Geotechnical Testing Journal, Vol. 35, No. 1
Paper ID GTJ103653
Available online at: www.astm.org

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A New Method for Soil Water Characteristic Curve Measurement Based on Similarities Between Soil Freezing and Drying

ABSTRACT: The soil water characteristic curve (SWCC) is the basis to explain a variety of processes in unsaturated soils, ranging from transport phenomena to mechanical behaviors. In this paper, a new method is developed for SWCC estimation based on the similarity between the freezing/thawing process and drying/wetting process in soils. The theoretical basis for this method is first reviewed. The concept of the soil freezing characteristic curve (SFCC) is introduced to describe the relationship between the unfrozen water content and matric suction in frozen soils. SFCC is analogous to SWCC in that both of them describe the energy status of liquid water associated with liquid water content. Relationships between SWCC and SFCC are discussed. To measure the SFCC, a thermo-time domain reflectometry (TDR) sensor was developed which combines both temperature sensors and conventional TDR sensor. The TDR module and algorithm measured the bulk free water content of soils during the freezing/thawing processes, while the built-in thermocouples measured the internal temperature distribution. SFCCs were obtained from the simultaneously measured TDR and temperature data. Experiments were conducted on a few types of soils to validate this new procedure. The SFCC was obtained from thermo-TDR data collected in specimens subjected to a controlled thawing process, while the SWCC was directly measured by ASTM D5298, the filter paper method. Reasonable agreements were found between SWCC and SFCC. The experimental results implied that the SWCC could be estimated from SFCC, which also provided more evidence of the similarity of freezing/thawing processes and desorption/sorption processes.

KEYWORDS: soil water characteristic curve, soil freezing characteristic curve, thermo-TDR sensor, unsaturated soils, frozen soil

Introduction

Soil water characteristic curves (SWCCs) describe the relationship between soil water content (or saturation) and soil water potential (or suction) (Williams 1989). The SWCC is influenced by soil internal structure, mineral constitution and the interactions among the liquid, solid and gas phases (Mualem 1976; Bachmann 2002; Wang 2008). Therefore it is related to many important phenomena in unsaturated soils, e.g., fluid migration, heat transfer, and salt and ion transportation (Simunek 1994; Hansson 2004). As an important moisture retention property of soils, SWCC has long been utilized and studied by soil scientists (Briggs 1907). More recently, SWCC has also been used in geotechnical engineering to construct the constitutive equations for the mechanical behaviors of unsaturated soils (Fredlund 1993). This paper describes the technical basis and experimental implementation of a new method for SWCC measurement based on the similarity between the freezing/thawing and drying/wetting processes. This method utilizes a thermo-time domain reflectometry (TDR) sensor that simultaneously measures the extent of freezing/thawing and the corresponding internal temperature. A special TDR calibration equation was utilized to determine the degree of freezing/thawing from TDR measurement. Experimental data indicate there are close similarity between SWCC and soil freezing characteristic curve (SFCC), from which the SWCC can be estimated.

Manuscript received December 3, 2010; accepted for publication June 26, 2011; published online September 2011.

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Background

Common Methods for SWCC Measurement

The measurement of SWCC is usually time-consuming and requires delicate experimental controls. The accuracy and ease of measurement depend on the operational principles for determining both soil suction and water content. For *soil suction*, various approaches have been proposed; for example, based on pressure balance, relative humidity, and resistivity, etc. These procedures have been widely applied in scientific and practical activities. Apparatus based on pressure (suction) balance include filter paper, pressure plate, suction plate, tensiometer, and pressure membrane, all of which measure pressure utilizing calibrated porous media. For *water content*, direct measurement by oven drying the soil is

