U_h is the average velocity of the frost heave amount.

However, though tendencies similar to the results of the frost heave tests with opened-system freezing can be observed in the frost heave tests with closed-system freezing, the influence of the overburden pressure on the frost heave ratio of T-soil is hardly noticeable, as shown in Table 1. This is considered to be because the frost heave ratio in the frost heave tests with closed-system freezing is much smaller than that in the tests with opened-system freezing. In general, frost heave refers to ground expansion caused by water migration and accumulation in a frozen fringe (i.e., a transitional zone just behind a freezing front, where soil is partially frozen). Accordingly, the difference in frost heave behaviors due to water supply systems seems to be caused by the water migration through the specimen because the water content in a specimen for the growth of ice lens is limited in frost heaving in the closed-system. Moreover, though T-soil has high water retentivity, the water content in unfrozen soil reduces drastically by frost heaving when water is not supplied from outside. The permeability of unfrozen soil degrades with a decrease in the volumetric water content, thereby leading to a decrease in the frost heave amount.

Next, we discuss the effect of the cooling rate in the freezing process on the frost heave behavior of T-soil. Figure 5 compares the test results under different cooling rates and overburden pressures. From this figure, it is found that slower u of 0.2 °C/h leads to a larger frost

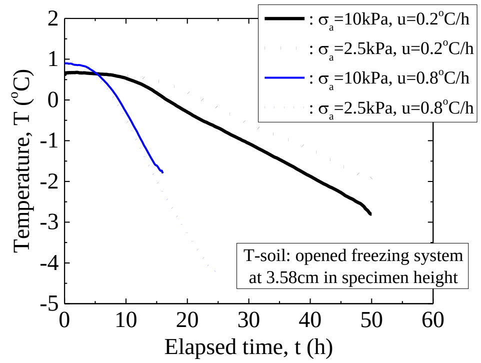

Figure 6. Temperature change of Touryo volcanic soil during freezing

heave ratio of T-soil than the other cooling rates, whereas the test results at cooling rates of 0.4 and 0.8 °C/h are almost identical irrespective of the overburden pressure. These results are considered to be related to the growth of ice lens, which needs the supply of abundant water from unfrozen soil to the frozen fringe. In this study, since a specimen is frozen from the bottom end, the ice lens begins to be formed from the specimen's lower part in the case of a cooling rate slow enough for the growth of the ice lens. However, as the specimen's upper part starts to freeze before the old ice lens at the lower part grows sufficiently in the case of a fast cooling rate, the frost heave behavior at the lower part is restrained. Therefore, it seems reasonable to consider that the influence of experimental conditions such as overburden pressure on the frost heave behavior can hardly be recognized in the frost heave tests at a fast cooling rate, even in high-frost-susceptibility geomaterials.

Figures 6 shows the temperature changes of T-soil measured at a specimen height of 3.58 cm during freezing in the frost heave tests with the opened-system under different cooling rates (u). Note that the temperature changes at other measuring points showed the same tendency as that at the 3.58 cm height. The influence of overburden pressure on the temperature changes is hardly noticeable in the test results for u of 0.8 °C/h, whereas the temperature change at σ_a of 2.5 kPa becomes gentler than that at σ_a of 10 kPa for u of 0.2 °C/h. Moreover, comparison of the test results under the same overburden pressure reveals that the temperature change at u of 0.2 °C/h becomes gentler than that at 0.8 °C/h. The abovementioned various types of differences in the temperature change with time can be considered to be caused by the water content variation in a specimen. For example, under the experimental conditions that make the frost heave ratio increase, abundant water for frost heaving is supplied to a specimen, and consequently, the heat capacity may increase depending on the specimen's water content. Therefore, the gradient of the temperature-time relationship under σ_a of 2.5 kPa and u of 0.2 °C/h becomes gentle, thereby increasing the duration time of frost heaving.

