Journal of Rock Mechanics and Geotechnical Engineering 7 (2015) 155–162

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full length article

A non-destructive method to measure the thermal properties of frozen soils during phase transition

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ARTICLE INFO

Article history:
Received 22 January 2015
Received in revised form
4 March 2015
Accepted 6 March 2015
Available online 20 March 2015

Keywords:
Frozen soil
Phase change materials
Thermal conductivity
Heat capacity
Sensor fusion

ABSTRACT

Frozen soils cover about 40% of the land surface on the earth and are responsible for the global energy balances affecting the climate. Measurement of the thermal properties of frozen soils during phase transition is important for analyzing the thermal transport process. Due to the involvement of phase transition, the thermal properties of frozen soils are rather complex. This paper introduces the uses of a multifunctional instrument that integrates time domain reflectometry (TDR) sensor and thermal pulse technology (TPT) to measure the thermal properties of soil during phase transition. With this method, the extent of phase transition (freezing/thawing) was measured with the TDR module; and the corresponding thermal properties were measured with the TPT module. Therefore, the variation of thermal properties with the extent of freezing/thawing can be obtained. Wet soils were used to demonstrate the performance of this measurement method. The performance of individual modules was first validated with designed experiments. The new sensor was then used to monitor the properties of soils during freezing–thawing process, from which the freezing/thawing degree and thermal properties were simultaneously measured. The results are consistent with documented trends of thermal properties variations.

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1. Introduction

Water is one of the most important factors determining the performance of geostructures. Excessive water accumulation behind retaining wall compromises its structural stability. Seepage through levee and earth dam can lead to piping (Drnevich et al., 2001a,b). And soil thermal properties are also of great importance for the study of soil water evaporation, pesticides volatilization, and trace gas emission from soil. In addition, under some circumstances, the heat transfer, water movement and solute transport are coupled such as in the vadose zone (Ren et al., 2003; Heitman et al., 2007). The seasonal frozen depth and duration in cold regions are of great importance for studying the biological, hydrological and mineralogical processes (Tarnawski and Wagner, 1993; Civan, 2000; Zhou and Huang, 2004; Lackner et al., 2005). Seasonal freezing and thawing of soil is frequently blamed for the underground water pipe damages (Takeda and Nakano, 1990; Song, 2006; Heitman et al., 2007). The thermal properties of the soil surface layer can also be used to determine the surface heat balance, and this surface energy balance can be further employed to predict the freezing–thawing depth of the active layer of the soil (Naidu and Singh, 2004; Overduin et al., 2006; Hotz and Ge, 2009).

Wet soil (soil mixed with water), by definition, is a phase change material system in which water acts as the phase transition component and soil solids provide the structural skeleton for the system. During the phase transition (i.e. when water crystallizes or ice melts), the thermal properties of the system (i.e. heat capacity and thermal conductivity) change together with the evolution of phase change. Measurement of thermal properties during such process will provide important input for studying and modeling the thermal transport in such material systems.

This paper demonstrates a method and tool to measure the thermal properties of phase change material system. Wet soils are used as the subject material due to its availability and defined phase transition temperature. A multifunctional probe that integrated the functions for time domain reflectometry (TDR) and thermal pulse technology (TPT) measurement was fabricated for measurement. The TDR function measures the extent of phase transition (freezing or thawing). The TPT function measures the corresponding thermal conductivities and heat capacities. By integration of both measurements, the variation of the thermal properties with the extent of phase transition in soil water can be

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

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http://dx.doi.org/10.1016/j.jrmge.2015.03.005

determined. While wet soil is used as the phase change materials system in this study, the methodology and tool can also be extended to study other phase change materials systems used for building energy efficiency applications.

2. Technical background

2.1. Background on time domain reflectometry (TDR)

TDR is a guided radar technology that was initially used by electrical engineers to locate cable breakages. The application was extended to measure soil water content due to the pioneering work by Topp et al. (1980). In civil engineering, TDR has become an established technology for soil water content measurement (O'Connor and Dowding, 1999; Benson, 2006; ASTM D6565, 2005; ASTM D6780, 2005). TDR features the advantages of being rugged, accurate and automatic. Various applications have been explored with TDR technology such as seepage through levee and earth dam (Zhang et al., 2010), water movement and solute transport (Ren et al., 2003; Heitman et al., 2007), seasonal frost development (Tarnawski and Wagner, 1993; Civan, 2000; Zhou and Huang, 2004; Lackner et al., 2005), soil freezing–thawing induced pipe damages (Takeda and Nakano, 1990; Song, 2006; Heitman et al., 2007).