TABLE 1—*Methods of suction and saturation measurement.*

Suction	Range	Suction	Range
Suction plate	0–100 kPa	Odometer	10 kPa–1 MPa
Continuous Flow	0–100 kPa	Centrifuge	100 kPa–3 MPa
Rapid Method	0–100 kPa	Freezing Point Depression	100 kPa–1 MPa
Field Tensiometer	0–200 kPa	Vacuum Desiccator	10–1000 MPa
Pressure Plate	1–100 kPa	Sorption Balance	10–1000 MPa
Pressure Membrane	0–150 MPa	Electrical Resistance Gauge	100 KPa–1000 MPa
Saturation	Mechanism	Saturation	Mechanism
Direct method	Directly	Ground Penetrating Radar	Wave Velocity
TDR	Permittivity	Gama-ray	Gama ray
Neutron Probe	Neutron	Capacitance Probe	Capacitance
FD	Impedance/Capacitance	GPR	Electromagnetic Radiation

accurate yet destructive. When testing a sample with varying water content, non-destructive tools such as the nuclear magnetic resonance (NMR) or TDR can be employed. Table 1 summarizes the range and principles of common approaches in SWCC measurement (Croney 1961; Scanlon 1997).

Despite the progresses in unsaturated soil mechanics, accurate measurements of SWCC remain challenging. Therefore, researchers have extended SWCC measurement techniques to physics-based methods or semi-empirical methods. These methods were developed based on the relationship of SWCC with other soil intrinsic properties. Examples are the theoretical models proposed by Maulem (1976) and Fredlund (1994) on the basis of a "bundle of capillary cylinder" model. The applications of these theoretical models require establishing the relationships of SWCC with soil index properties or pore-size distribution (Zapata 2000). There are also semi-empirical approaches for SWCC prediction based on soil index properties such as the grain-size distribution (Arya 1999; Aung 2001; Kosugi 1998). These empirical methods yielded good agreements with experimental data. Considering the important role of SWCC for unsaturated soils, development of accurate and simple measurement technology is highly desirable for both the research and practice community.

Similarity Between Wetting/Drying Process and Freezing/Thawing Process

The similarity between adsorption (wetting) or desorption (drying) process and thawing or freezing process, respectively, was observed long time ago. They; however, have not been paid sufficient attention. Buckingham (1907) and Gardner (1919) in their pioneering work have worked out the similarity between the energy relationships for the thermal process and drying process. Their study was followed by Schofield (1935), who introduced the pF scale to indicate suction in the unit of cm H_2O. A method named freezing point depression was developed based on this concept (Croney 1952). Quantitative measurement of freezing point depression typically requires very sophisticated equipment. Smith and Tice (1988) developed TDR technology to measure the freezing point depression in soils. The results compared favorably with NMR measurement. Although a relationship was believed to exist between freezing/thawing and drying/wetting processes, the mechanism was not well understood due to inadequate knowledge about the surface phenomena as well as the colloidal behaviors (Pires 2005). This dilemma was later reconciled by the breakthrough in observing the similarity between the drying process and the freezing process, by means of the SFCC and SWCC (Koopmans 1966; Spaans 1996). The SFCC describes the relationship between the unfrozen water content and soil suction in freezing soils. Microscopically, it represents the variation of the amount of liquid water and its energy status during freezing/thawing progresses. SFCC is analogous to SWCC in that both of them describe the energy status of liquid water associated with liquid water content.

The idea of taking advantage of this resemblance can lead to the possibility that SWCC can be obtained by measuring temperature (freezing point depression) and degree of freezing/thawing. This is distinctive from common technologies for SWCC measurements.

Recent developments in sensor technology make it possible to simultaneously measure temperature and free water content, and consequently degree of freeze/thawing. This provides sufficient technical support for developing a new method for the SWCC measurement by means of SFCC measurement. In this paper, we describe the procedures to estimate SWCC from SFCC by use of a thermo-TDR sensor.

Time Domain Reflectometry

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, and ASTM D6780). It features the advantages of being rugged, accurate, and automatic.