Figure 7 shows the relationships between the gradient of temperature change and the water-intake volume under various cooling rates and overburden pressures. Here, the gradient of temperature change is defined as the gradient

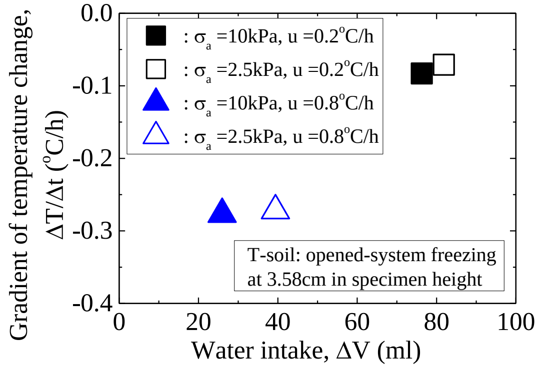

Figure 7. Relationships between temperature changes and water-intake volume

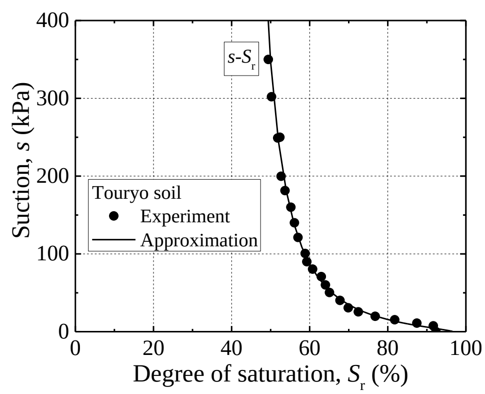

Figure 8. Soil-water characteristic curve (SWCC) of T-soil

of the approximation line when considering the temperature-time relationship shown in Figure 5 as a linear function with a constant gradient. The gradients of temperature change at *u* of 0.8 °C/h are almost identical, irrespective of the overburden pressure or water-intake volume during freezing. However, the gradients of temperature change at *u* of 0.2 °C/h are slightly different. These results indicate that water-intake volume does not necessarily lead to the difference in the gradients of temperature change in the case of the fast cooling rate. The reason for this appears that the fast freezing rate weakens the effect of the heat capacity increase that is followed by water intake.

2.3.2 Water Retention Test

Figure 8 shows the results of water retention tests of T-soil. The figure also shows the regression analysis result of the Mualem–van Genuchten model (Eq. 1, Mualem 1976, van Genuchten 1980).

$$s = \frac{1}{a}\left\{\left(S_e\right)^{\frac{\lambda}{1-\lambda}} - 1\right\}^{\frac{1}{\lambda}} \qquad [1]$$

$$S_e = \frac{S_r - S_{rr}}{S_{rs} - S_{rr}} \qquad [2]$$

where *s*: matric suction, S_e: effective degree of saturation, S_r: degree of saturation, S_r: residual degree of saturation, S_{rs}: maximum degree of saturation, and *a* and λ: constant parameters.

From the figure, it is found that Equation 1 is able to well estimate the drying process of the SWCC for T-soil. According to the estimation result by Equation 1, the residual degree of saturation and the maximum degree of saturation of T-soil are 37.8% and 96.7%, respectively. As T-soil exhibits higher water retentivity than sand, the suction stress (p_s) of about 11 kPa calculated by Bishop's effective stress for unsaturated soils (Eq. 3, Bishop 1959) acts on a soil element even at the recommended degree of saturation of over 80%.

$$\sigma' = \left(\sigma - u_a\right) + \chi\left(u_a - u_w\right) = \sigma_{net} + p_s \qquad [3]$$

where σ': effective stress; σ: total stress; σ_{net}: net normal stress; χ: a parameter related to the degree of saturation, which ranges from 0 to 1; and p_s: suction stress ($p_s = \chi(u_a - u_w)$). Note that this study assumes χ to be equal to S_e (Vanapalli et al. 1996).

In Hokkaido, a cold and snowy island in northern Japan, the freezing depth during winter season is usually lower than 1.0 m, where the effective overburden pressure is in the 10–20 kPa range. Accordingly, it is considered that the influence of suction stress against the effective stress of a soil element on the mechanical behavior at the subsurface layer cannot be neglected.

3 ESTIMATION OF FROST HEAVE RATIO

This section proposes two kinds of estimation methods for the frost heave ratio of unsaturated frost-susceptible soils under low overburden pressure. One is the modified Takashi's equation in consideration of the matric suction of soils under low overburden pressure. The other is a simple frost heave model that evaluates the effects of the initial water content, Bishop's effective stress, and water absorption during freezing on the frost heave ratio.

