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An improved thermo-time domain reflectometry method for determination of ice contents in partially frozen soils

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ABSTRACT

Summary: Measuring ice contents (θ_i) in partially frozen soils is important for both engineering and environmental applications. Thermo-time domain reflectometry (thermo-TDR) probes can be used to determine θ_i based on the relationship between θ_i and soil heat capacity (C). This approach, however, is accurate in partially frozen soils only at temperatures below −5 °C, and it performs poorly on clayey soils. In this study, we present and evaluate a soil thermal conductivity (λ)-based approach to determine θ_i with thermo-TDR probes. Bulk soil λ is described with a simplified de Vries model that relates λ to θ_i. From this model, θ_i is estimated using inverse modeling of thermo-TDR measured λ. Soil bulk density (ρ_b) and thermo-TDR measured liquid water content (θ_l) are also needed for both C-based and λ-based approaches. A theoretical analysis is performed to quantify the sensitivity of C-based and λ-based θ_i estimates to errors in these input parameters. The analysis indicates that the λ-based approach is less sensitive to errors in the inputs (C, λ, θ_l, and ρ_b) than is the C-based approach when the same or the same percentage errors occur. Further evaluations of the C-based and λ-based approaches are made using experimentally determined θ_i at different temperatures on eight soils with various textures, total water contents, and ρ_b. The results show that the λ-based thermo-TDR approach significantly improves the accuracy of θ_i measurements at temperatures ≤ -5 °C. The root mean square errors of λ-based θ_i estimates are only half those of C-based θ_i. At temperatures of −1 and −2 °C, the λ-based thermo-TDR approach also provides reasonable θ_i, while the C-based approach fails. We conclude that the λ-based thermo-TDR method can reliably determine θ_i even at temperatures near the freezing point of water (0 °C).

1. Introduction

In cold regions, frequent freeze-thaw events occur in the topsoil during winter and spring. Such phenomena are of great importance for engineering design and construction activities. For example, precautions must be taken to avoid frost damage to railways, roads, and airfields (Farouki, 1986; Vitel et al., 2015). Freeze-thaw cycles also have environmental impacts. For instance, the upward movement of water and salt during soil freezing can cause salinity problems (Cary and Mayland, 1972; Wu et al., 2016). In addition, seasonal freezing and thawing can have a significant influence on soil carbon cycling (Elberling, 2003; Schuur et al., 2015). The freezing and thawing processes of soil water are essential components of terrestrial hydrology (Seyfried and Murdock, 1997; Wang et al., 2009; Walvoord and Kurylyk, 2016). Accurate determination of both liquid water content (θ_l) and ice content (θ_i) are required to verify the accuracy of soil freeze-thaw models (Lundin, 1990; Kurylyk and Watanabe, 2013). There are several available methods to measure θ_l (Dobriyal et al., 2012; He et al., 2015a), but it is challenging to measure in-situ variations of θ_i (Overduin and Kane, 2006; Cheng et al., 2013). Thus, a need exists for an improved method to determine θ_i to further understand freeze-thaw processes in surface soil.

Table 1 summarizes the key references about the determination of soil θ_i in the laboratory and in situ. The common approach to estimate θ_i is to simultaneously measure the soil total water content (θ_{tot}) and θ_l with two different methods, and then to calculate θ_i as the difference between θ_{tot} and θ_l (Hayhoe and Bailey, 1985; Bittelli et al., 2004; Cheng et al., 2013; Zhou et al., 2014). The

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Nomenclature

C	Soil heat capacity
C_a	Volumetric heat capacity of air
C_i	Volumetric heat capacity of ice
C_l	Volumetric heat capacity of liquid water
C_s	Volumetric heat capacity of soil solids
f_a	Air-filled porosity
f_s	Volume fraction of soil solids
f_{clay}	Fraction of clay in soil solids
f_{sand}	Fraction of sand in soil solids
f_{silt}	Fraction of silt in soil solids
g_a	Shape factor of ellipsoidal particles
$g_{a(air)}$	Shape factor of air voids
$g_{a(clay)}$	Shape factor of clay particles
$g_{a(ice)}$	Shape factor of ice crystals
$g_{a(sand)}$	Shape factor of sand particles
$g_{a(silt)}$	Shape factor of silt particles
$g_{a(solids)}$	Shape factor of solid particles
k_a	Weighting factor of air
k_i	Weighting factor of ice
k_s	Weighting factor of soil solids
m	Number of data points
n (in subscript)	Soil solids, ice, or air
RMSE	Root mean square error
T	Temperature
TDR	Time domain reflectometry