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. 1(*a*)). 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 between 3–7), the bulk dielectric constants of soils are very sensitive to the water

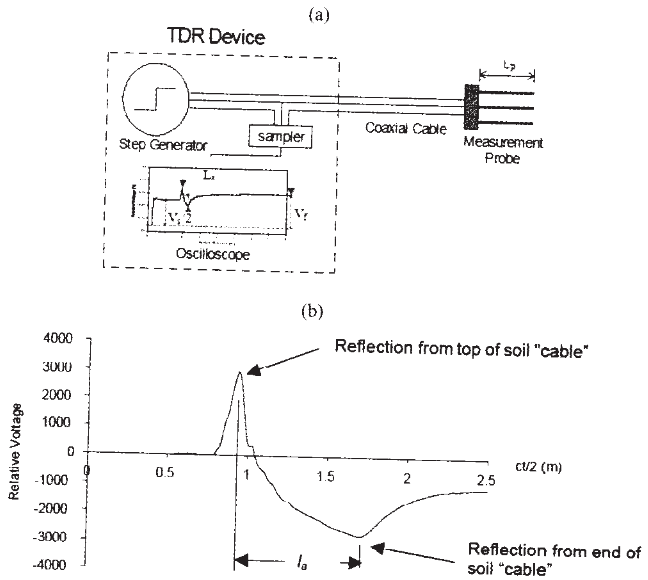


FIG. 1—*(a) Schema of an example TDR system and output signal; (b) a typical TDR curve for soil and measurement of apparent length l_a (Drnevich et al. 2001).*

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. 1(*b*)). In displaying a TDR signal, the time scale, t, is typically displaced as round trip distance using

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

where L_a is typically called apparent length, c is the speed of electromagnetic wave in the vacuum (3.0×10^8 m/s), and t is the time scale.

From the apparent length, L_a, displayed on the TDR signal (Fig. 1(*b*)), 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 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_a is the apparent length from displayed TDR signal, L is the physical length of TDR sensor section; t is the time difference between the two reflections that occur at the interfaces of material layers.

The velocity of 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 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). The pioneering work of Topp et al. (1980) estimated a third order polynomial relationship between the apparent dielectric constant and the volumetric water content, which is the basis of ASTM D6565 and is generally called a "universal" relationship.

Siddiqui and Drnevich (1996) developed an equation that relates TDR measured dielectric constant to gravimetric water content (gravimetric water content, w, i.e., the rate of the mass of water to mass of dry soil solids; volumetric water content, θ, i.e., the ratio of the volume of water to total volume of soil). This equation accounts for the effects of soil type and density by incorporating two calibration constants. This equation is shown below

$$w = \frac{1}{b}\left[\frac{\rho_w}{\rho_d}\sqrt{K_a} - a\right] \tag{5}$$

where ρ_d is the dry density of soil, ρ_w is the density of water, a and b are soil-dependent calibration constants, typically a is around 1, b is around 8.

Theoretical Basis of the New Method for SWCC

Soil Freezing Characteristic Curve (SFCC) and Its Relationship to SWCC

As mentioned in the earlier context, the soil freezing characteristic curve (SFCC) describes the relationship between the unfrozen water content and soil suction in freezing soils. Microscopically, it represents the variation of the amount of liquid water and its energy status as freezing/thawing progresses.

When freezing or thawing process occurs under small temperature gradient across specimens and their boundaries, phase change and mass migration of moisture are slow. By this slow transient process, it can be reasonably assumed that equilibrium is reached during every short time span inside the soil specimen. Freezing point depression of water due to the existence of menisci of pore water-air/ice interface is then described by the Clapeyron equation. Integrating the Claypeyron equation with proper initial conditions, there is (Groenevelt 1974)

$$\psi = \rho_w L_f \ln\frac{T}{273.15} \tag{6}$$

where ψ is soil suction, ρ_w is water density, L_f is the latent heat of water fusion, T is temperature in K, which can be easily measured with established technologies.

The soil suction at different freezing/thawing stage in frozen soils can be obtained by the Clapeyron's equation in the integral form (Eq 6). The SFCC can be obtained by plotting the soil suction versus the corresponding amount of liquid water in soils subjected to controlled freezing/thawing process.

