Effect of macropores on soil freezing and thawing with infiltration

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Abstract:
An understanding of heat transport and water flow in unsaturated soils experiencing freezing and thawing is important when considering hydrological and thermal processes in cold regions. Macropores, such as cracks, roots, and animal holes, provide efficient conduits for enhanced infiltration, resulting in a unique distribution of water content. However, the effects of macropores on soil freezing and thawing with infiltration have not been well studied. A one-directional soil-column freezing and thawing experiment was conducted using unsaturated sandy and silt loams with different sizes and numbers of macropores. During freezing, macropores were found to retard the formation of the frozen layer, depending on their size and number. During thawing, water flowed through macropores in the frozen layer and reached the underlying unfrozen soil. However, infiltrated water sometimes refroze in a macropore. The ice started to form at near inner wall of the macropore, grew to the centre, and blocked flow through the macropore. The blockage ice in the macropore could not melt until the frozen layer disappeared. Improving a soil freezing model to consider these macropore effects is required. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS ground freezing; unfrozen water; pore ice; water flow in macropore; soil thaw; snowmelt infiltration

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INTRODUCTION
Exposure of a ground surface to subzero temperatures leads to the formation of a frozen soil layer, in which gas, ice, and liquid water coexist (Dash et al., 2006). The amount of unfrozen water decreases with temperature, which can cause large negative water pressures (Schofield, 1935; Hohmann, 1997; Watanabe et al., 2012b). Because negative pressure induces water flow from unfrozen soils at greater depths, the frozen soil layer tends to have a relatively high water content (Iwata et al., 2010; Tokumoto et al., 2010). The frozen layer often has low water and air permeabilities (Burt and Williams, 1976; McCauley et al., 2002; Al Houri et al., 2009), which inhibits water infiltration and aeration to the underlying unfrozen soil. When the frozen layer begins to thaw in spring, snowmelt starts to infiltrate through the thawing layer (Hayashi et al., 2003) and greenhouse gases accumulated beneath the frozen layer are emitted to the atmosphere (Yanai et al., 2011). An understanding of water and heat flows associated with the freezing and thawing of unsaturated soils is important when considering hydrological processes in cold regions. These concepts are also important for the management of microbial activity and fertilizer use on farmland, as water flow influences solute transport.

Soil water flow during the freezing of disturbed soils has been investigated thoroughly using laboratory experiments (Stähli and Studler, 1997; Weigert and Schmidt, 2005) and numerical simulations (Harlan, 1973; Hansson et al., 2004). Although the infiltration of water into thawing soils has received less attention than redistribution of water in freezing soils, relationships between water content of the frozen layer and the timing and rate of infiltration have been investigated with field and laboratory observations (Gray et al., 2001; Watanabe et al., 2012a, b). However, ground is rarely uniform; it contains macropores, such as cracks, roots, and animal holes. Macropores enhance infiltration and aeration, resulting in unique water distributions and redox states in the soil profile (Beven and Germann, 1982; Sammartino et al., 2015). The existence of macropores is also thought to affect the hydraulic and thermal properties of frozen soils (Mackay, 1982; Shirazi et al., 2009; Walvoord and Kurylyk, 2016). Clarification of the effects of macropores is therefore required for the estimation of groundwater recharge by snowmelt infiltration (Lilbæk and Pomeroy, 2010) and change in stream water quality by snowmelt runoff (Shanley and Chalmers, 2010).
1999), and for the investigation of the relationship between groundwater flow and the stability of the artificial frozen soil barrier (Subcommittee of Ground Freezing, 2014). Currently, however, only limited reports on the effect of macropores in frozen soils are available. Woo and Heron (1981) studied the formation of a basal ice layer because of water flow through macropores in snowpack. Stadler et al. (2000) examined unsaturated frozen sands using a dye tracing technique, and detected preferential water flow through relatively large pores that had not contained ice before infiltration. Boike et al. (1998) and Stähli et al. (2004) also visualized preferential flow in frozen soil by using the dye tracing technique. Stähli et al. (1996) developed a two-domain model to describe the preferential flow, and this model has been applied to observations such as frozen sandy soil (Stähli et al., 1999) and alpine permafrost (Scherler et al., 2010). However, direct measurements of the effects of macropores on soil freezing and thawing are still lacking. In this study, laboratory column freeze/thaw experiments were undertaken to investigate in situ freezing and thawing are still lacking. However, direct measurements of the effects of macropores on soil freezing and thawing are still lacking. In this study, laboratory column freeze/thaw experiments were undertaken to investigate infiltration in soils containing vertical and continuous macropores. Soil temperature and the depth distributions of liquid water and ice were monitored during soil freezing and thawing. The effects of macropores on the progression of the freezing front and water redistribution during infiltration with simultaneous thawing of the frozen layer were also investigated.