The configuration of a typical TDR system is shown in Fig. 1. The system generally consists of a TDR device (including an electrical pulse generator and a sampler), a connection cable, and a measurement probe (Fig. 1a). TDR works by sending a fast rising step pulse or impulse to the measurement probe and measuring the reflections due to the change of material dielectric permittivity. Due to the large contrast between the dielectric constant of water (around 81) and those of the air (1) or soil solids (the dielectric constant for dry solids is typically 3–7), the bulk dielectric constants of soils are very sensitive to the water content. The large contrast in the dielectric properties of air and soil causes one reflection when the electrical signal enters soil from the air; another reflection takes place when the electrical signal arrives at the end of the measurement probe (Fig. 1b). In displaying a TDR signal, the time scale, t, is typically displaced as round trip distance using Eq. (1):

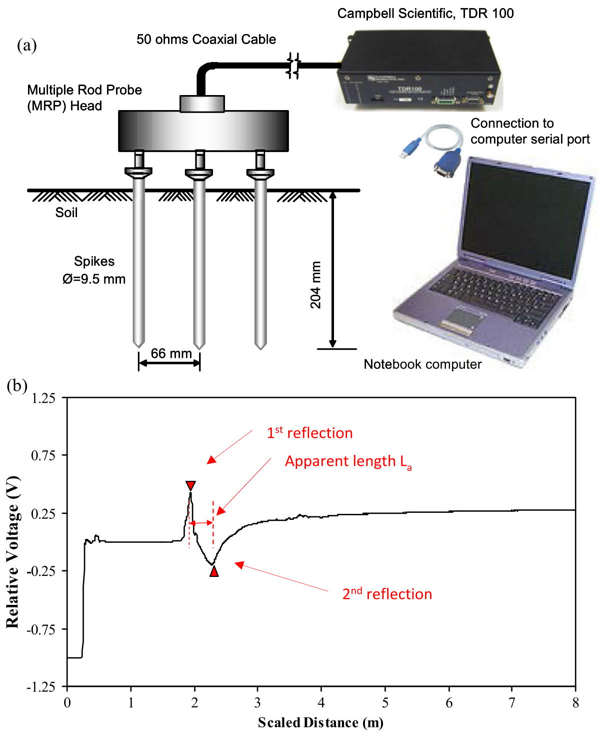

Fig. 1. (a) Schema of an example TDR system and output signal; (b) A typical TDR curve for soil and measurement of apparent length L_a.

$$L_a = \frac{ct}{2} \tag{1}$$

where L_a is typically called apparent length, and c is the speed of the electromagnetic wave in the vacuum (3×10^8 m/s).

From the apparent length, L_a, displayed on TDR signal (Fig. 1b), the round trip time required for an electrical pulse to travel through the measurement probe can be determined as $t = 2L_a/c$.

The velocity of the electromagnetic wave traveling in the testing material can then be calculated by

$$v = \frac{2L}{t} = \frac{2L}{2L_a/c} = \frac{L}{L_a}c \tag{2}$$

where v is the velocity of an electromagnetic wave traveling in the material, L is the physical length of TDR sensor section, t is the travel time between the two reflections that occur at the interfaces of material layers.

The velocity of the electric signal is inversely proportional to the square root of dielectric constant, K_a (Ramo et al., 1994):

$$v = \frac{c}{\sqrt{K_a}} \tag{3}$$

Combining Eqs. (2) and (3), the dielectric constant, K_a, of a material can be calculated by

$$K_a = \left(\frac{c}{v}\right)^2 = \left(\frac{L_a}{L}\right)^2 \tag{4}$$

The dielectric constant, K_a, measured by TDR is typically called "apparent dielectric constant" to reflect the fact that it does not consider the frequency-dependency of the dielectric permittivity (Topp et al., 1980).

2.2. Theory of thermal pulse technology (TPT)

TPT measures the thermal properties of a material by generating a heat pulse and measuring its propagation and attenuation. Typically, a line heat pulse of short duration is generated. The thermal pulse propagates in the cylinder directions away from the line heat source (Fig. 2a). This causes a radial propagating temperature disturbance which is a function of time and distance from the heat source (Fig. 2b).

Data analysis for the thermal pulse technology is based on modeling the thermal diffusion process in continuous homogeneous materials. The fundamental solution for the thermal field distribution around an infinite line heat source has been solved for the axial-symmetric system (de Vries, 1952; Kluitenberg and Bristow, 1993; Bristow et al., 1994; Kluitenberg et al., 1995). For a line heat pulse of duration t_0, the temperature disturbance at radial distance, r, away from the heat source is described by

$$\Delta T(r, t) = \frac{Q}{4\pi\alpha}\left\{Ei\left[\frac{-r^2}{4\alpha(t-t_0)}\right] - Ei\left(\frac{-r^2}{4\alpha t}\right)\right\} \tag{5}$$

where ΔT denotes the temperature variation ($^\circ$C or F), t_0 is the duration of the heat pulse (s), $Ei(x)$ is the exponential integral, α is the thermal diffusivity, and Q denotes the strength of the heat resource, which is calculated by

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