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Simultaneous measurement of unfrozen water content and hydraulic conductivity of partially frozen soil near 0 °C

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A R T I C L E I N F O

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A B S T R A C T

It is important to know the unfrozen water content and hydraulic conductivity of frozen soils when assessing water, heat, and solute transport in freezing and thawing soils for frozen soil engineering. To study these effects, an Andisol was packed into an acrylic column with an inner diameter of 70 mm and a height of 30 mm. First, the soil was frozen and thawed at different rates, and the soil freezing and thawing curves were measured. Second, water was added to flow through the thawing soil, and change in hydraulic conductivity with temperature was measured simultaneously with the thawing curve. The frozen soil contained more unfrozen water under a faster freezing rate and less unfrozen water under a faster thawing rate, resulting in a hysteresis-like behavior in the soil freezing and thawing curves. This is considered to be related to the pore ice growth lagging behind the change in the bulk soil temperature. Frozen soil below − 0.5 °C was practically impermeable. When water flows through a frozen soil, the soil has a higher unfrozen water content than without water flow. For a temperature increase from − 0.5 to − 0.2 °C, the hydraulic conductivity increased by more than four orders of magnitude with increasing unfrozen water content. No significant difference was observed in the hydraulic conductivity of soils with different bulk densities or water flow rates. The hydraulic conductivity of the frozen soil was higher than that estimated from the unsaturated hydraulic conductivity of unfrozen soil through the Clausius–Clapeyron equation. This is likely related to the frozen soil having more unfrozen water than the amount estimated from the water retention curve of the unfrozen soil. At temperatures warmer than − 0.2 °C, the hydraulic conductivity approached a constant value, while the unfrozen water content continuously increased. Near 0 °C, pore ice, which does not contribute to the water flow path, would remain frozen such as in inner-aggregate pores.

1. Introduction

Some of the water in soil remains unfrozen at subzero temperatures. This can be attributed to the surface forces of soil particles and the effect of pore curvature (Dash et al., 1995). The amount of unfrozen water changes drastically near 0 °C, decreasing with decreasing temperature, and has a significant influence on the mechanical strength of frozen soil (Kinosita, 1966; Izuta et al., 2007), water and solute transport in freezing and thawing soil, and microbial activity in a frozen soil (Watanabe and Ito, 2008; Yanai et al., 2011). Ice in soil pores grows in proportion to the degree of supercooling of the ice surface (Kuroda, 1985); it also releases latent heat, and takes time to reach its equilibrium volume with the surrounding temperature. Therefore, it is important to understand the relationship between the unfrozen water content and temperature of the frozen soil (the so-called soil "freezing" or "thawing curve") under various rates of temperature change and freeze-thaw histories at temperatures near 0 °C. Recently, hysteresis-like behavior of the soil freezing curve has been reported (Smerdon and Mendoza, 2010; Parkin et al., 2013; Tian et al., 2014). This behavior may arise from changes in soil thermal properties during the freeze-thaw cycle, solute redistribution, or disequilibrium between ice formation and soil temperature. However, the governing processes which control this phenomenon remain incompletely understood.

The amount of unfrozen water is also important when considering the hydraulic conductivity of a frozen soil because it contributes to open water flow paths. The estimation of the hydraulic conductivity of a frozen soil is necessary to provide key information on strategies, for example, for water management of farmland during spring (Baker and Spaans, 1997), snowmelt infiltration and groundwater recharge (Hayashi et al., 2003; Watanabe et al., 2012), soil erosion and degradation of stream water quality due to snowmelt runoff (Shanley and Chalmers, 1999; Singh et al., 2009), and contaminant control using artificially frozen ground (Andersland et al., 1996a; Wiggert et al., 1997; Subcommittee on Ground Freezing, 2014). The hydraulic

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conductivity of frozen soils is sometimes estimated using oil, antifreeze liquids, or gases as the fluid rather than water (Andersland et al., 1996b; Seyfried and Murdock, 1997; McCauley et al., 2002; Al-Houri et al., 2009; Zhao et al., 2013). However, this method overestimates the hydraulic conductivity of unsaturated frozen soil because the fluid flows not only through paths made by unfrozen water but also through pore spaces where ice and unfrozen water are absent. The hydraulic conductivity of a frozen soil can be estimated roughly by analyzing the mass balance of water in arbitrary segments of a frozen soil profile (Weigert and Schmidt, 2005; Watanabe and Wake, 2008). Direct measurement of the hydraulic conductivity has been performed in several studies by applying water or dilute solution flow through frozen soil near 0 °C (Williams and Burt, 1974; Miller et al., 1975; Horiguchi and Miller, 1980; Black and Miller, 1990; Tokoro et al., 2010), but these studies did not simultaneously measure the unfrozen water content. Furthermore, the hydraulic conductivity and the unfrozen water content of a frozen soil have generally been measured under constant temperature conditions (Anderson and Tice, 1972; Spaans and Baker, 1995; Watanabe and Mizoguchi, 2002; Watanabe and Wake, 2008). To improve our understanding of water infiltration in frozen soils, it is useful to evaluate the hydraulic conductivity and the unfrozen water content under conditions of changing temperature, such as soil thawing, with water flow.