SAMPLES AND METHODS

Iwate sandy loam and Fujinomori silt loam were used for this study. The sandy loam was collected from the A horizon in an experimental field at Iwate University, Japan. The experimental field had been managed as a weeded fallow field for several years. The soil had a high ignition loss (10.1%), high saturated hydraulic conductivity, and low bulk density (0.8–1.1 mg/m³); it formed small aggregates and was classified as Andisol (volcanic ash soil). The silt loam was a mineral subsoil known as frost susceptible soil. Both soils were sieved through 2-mm mesh. The physical properties of the soils are listed in Table I, and soil water retention curves and unsaturated hydraulic conductivities are shown in Figure 1. As the electrical conductivities of both samples were relatively low, molar depression of the freezing point of soil water was assumed to be negligible. Assuming that ice in a freezing saturated soil has the same configuration as air in a drying unfrozen soil, and that the ice is at atmospheric pressure, the soil water potential \( \psi \) [Pa] in the water retention curve can be converted to a corresponding temperature \( T \) [°C] of frozen soil using the Clausius–Clapeyron Equation 1 (Kurylyk and Watanabe 2013):\
\[
\psi = \frac{L_f}{v} \ln \frac{T_m + T}{T_m},
\]
where \( L_f \) [J kg\(^{-1}\)] is the latent heat of fusion for water, \( v \) is the specific volume of water [m\(^3\) kg\(^{-1}\)], and \( T_m \) [K] is the bulk melting temperature. The second abscissa axis on Figure 1 depicts the temperature calculated using Equation 1. The soil freezing curve, which is the relationship between unfrozen water content and the temperature of frozen soil, measured using nuclear magnetic resonance (NMR) (Watanabe and Wake 2009), is also shown in Figure 1 for comparison.

Samples were mixed with deionized water in a plastic pack and settled for 24 h to a given initial water content \( \theta_{init} \) (Table I). Samples were then packed into acrylic columns with inner diameters of 78 mm and heights of 350 mm (Figure 2), with uniform bulk density (Table I). The two soils had similar thermal properties at this water content and bulk density (Table I). A round bar (2.0- or 5.0-mm diameter) was inserted vertically from the top to the bottom of each column, then removed to make two or four macropores (\( \varphi \) 2 mm × 4, \( \varphi \) 5 mm × 2, and \( \varphi \) 5 mm × 4; Figure 2). Each column was set between two temperature control units that regulated the top and bottom temperatures, and had a water supply tube (6-mm inner diameter, connected to a Mariotte bottle placed on an electronic balance) at the top and a drain tube (6-mm inner diameter) at the bottom. Thirty-four copper-constantan thermocouples (placed at 10-mm intervals), seven time-domain reflectometry (TDR) probes (placed at 50-mm intervals), and seven tensiometers (placed at 50-mm intervals) were placed at 10-mm intervals)

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Particle fraction [%]</th>
<th>( \theta_{init} )</th>
<th>( \rho_b )</th>
<th>( K_s )</th>
<th>( \lambda )</th>
<th>( C )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sand</td>
<td>Silt</td>
<td>Clay</td>
<td>[m³ m⁻³]</td>
<td>[Mg m⁻³]</td>
<td>[m d⁻¹]</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>69.4</td>
<td>19.1</td>
<td>11.5</td>
<td>0.4</td>
<td>1.05</td>
<td>14.6</td>
</tr>
<tr>
<td>Silt loam</td>
<td>14.8</td>
<td>61.2</td>
<td>24.0</td>
<td>0.4</td>
<td>1.18</td>
<td>2.0</td>
</tr>
</tbody>
</table>

\( \theta_{init} \) and \( \rho_b \): water content and bulk dry density when packed, \( K_s \): saturated hydraulic conductivity, \( \lambda \) and \( C \): thermal conductivity and heat capacity at water content and bulk density.
inserted horizontally into each column, and the side wall of the column was insulated with a 10-mm rubber sheet and a 50-mm glass wool layer. The TDR probes were calibrated preliminarily to estimate unfrozen water content by comparing the TDR readings with NMR measurements (Watanabe and Wake, 2009).