SFCC is analogous to SWCC in that both of them describe the energy status of liquid water associated with liquid water content. Therefore, they are related in theory. Schofield (1935) succeeded in indirectly obtaining SWCC by measuring SFCC. Koopmans (1966) and Spaans (1996) suggested that a soil-dependent constant may be needed to convert SFCC to SWCC. Equation 7 is a general format summarizing these previous studies

$$u_a - u_w = A \cdot (u_i - u_w) \quad (7)$$

where the difference between air and water pressure, $u_a - u_w$, is the soil suction in unsaturated soils, and that between ice and water pressure, $u_i - u_w$, is the suction in freezing soils. A is a conversion constant between SWCC and SFCC. For colloidal soil where the soil particles are completely surrounded by adsorbed water, A was theoretically predicted to be 1 (Schofield 1935). For non-colloidal soil, the value of A was predicted to be equal to the ratio of surface tension at air-water and ice-water interfaces using thermodynamics theory (Koopman 1966).

Measurement of SFCC

To estimate SWCC from the similarity between the wetting process and the thawing process, the SFCC needs to be obtained. This can be accomplished by measuring (1) the temperature and (2) the corresponding degree of thawing (or unfrozen water content) in frozen soils. The soil suction can be obtained by use of Clapeyron equation (Eq 7). The measurement of temperature and the extent of freezing/thawing were accomplished in this study by use of a thermo-TDR sensor, which is described in the following text. To approximate the thermo-equilibrium conditions demanded by the Clapeyron equation, the thermal boundary conditions around the testing specimen (i.e., the speed of freezing/thawing) have to be controlled.

Experimental Apparatus: Thermo-TDR Sensor Design

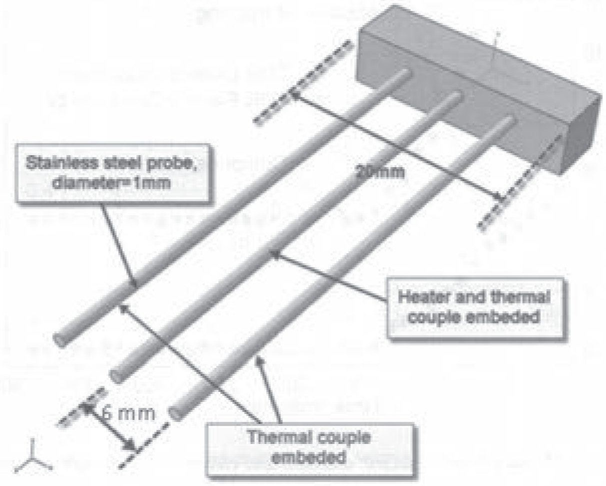
A thermo-TDR sensor was fabricated to simultaneously measure the internal temperature and unfrozen liquid water content. The geometry and components of the thermo-TDR sensor is shown in Fig. 2. The rods are 40 mm in length and spaced 6 mm apart. The diameter of the probe rod is around 1 mm. The probe design achieved an electrical impedance of around 150 Ω s when exposed to the air (O'Connor 1999). Instead of solid rods used in traditional TDR probe, hollow steel rods were used for the thermo-TDR probes. A resistance heater was embedded inside the central rod to generate the heat pulse. Three type-K thermocouples were installed in each rod respectively. The tubes were then backfilled with high thermal conductive epoxy.

The thermo-TDR combines the TDR module with the thermal measurement module. The TDR module functions similar as the conventional TDR sensor and provides accurate measurement of unfrozen liquid water content in soils. The thermal module by the thermocouples provides accurate measurement of the temperature. The thermo-TDR therefore provides a way to obtain the freezing status and temperature data synchronously.

Measurement of the Degree of Freezing/Thawing and the Degree of Saturation from TDR Module

The application of TDR to frozen soil is the natural extension of its application in measuring the soil water content. Compared with natural soil, the frozen soil is a four-phase system containing solid mineral particles, ice inclusions (cementing ice and interlayer ice), water in the bound and liquid states, and air. When freezing process occurs in fine grained soils, not all of pore water changes to ice immediately at the freezing temperature. With further decrease of the temperature, phase transition from water to ice continues, but at a steadily decreasing rate (Lee 1999).