3.1 Verification of Existing Estimation Method in Japan

3.1.1 Modified Takashi's Equation

In Takashi's equation adopted in the standard "Test method for frost heave prediction of soils" (JGS 0171-2003) of the Japanese Geotechnical Society, the frost heave ratio (ξ) is considered to depend on the overburden pressure (σ_a) and freezing rate (U) as follows:

$$\xi = \xi_0 + \frac{100\sigma_0}{\sigma_a} \times \left(1 + \frac{\sqrt{U_0}}{\sqrt{U}}\right) \qquad [4]$$

where ξ_0, σ_0, U_0: constant parameters characteristic to soil. In contrast, Nixon (1991) reported that both the overburden pressure and the matric suction influence the frost heave rate (U_h), and Kawabata et al. (2014) revealed that the frost heave rate (U_h) is proportional to the frost heave ratio (ξ). Furthermore, since ξ of saturated soils is determined by the effective stress (Takashi et al. 1975), it seems reasonable to consider that ξ of unsaturated soils

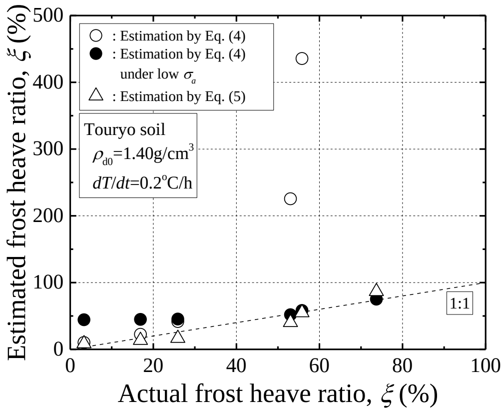

Figure 9. Comparison of prediction accuracy between Takashi's equation and modified Takashi's equation

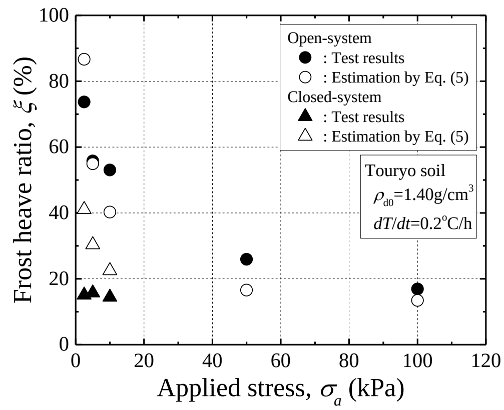

Figure 10. Applicability of modified Takashi's equation to estimation of frost heave ratio

is determined by Bishop's effective stress given in Equation 3. In consideration of these discussions, this section proposes the "modified Takashi's equation," where the overburden pressure (σ_a) is given as the sum of the effective overburden pressure (σ'_a) and the suction stress (p_s) as follows:

$$\xi = \xi_0 + \frac{100\sigma_0}{\sigma'_a + p_s} \times \left(1 + \frac{\sqrt{U_0}}{\sqrt{U}}\right) \quad [5]$$

Equation 5 may expand the application range of Equation 4 from the conventional range of the overburden pressure over 100 kPa (Takashi et al. 1974) to the estimation of the frost heave ratio for unsaturated soils under low overburden pressure, such as the subsurface layer. However, since Equation 5 does not include an evaluation index against the water content of soils, the change in water content is indirectly evaluated by the increase and decrease in the freezing rate as discussed in subsection 2.3.1. For this reason, the ability of Equation 5 to track the change in the water content decides its applicability to the estimation of the frost heave behavior of unsaturated soils. This problem is discussed in the next subsection.