The experiments were conducted in a room at constant temperature (4 °C). The soil columns were acclimatized to the room temperature for more than 48 h to establish equilibrium water content profiles and soil temperatures. The columns were then frozen from the upper ends by setting the top and bottom temperatures to $T_{\text{top}} = -6.6$ °C and $T_{\text{bottom}} = 2.0$ °C for 48 h. During the freezing process, the water supply and drain tubes were closed, and no water flux was permitted from either end of the column. Another similarly prepared column was frozen simultaneously, with the same water content and temperature profiles confirmed by thermocouple and TDR readings. After freezing for 48 h, one of the paired columns was sectioned at 50-mm intervals to determine the total water content profile using the oven drying method. Ice profiles were obtained from the difference between total water content and unfrozen water content measured using the TDR probes. For the other column, temperature control at both ends was stopped, and water with a temperature near 0 °C was applied to the top end with a 150-mm constant head using the Mariotte bottle; the bottom end was opened to the atmosphere at 4 °C to allow drainage. The experiment was continued until the drainage started.
During the experiment, soil temperature, liquid water content, pressure head, and weight of the Mariotte bottle were monitored at 2.5-min intervals. The infiltration rate was obtained from the weight change of the Mariotte bottle. After freezing for 48 h and after thawing, the samples were examined to confirm that they retained macropores and that no frost heave had occurred.

RESULTS

Formation of frozen soil layer

Soil temperatures before freezing were close to 4 °C at all depths. When the temperature of the top end of each column started to decrease, the soil froze from the top and the freezing front advanced downward. Figure 3 shows the depth of the freezing front, which was defined in this study as the depth at which the soil temperature reached 0 °C, for each soil type. The advance rate of the freezing front was almost proportional to the square root of time, as described by the Stefan equation (solid lines in Figure 3) (e.g. Kurylyk and Hayashi, 2015), and virtually stopped at 48 h. The frost depth in sandy loam with no macropores was 182 mm after 48 h of freezing; in sandy loam containing 4 × φ 2-mm and 4 × φ 5-mm macropores, the frost depths were 157 and 132 mm, respectively at 48 h. The frost depth was shallower in soils containing larger macropores (Figure 3). The freezing front in sandy loam with 2 × φ 5-mm macropores moved similarly to that in soil with 4 × φ 2-mm macropores, and the frost depth at 48 h was 157 mm. Compared with the sandy loam, the freezing rate of the silt loam was higher in earlier stages of freezing, and the effect of macropores on the progress of the freezing front was smaller.

Temperature profiles of the sandy loam and silt loam samples with no macropores after freezing for 0, 6, 24, and 48 h are shown in Figure 4a and c, and profiles of samples with four φ 5-mm macropores are shown in Figure 4e and g, respectively. These profiles confirmed that macropores retarded the freezing progress (Figure 4a and e), and that macropores had greater effects in sandy loam than in silt loam (Figure 4e and g). Figure 4b, d, f, and h shows water content profiles taken at the same time as temperature profiles. In these figure panels, solid and dashed lines indicate unfrozen water contents at each time point and total water content at 48 h, respectively, and the differences between total and unfrozen water contents represent the ice content. During freezing, all the sandy loam samples experienced water redistribution from unfrozen soil to the freezing front, resulting in an increase in water content by about 0.025 m³/m³ in the frozen layer at all measured depths (Figure 4b). Unfrozen water in frozen soil decreased with temperature, and ice content increased. Shaded area in Figure 4b indicates total decrease in water content in unfrozen soil during freezing for 48 h. The decrease in water content was notable near the freezing front and was not significant near the bottom of the column. In sandy loam containing macropores (Figure 4f), the total water content in the frozen layer increased by 0.05 m³/m³, and the water content in unfrozen soil decreased across the whole depth. These results suggest that the lower freezing rate in soil samples with macropores enhanced water flow from unfrozen to frozen soil.