(a)



(b)

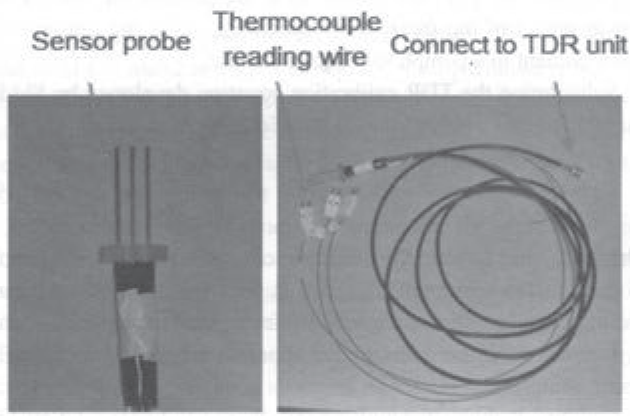


FIG. 2—*(a) Schematic design of the thermal-TDR probe; (b) photos of the fabricated thermo-TDR probe.*

Applications of TDR to frozen soils were investigated by Patterson and Smith (1981), Smith and Tice (1988), Spaans and Baker (1995), and Kahimba and Ranjan (2007), etc. TDR was found to be able to measure specifically the amount of unfrozen water in soil, due to the significant drop of the dielectric constant of free water (around 81) as it changes into ice (around 3.2) (Warrick 2002; Evett 2003).

Based on the physical nature of freezing and thawing process, unfrozen water content is a real indicator, instead of temperature, of freezing and thawing status. The degree of freeze/thaw can thus be defined as the percentage change of liquid water content, i.e.,

$$\Gamma(\%) = \frac{w_t - w_f}{w_u - w_f} \times 100\% \quad (8)$$

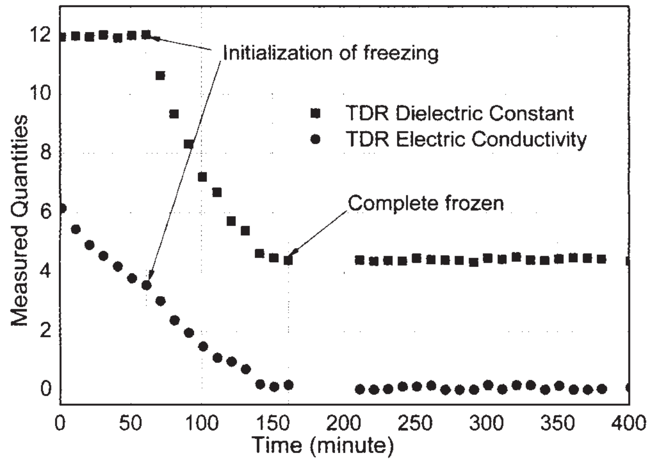


FIG. 3—*Measured soil dielectric constant and electrical conductivity in freezing process.*

where $\Gamma(\%)$ is the % of thawing, w_u is the gravimetric water content at complete unfrozen status, w_t is the gravimetric water content at time t of the freeze-thaw specimen, w_f is the gravimetric water content in a completely frozen sample.

Substituting the TDR calibration equation developed by Siddiqui and Drnevich (1996) (Eq 5) into Eq 8, there is

$$\Gamma(\%) = \frac{\sqrt{K_{a,t}} - \sqrt{K_{a,f}}}{\sqrt{K_{a,u}} - \sqrt{K_{a,f}}} \times 100\% = \frac{L_{a,t} - L_{a,f}}{L_{a,u} - L_{a,f}} \times 100\% \quad (9)$$

where $K_{a,u}$ and $L_{a,u}$ are the dielectric constant and apparent length of an unfrozen specimen, $K_{a,t}$ and $L_{a,t}$ are the dielectric constant and apparent length at time t of the freeze-thaw sample, $K_{a,f}$ and $L_{a,f}$ are the dielectric constant and apparent length of a completely frozen sample.