Most of the coupled water and heat flow models for soil freezing assume that unfrozen water and ice in freezing and thawing pores have similar geometries as those of water and air in drying and wetting unfrozen pores; these models estimate the soil freezing curve and hydraulic conductivity of frozen soil from the water retention curve and the unsaturated hydraulic conductivity of unfrozen soil using the Clausius–Clapeyron equation (Harlan, 1973; Newman and Wilson, 1997; Hansson et al., 2004). However, these models tend to overestimate the amount of water flow from the unfrozen to the frozen regions (Harlan, 1973), and previous studies have applied an impedance factor to decrease the hydraulic conductivity for frozen soils (Jame and Norum, 1980; Lundin, 1990; Zhao et al., 1997; Hansson et al., 2004). However, a decrease in the hydraulic conductivity expressed by the impedance factor has not been experimentally verified. In addition, the water retention curve at equilibrium state does not always reproduce the soil freezing curve. Therefore, Azmatch et al. (2012) estimated the soil water retention curve from the soil freezing curve. Watanabe et al. (2010) proposed a simultaneous estimation of both the soil water retention and freezing curves to enable feasible numerical calculation (Kurylyk and Watanabe, 2013). However, less information is available for determining the hydraulic conductivity function of frozen soils. In general, emerging cold regions groundwater flow models (Kurylyk et al., 2014; Rühaak et al., 2015) could be improved by an enhanced understanding of the processes governing freezing and thawing in soils and the concomitant reduction in hydraulic conductivity.

In this study, we measured the soil freezing and thawing curves of an arable soil under different freeze-thaw conditions. Water flow was applied to the soil during thawing, and the hydraulic conductivity was measured simultaneously with the soil thawing curve. Then, the soil thawing process with water flow was considered by comparing the thawing curve and hydraulic conductivity of the frozen soil to the water retention curve and unsaturated hydraulic conductivity of an unfrozen soil.

2. Materials and methods

The soil used for this study was collected from the A horizon at an experimental field located in Iwate, Japan. The experimental field has been managed as a weeded fallow field for several years, and the soil freezes to a depth of about 0.2 m during winter, depending on the snow cover and winter air temperatures. The A horizon is 0.3–0.4 m thick, and consists of volcanic ash soil with a low bulk density

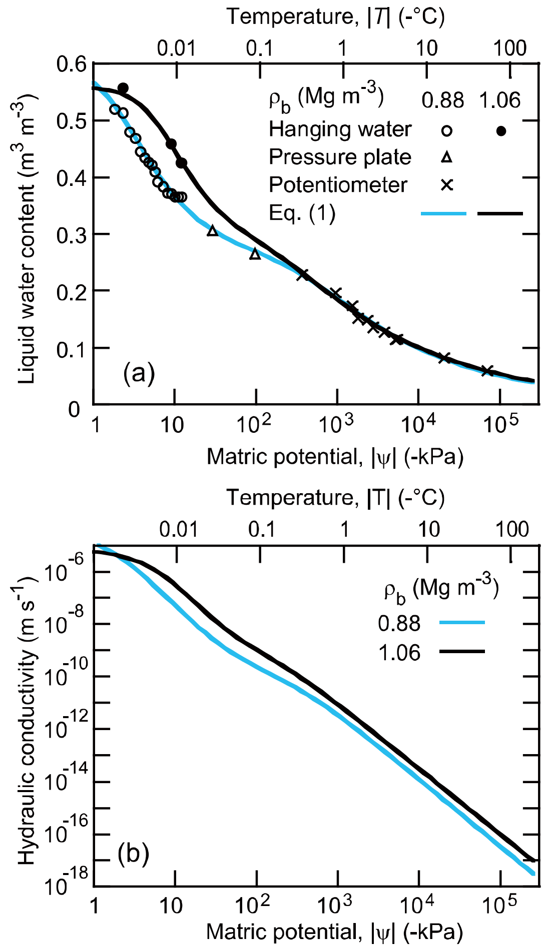

Fig. 1. (a) Water retention curve of sample soil with different bulk density (ρ_b = 0.88 and 1.06 Mg m^{-3}) measured at 25 °C. (b) Unsaturated hydraulic conductivity derived from water retention curve using Eq. (2). Secondary horizontal axis shows corresponded temperature converted using Eq. (3).

(ρ_b = 0.85–1.1 Mg m^{-3}) and high porosity (approx. 0.62 m^3 m^{-3}). The soil is an Andisol with a sandy loam texture. The saturated hydraulic conductivity of unfrozen soil, measured using the falling head method with 100-mL soil cores, decreased from 5×10^{-5} to 1×10^{-5} m s^{-1} with increasing bulk density from 0.85 to 0.95 Mg m^{-3}. The soil $EC_{1:5}$, i.e., the electrical conductivity of a suspension of one part air-dry soil by weight to five parts water by weight, was 0.05 S m^{-1}, and therefore we neglected the solute effect on the soil freezing processes.

The soil was sieved with a 2-mm mesh screen. Fig. 1a shows the soil water retention curves (relationship between water potential ψ and water content θ) at different bulk densities (0.88 and 1.06 Mg m^{-3}) determined by the hanging head method ($-16 < \psi < -1$ kPa), the pressure plate method ($-10^3 < \psi < -15$ kPa), and a dew-point water potential meter ($\psi < -10^3$ kPa) at 25 °C. Independent on the bulk density, the soil had a similar water retention curve, while the soil with a high bulk density contained slightly more water at higher water potential due to compaction of large pores. The dual van Genuchten (1980) equation (Durner, 1994) was fitted to the observed ψ vs. θ:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = (1 - w)[1 + (\alpha_1\psi)^{-n_1}]^{-m_1} + w[1 + (\alpha_2\psi)^{-n_2}]^{-m_2} \quad (1)$$

where S_e is the effective saturation, θ_s and θ_r are the saturated and residual water contents, respectively, α, n, and $m = 1 - 1/n$ are parameters determining the shape of the water retention curve, and w is the weighting factor. From the van Genuchten–Mualem model, the hydraulic conductivity is given as follows (Durner, 1994):