In silt loam (Figure 4d), water migrated less during freezing than in sandy loam. This result may be because of the difference in the shapes of the soil water retention and hydraulic conductivity curves between −10 and −50 kPa (Figure 1), as the pressure head just beneath the freezing front at 48 h was about −50 kPa and the initial pressure head was about −10 kPa for each soil. The amount of ice in the silt loam was also smaller, as the water supply from unfrozen to frozen soil was smaller. The reason for the higher freezing rate in silt loam compared with sandy loam at the onset of freezing, despite the similar initial water content and thermal properties of the two soils (Table I), is a small release of latent heat in the silt loam because of larger unfrozen water content. The shallower frost depth in silt loam at
48 h, when the advance of the freezing front had almost stopped, occurred because that smaller increase in ice content compared to the sandy loam imparted a lower thermal conductivity to the silt loam. Even in samples with macropores (Figure 4h), water migration to the freezing front did not increase in the silt loam as it did in the sandy loam. The change in ice content in the silt loam did not differ greatly with the presence of macropores. Therefore, the effects of macropores on the freezing rate and frost depth appear to be less pronounced in silt loam than in sandy loam.

**Infiltration into the frozen soils**

After freezing for 48 h, temperature control at both ends of the samples was stopped, and the samples were thawed with application of water from the top ends. Cumulative infiltration during this period with each scenario under the same submerged condition is shown in Figure 5. Although water could not infiltrate into the frozen sandy loam with no macropores at the onset of thawing, it infiltrated slowly, at a rate of 5.6 mm d⁻¹, from 20 h to 50 h after thawing. The infiltration ratio increased at 50 h and reached a value similar to that in unfrozen soil after 55 h. This behaviour is identical to the three phases of infiltration reported by Watanabe et al. (2012a). No infiltration at the beginning of thawing, slow infiltration from 15 h to 40 h, and increased infiltration after 40 h were also observed in the frozen silt loam (Figure 5b). However, the initiation of infiltration and its rapid increase occurred earlier in the silt loam than in the sandy loam. Figure 6a–d shows the temperature and water profiles of frozen sandy loam and silt loam with no macropores. The temperature of the frozen layer in the sandy loam increased gradually to −1 °C at 12.8 h, and the bottom of the frozen layer thawed upward by 6 mm. No infiltration was observed, but the liquid water content at 26.5-mm depth increased because of pore ice melting. The temperature of the frozen layer then increased (Figure 5a), and the sandy loam became saturated at 26.5-mm depth at 36 h, implying that the infiltration front had reached the bottom depth. The frozen layer had thawed 40 mm from the top by 55 h. Liquid water in the frozen layer increased with temperature and decreasing ice content, whereas water content in the unfrozen soil beneath the frozen layer increased only slightly (Figure 6b). These results suggest that the infiltration front moved slowly downward in the frozen layer during this period. At 55.8 h, the frozen layer (temperature near 0 °C) remained at 60 to 130-mm depth, but the water pressure of the unfrozen soil beneath the frozen layer increased.
with a steep increase in the water content. An increase in the hydraulic conductivity of the frozen layer (temperature near 0 °C) would enable water flow through this layer. In the silt loam, a frozen layer was present at 20 to 140-mm depth at 40 h, and infiltration into the unfrozen soil beneath the frozen layer had started (Figure 6c and d). The hydraulic conductivity of the silt loam at 0.01 °C to 0.5 °C may have been higher than that of the sandy loam, as the silt loam had a higher unfrozen water content (Figure 1). This would be associated with earlier initiation of infiltration through the frozen layer of the silt loam, which was thicker than that of the sandy loam.

Infiltration into frozen sandy loam with 4 × φ 2-mm macropores was coincident with that into the sample with no macropores (Figure 5a). Infiltration did not occur at the onset of thawing in sandy loam with 5-mm macropores, but it increased dramatically after 12 h in samples with two macropores (Figure 5a). In samples containing four macropores, infiltration increased at around 17 h and decreased at 22 h (Figure 5a). In silt loam, the effect of macropores was observed after 15 h, but the increase in water content and decrease in temperature were smaller than in sandy loam.

**DISCUSSION**

**Retardation of soil freezing by macropores**

Soil freezing was slower in samples containing macropores. Under a constant boundary temperature, the progression of the frost front is proportional to the square root of the thermal conductivity, which in turn depends on the matrix and macropore composition (Kurylyk and Hayashi, 2015). However, the four macropores only contain 1.6% of the soil matrix, and should have a small effect on thermal conduction through the soil column. Two processes may explain the retardation of soil freezing: convection of relatively warm vapour from unfrozen soil through the macropores, and condensation of water vapour in the macropores near the freezing front. The convection of water vapour would depend on the sectional areas of the macropores, assuming the same temperature gradient and humidity. On the other hand, the amount of water vapour condensation would depend on the inner perimeters of the macropores, as condensation would occur on the inner walls. In this experiment, similar frost depths were observed in samples with similar total inner perimeters (4 × φ 2 mm and 2 × φ 5 mm). These results imply that condensation of water vapour in macropores could be a significant factor in the retardation of soil freezing. Once soil freezing slows, the rate of water migration from unfrozen soil to the freezing front would increase, causing an increase in latent heat release. This kind of feedback also would cause further retardation of soil freezing.