Equation 9 shows for a given soil, there is a linear relationship between $\sqrt{K_a}$ and degree of freeze/thaw. As the soil dependent constants in Eq 5 were automatically canceled from the numerator and denominator, the degree of freeze-thaw in Eq 9 expressed in TDR measurement is not dependent upon a specific soil type. This is an advantage of TDR technology for degree of freeze-thaw determination.

Figure 3 is an example of measured dielectric constants of an ASTM standard fine sand during freezing process. Also plotted on the figure is the measured electrical conductivity (inverse of resistivity) evolution. As shown in this figure, different stages of freeze/thaw can be clearly identified from the evolution curve of measured dielectric constant. The change of dielectric constant is attributed to the change of the physical status of soil water. Degree of freezing can be determined via Eq 9, from which the degree of saturation can also be directly obtained.

The ability of TDR to measure the unfrozen water content provides a method to assess the status of freeze/thaw development.

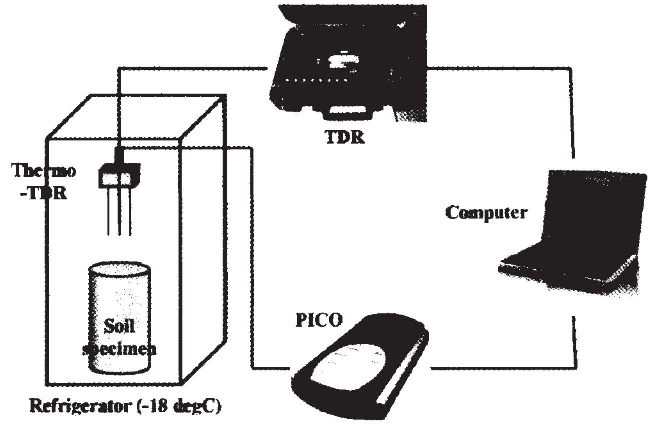


FIG. 4—*Schematic of the testing system.*

The degree of freezing/thawing in frozen soils obtained from TDR measurement can be directly translated into degree of saturation of liquid water.

Experimental Apparatus, Procedure, and Data Analysis

Laboratory experiments were conducted to measure SFCC by use of the thermoTDR sensor. Schematic of the testing system is shown in Fig. 4. The TDR system included the TDR100@ pulse generator by Campbell Scientific, Inc. The thermo-TDR sensor was connected to TDR unit via a 12 ft coaxial cable. An in-house software was used to automatically acquire TDR signals at given time intervals. A USB-based datalogger was used to automatically monitor five channels of temperature data.

Experiments were conducted on two representative types of subgrade soils from the State of Ohio, USA. The index properties of these soils are summarized in Table 2.

For soil #1, specimens were prepared using a Harvard Miniature compactor with an initial gravimetric water content of around 15 %. The method of compaction, i.e., the mass of soil solids in each layer, amount of compaction energy, was carefully controlled to ensure the specimen is uniform.

The SFCC measurement was taken during the thawing stage of a frozen specimen. First, the prepared specimen was sandwiched by two pieces of porous stone, wrapped up with a permeable cloth and soaked in water for more than 48 h. The purpose of soaking the specimens in water was to ensure they have sufficient water content to cover the range of SFCC curve. The gravimetric water content after soaking was 16.8 %, corresponding to volumetric water content of 31.7 %.

The thermo-TDR probe was then installed into the soil specimen. The three rods were inserted in full depth in the direction of

TABLE 2—*Index properties of soils tested in this study.*

Soil Notation	% Gravel	% Coarse Sand	% Fine Sand	% Silt	% Clay	Liquid Limit	Plastic Limit	w_{opt}[a]	γ_{dry}[a] (kN/m^3)
Soil #1	7	5	10	28	50	25	14	15.2%	18.42
Soil #2	10	7	10	14	59	40	18	16%	18.37

[a]Determined by Harvard miniature compactor.

the axis of the cylindrical soil specimens. Thus the axis of the middle probe coincides with that of the specimens. The specimen and thermo-TDR were wrapped in plastic wrap to prevent evaporation. In addition to the three thermocouples built inside the thermo-TDR, two more thermocouple was installed to monitor the air temperature in the refrigerator and environmental temperature, respectively. All the thermocouples were calibrated to achieve a precision of 0.01°C. The specimens were then placed into a −18°C freezer for about 24 h for soil to be complete frozen.