3.1.2 Applicability of Modified Takashi's Equation

Figure 9 compares the actual frost heave ratio (ξ) measured in the frost heave tests with opened-system freezing under various experimental conditions with the frost heave ratio calculated by Equations 4 and 5 in order to examine the prediction accuracy. The open circles and triangles in Figure 9 indicate the values estimated by Equations 4 and 5, respectively, using the constant parameters that were determined based on the results of all frost heave tests with opened-system freezing, whereas the solid circles in Figure 9 indicate the value estimated by Equation 5 using the constant parameters that were determined based on only the results under an overburden pressure (σ_a) of 10 kPa or lower in frost heave tests with opened-system freezing. Comparison of the estimated and measured frost heave ratios in Figure 9 reveals a large deviation between the experiment and the estimation by Equation 4 in the high-frost-heave-ratio range (i.e., in the low-overburden-pressure range) in the case of the results indicated by the open circles, whereas the deviation is observed in the low-frost-heave-ratio range (i.e., in the high-overburden-pressure range) in the case of the results indicated by the solid circles. Therefore, Equation 4 with constant parameters determined by regression analysis using the test results under low overburden pressure is hardly applicable in the high-overburden-pressure range of over 100 kPa; in contrast, Equation 4 with constant parameters determined by regression analysis using all test results is hardly applicable in the low-overburden-pressure range of under 10 kPa. These results indicate that Takashi's equation has a limited range of application. In contrast, the estimation by Equation 5, as indicated by triangles, agrees well with the experimental results in all ranges of overburden pressure in this study, which indicates that Equation 5 has wider applicability than Equation 4.

Figure 10 compares the actual frost heave ratio (ξ) measured in all the test results with the frost heave ratio calculated by Equation 5 at the same overburden pressure in order to examine the applicability of the modified Takashi's equation to the estimation of the frost heave ratio in frost heave tests with closed-system freezing. The modified Takashi's equation can well reproduce the overburden pressure dependency of the frost heave behavior of T-soil under the opened-system condition. However, under the closed-system freezing condition, even the modified Takashi's equation cannot properly reproduce the actual frost heave behavior quantitatively, because the estimation by Equation 5 is larger than that by the experiment irrespective of the overburden pressure. This indicates that there is a limit to the application of the modified Takashi's equation to the estimation of the frost heave ratio under different soil water contents and water supply systems.

3.2 Proposal of New Simple Frost Heave Model

3.2.1 Experimental Equation for Frost Heave

As discussed in subsection 2.3.1, insufficient water supply resulting from the fast cooling rate and closed-system freezing results in the growth inhibition of the ice lens, regardless of the overburden pressure. In this case, the

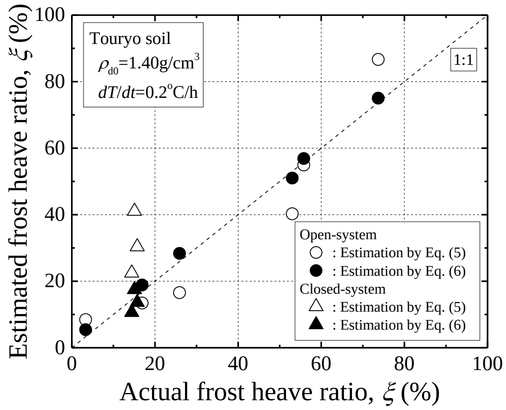

Figure 11. Applicability of simple frost heave model to estimation of frost heave ratio

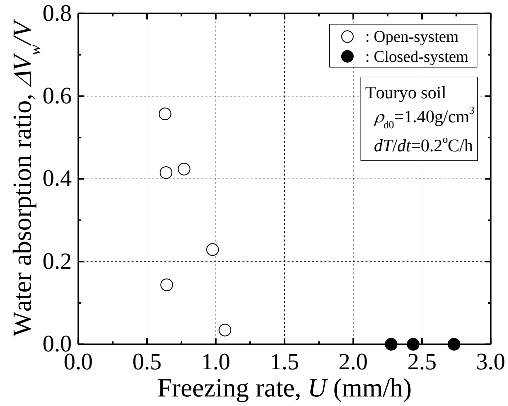

Figure 12. Relationships between absorbed water volume and freezing rate

effects of the freezing velocity and water supply system on the frost heave behavior are equivalent to that of the water volume absorbed to geomaterials during freezing. Therefore, it seems reasonable to consider that three independent factors among all the experimental conditions (the effective overburden pressure (σ'_a), initial degree of saturation (S_{r0}), and absorbed water volume during freezing (ΔV_w)) strongly affect the frost heave amount of T-soil.