Greek characters

α	Geometric factor
ε	Soil bulk dielectric permittivity
ε_a	Dielectric permittivity of air
ε_i	Dielectric permittivity of ice
ε_l	Dielectric permittivity of liquid water
ε_s	Dielectric permittivity of soil solids
θ_i	Ice content
θ_l	Liquid water content
θ_{tot}	Soil total water content
κ	Soil thermal diffusivity
λ	Soil thermal conductivity
λ_a	Thermal conductivity of air
λ_i	Thermal conductivity of ice
λ_l	Thermal conductivity of liquid water
λ_s	Thermal conductivity of soil solids
λ_{clay}	Thermal conductivity of clay
λ_{sand}	Thermal conductivity of sand
λ_{silt}	Thermal conductivity of silt
ρ_b	Soil bulk density
ρ_i	Ice density
ρ_l	Water density
ρ_s	Soil particle density

oven-drying method, neutron moisture meter, cosmic-ray probe, and gamma ray attenuation have been used to determine θ_{tot} in frozen soils, and time domain reflectometry (TDR), dielectric tube sensor, and nuclear magnetic resonance have been used to measure θ_l (Watanabe and Mizoguchi, 2002; Watanabe and Wake, 2009; Cheng et al., 2013, 2014; Zhou et al., 2014; Tian et al., 2016a). Although, in principle, a combination of the methods can be used to estimate θ_i, each method has limitations on providing accurate in-situ measurements (Table 1). Gas dilatometry, dielectric spectroscopy, heat pulse probe, and the sensible heat balance method have also been used to determine θ_i in laboratory studies, but they were feasible only under limited conditions (Spaans and Baker, 1995; Bittelli et al., 2004; Liu and Si, 2011; Kojima et al., 2013, 2016). Very few methods are available for continuously measuring θ_i in situ (Kojima et al., 2014; Tian et al., 2015).

Thermo-time domain reflectometry (thermo-TDR) probes, which can measure soil thermal properties (i.e., volumetric heat capacity, C, thermal diffusivity, κ, and thermal conductivity, λ) and θ_l simultaneously (Ren et al., 1999), have the potential for continuous in-situ determination of θ_i (Zhang et al., 2011; Tian et al., 2015). Because the C of partially frozen soil is the weighted sum of the C values of individual soil constituents (de Vries, 1963), θ_i can be estimated from thermo-TDR measured C and θ_l. However, this C-based approach was reported to have relatively large errors in θ_i estimates, especially on clayey soils (Tian et al., 2015). Additionally, the C-based thermo-TDR method failed to provide reasonable θ_i estimates when soil temperature was between −5 and 0 °C (Tian et al., 2015). For this method to have practical use, it is necessary to improve the accuracy of θ_i measurements with the thermo-TDR method.

The λ of partially frozen soil can be predicted as the weighted average of the λ values of individual soil constituents (de Vries, 1963; Farouki, 1982). Thus, thermo-TDR has the possibility of estimating θ_i from measured λ and θ_l by using a λ-prediction model inversely. The λ-based thermo-TDR approach may have some important advantages over the C-based approach. This is because probe deflection and finite probe properties affect the accuracy of thermo-TDR measured C, but have less influence on the measurement of λ (Kluitenberg et al., 1995; Lu et al., 2016). Given that needle deflection of thermo-TDR probes may be particularly significant in partially frozen soils due to the expansion of ice, the λ-based thermo-TDR approach may have a practical advantage for estimating θ_i compared to the C-based approach. Recently, Tian et al. (2016b) developed a simplified de Vries model for estimating λ of partially frozen soils. The model related λ to soil texture, bulk density (ρ_b), θ_l, and θ_i. The simplified de Vries model is easy to use and provides more accurate and consistent λ estimates than other models (Tian et al., 2016b). It has the potential for use in inversely calculating θ_i from thermo-TDR measured λ and θ_l.

The objectives of this study are to: (1) introduce a λ-based thermo-TDR method using the simplified de Vries model for determining θ_i in partially frozen soil; (2) quantify and compare the sensitivity of θ_i estimates to errors in the input parameters for the C-based and λ-based approaches; and (3) evaluate the accuracy of these two approaches by comparing their estimates of θ_i with measured θ_i values obtained by independent measurements.

2. Materials and methods

2.1. Thermo-TDR technique

The thermo-TDR technique combines a heat pulse sensor and a TDR probe into one unit and can simultaneously measure soil thermal properties (C, κ, and λ), θ_l, and electrical conductivity (Ren et al., 1999). The thermo-TDR technique can also estimate ρ_b, θ_i, air-filled porosity, and pore water velocity (Ren et al., 2000 and 2003; Ochsner et al., 2001; Liu et al., 2008; Lu et al., 2016; Tian et al., 2015).

Thermo-TDR probes identical to those described by Liu et al. (2008) were used in this study. Each probe consisted of three parallel needles (4.5-cm length, 2-mm diameter, and 8-mm needle-to-needle spacing) fixed in an epoxy body (Fig. 1). A heating wire was