**Blockage of macropores by refreezing of infiltrated water**

The capillary potential of a macropore with a diameter of 5 mm, calculated using the Laplace equation, is about 30 Pa; the freezing point depression of water in the macropore is about −0.000024 °C, according to Equation 1. Therefore, unless water flows from unfrozen soil and
saturates the frozen soil, macropore in unsaturated frozen soil has no water and ice except slight film of unfrozen water on the inner surface. During thawing, the frozen layer thins gradually from the top and bottom, but little water can flow through the thin frozen layer until it reaches a temperature near 0 °C, as the hydraulic conductivity of the frozen soil matrix is low at temperatures below −0.5 °C (Watanabe and Osada, 2016). This process induces the flow of infiltrated water into macropores. This water fills the macropores and is cooled by the surrounding frozen layer. The infiltrated water in the central portion of a macropore with a high flow rate, and water in the vicinity of an inner macropore surface with a low energy state, would not freeze immediately. Thus, ice would start to grow from areas with low flow rates, such as dents between soil particles. Although thin film of unfrozen water may remain between the ice and soil particle, this ice formation would choke the flow path in the macropore and reduce hydraulic conductivity. This process would reduce the flow rate in the macropore, resulting in freezing of most of the infiltrated water and blockage of the macropore. Whether ice blocks a macropore would depend on the temperature and flow rate of the infiltrated water, the temperature and thickness of the frozen layer, and the length and shape of the macropore.

The observed lack of water flow through macropores until 17 h in the sandy loam may be because of blockage of the macropores or flow paths to them by ice or frozen soil. We sectioned the soil columns after 50 h of thawing, and found that ice with a thickness of about 30 mm had formed in the frozen layer, closing the macropore (Figure 7). The decrease in the infiltration rate at 22 h (Figure 5a) may be because of this inhibition of water flow in the macropore by ice. Similarly, a rapid increase in infiltration was observed in the sandy loam with 2 × φ 5-mm macropores at 14 h, and ice formation was

Figure 6. Profiles of temperature (a, c, e, g) and water content (b, d, f, h) in samples with no macropores (a–d) and 4 × φ 5-mm macropores (e–h) during thawing of sandy loam (a, b, e, f) and silt loam (c, d, g, h). The dotted lines in and ▼ in water content profiles indicate total water content at the beginning of thawing, and shaded depth indicates the frozen layers when infiltration into unfrozen soil beneath the frozen layer was observed
confirmed in macropores at 50 to 100-mm depth when the sample was sectioned. These findings imply that infiltrated water can refreeze in a macropore, even when the flow rate is relatively high. Furthermore, most of this macropore ice formed as hollow cylinders, and it was brittle, collapsing under touch. These findings support the hypothesis that infiltrated water froze from the inner walls of the macropores, and that the ice could not grow completely. Macropores with 2-mm diameters showed no effect on infiltration, also probably because of their blockage because of refreezing of infiltrated water.

CONCLUSION

A one-directional column freezing experiment was conducted to clarify the effects of macropores on the formation of frozen layers in unsaturated soils and subsequent water infiltration into the frozen soils. Macropores were found to retard the formation of a frozen layer during soil freezing. This retardation depended not only on the size and number of macropores, but also on the amount of water flowing from unfrozen soil to the freezing front, which varied with soil. One reason for this retardation seemed to be condensation of water in macropores. During thawing, water flowed through macropores in the frozen layer, increasing the water content of unfrozen soil beneath this layer. However, the infiltrated water sometimes refroze in macropores; ice started to form near inner wall, grew to the centre, and blocked flow through them. Ice blocking macropores could not melt until the frozen layer disappeared. The timing of macropore blockage because of refreezing of infiltrated water, which depends on the temperatures of the infiltrating water and the frozen layer, is difficult to predict. To consider hydrological and thermal processes in cold regions, analysing vapour flow during soil freezing by using a numerical model and improving the model for describing refreezing of infiltrated water in macropores, as well as changes in soil hydraulic conductivity and pressure during freezing and thawing with infiltration, should be undertaken.

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