To reproduce the frost heave phenomenon of soils under saturated and unsaturated conditions, based on the discussion in the preceding section, this section assumes that the frost expansion strain (ε_f), which is generated by the frost heave of soils over the temperature range of 0°C to the final freezing temperature of soil (T_f), can be expressed as

$$\varepsilon_f = \frac{\varepsilon_{f\,\max} S_{e0}}{\varsigma\left(\sigma'_a + p_s\right)+1} + \zeta \frac{\Delta V_w}{V_0} \quad [6]$$

where ε_{fmax}: maximum frost expansion strain of soil (constant parameter), S_{e0}: initial effective degree of saturation, $\Delta V_w/V_0$: water volume absorbed to a unit volume of soil from the surroundings per unit time, T_f: final freezing temperature of soil at which the change in the unfrozen water content converges during a temperature drop, and ς and ζ: constant parameters. Note that the frost expansion strain (ε_f) is closely related to the frost heave ratio (ξ) obtained from the frost heave tests of soils. In Equation 6, the frost expansion strain (ε_f) is composed of the first term, which depends on the effective stress in the frost heave direction (σ'_f) and the initial degree of saturation (S_{r0}), and the second term, which expresses the ratio of the absorbed water volume during freezing (ΔV_w) to the initial volume of soil (V_0). The former acts as the driving force mainly at the beginning of freezing when the unfrozen pore water flows from the unfrozen soil to the freezing front, whereas the latter represents the phase change from water to ice, where the volume of water absorbed to the frozen fringe increases 1.09 times owing to frost expansion.

3.2.2 Applicability of Simple Frost Heave Model

Figure 11 compares the actual frost heave ratio (ξ) measured in frost heave tests under various experimental conditions with that calculated by Equations 5 and 6. Note that the constant parameters in Equation 6 were determined using all test results, including the frost heave tests with closed-system freezing, whereas those in Equation 5 were determined using only the results of the frost heave tests with opened-system freezing. Comparison of the estimated frost heave ratios with the measured ones under opened-system freezing reveals that the plots estimated by Equation 5 show a wider range of variation against the 1:1 line of the ratio of the estimated value to the measured one than the plots estimated by Equation 6. This indicates that the simple frost heave model expressed in Equation 6 can well reproduce the dependency of the frost heave behavior of T-soil on the overburden pressure and initial degree of saturation. In contrast, the corresponding comparison under the closed-system freezing condition reveals that though there is a large deviation between the experiment and the estimation by Equation 5, the estimation by Equation 6 agrees well with the experiment, irrespective of experimental conditions such as the effective overburden pressure, initial degree of saturation, and water supply system. This indicates greater applicability of the simple frost heave model compared to the modified Takashi's equation to the frost heave behavior estimation of geomaterials.

Incidentally, Takashi's equation is based on the frost heave amount dependency of the freezing rate. In Table 1, a high correlation between both can be seen. In contrast to this, since Equation 6 is not formularized so as to include the term related to the freezing rate explicitly, the ability of Equation 6 to track the change in the freezing rate should be examined. Figure 12 shows the relationships between the water volume absorbed to a unit volume of soil from the surroundings per unit time ($\Delta V_w/V_0$) and the freezing rate (U) obtained from all the tests presented in Table 1. In Figure 12, a unique relationship whereby $\Delta V_w/V_0$ decreases with increasing U can be seen, though the initial degree of saturation affects the relationship slightly. This indicates that in the simple frost heave model, the change in the freezing rate can be indirectly expressed by the increase and decrease in

$\Delta V_w/V_0$. Therefore, it seems reasonable to conclude that Equation 6 proposed in this study can estimate the frost heave ratio of frost-susceptible soils under various experimental conditions with a sufficiently high degree of precision.

4 CONCLUSIONS

The main findings of this study are as follows:

- According to a series of frost heave tests under various experimental conditions, the frost heave ratio of soil strongly depends on the initial degree of saturation, effective overburden pressure, and water supply system and shows a strong correlation with the frost heave rate, freezing rate, and absorbed water amount during freezing.
- This study proposed the modified Takashi's equation in consideration of the matric suction of unsaturated soils and revealed that it improves the prediction accuracy in the estimation of the frost heave amount of quasi-saturated geomaterials under low overburden pressure in comparison to the existing Takashi's equation.
- This study proposed a simple frost heave model that estimates the frost heave amount of soils in consideration of the effects of the initial water content, Bishop's effective stress, and water absorption during freezing on the frost heave ratio, and verified its usefulness and applicability in terms of the dependency of the frost heave behavior on the overburden pressure, water supply system, and water content.

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