Monitoring of TDR signals and temperature data was started when the thawing process was initialized. The thawing process was started by unplugging the power of the refrigerator. The hope was that the thermal insulation by the refrigerator ensures the thawing rate is sufficiently slow to approximate thermodynamic equilibrium (or quasi-thermodynamic equilibrium). The TDR reading was taken with Campbell Scientific TDR100@ at 1 min interval. Figure 5 shows examples of measured TDR signals during the course of the experiment. As thawing evolves, the TDR signals evolve in a pattern. The TDR signals were analyzed using commonly used algorithm to determine the dielectric constants. From this the degree of thawing was calculated using Eq 9.

The temperature data was also collected at 1 s interval by use of a TC-08 USB thermocouple recording unit produced by Pico technology, Inc. The automatic monitoring process continues until the specimen completely thawed.

The experimental data analyses involve:

(1) Determine the degree of thawing or unfrozen water content from the TDR measurements. From this calculate the unfrozen volumetric water content and degree of saturation.
(2) Determine the average temperature in soil specimens. Estimate the soil suction from temperature using the Clapeyron equation (Eq 6).
(3) Plot the SFCC by plotting the unfrozen water content estimated from step (1) and the corresponding (in time) soil suction estimated from step (2).

Experiments were also conducted to directly measure the SWCC by ASTM D5298 the filter paper method. The filter paper used in the experiments was Whatman No. 42, which is ash-free quantitative type II filter paper.

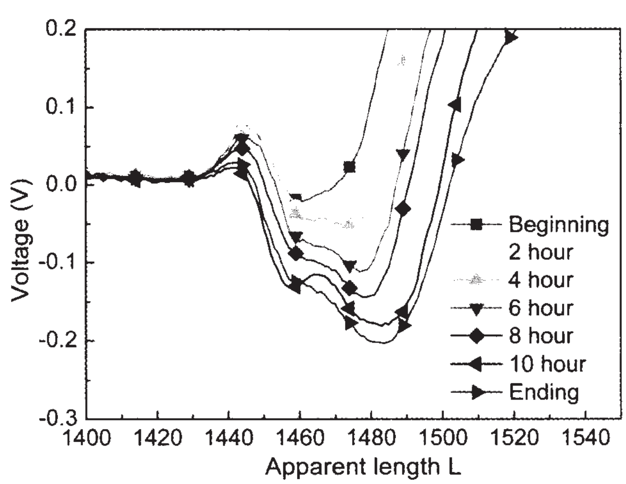


FIG. 5—*Typical TDR signals during the thawing process.*

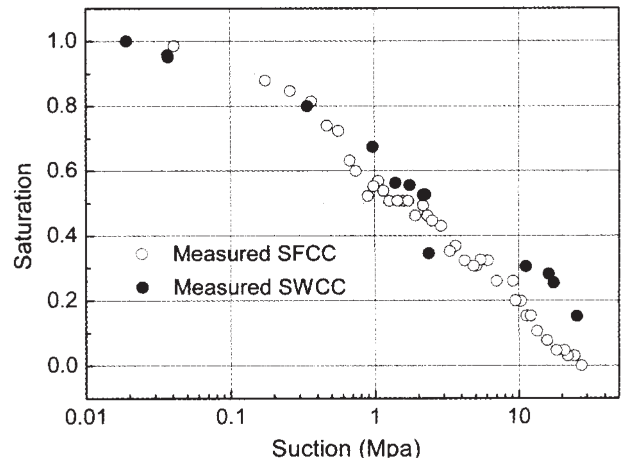


FIG. 6—*Comparison of the measured SFCC versus the SWCC directly measured by ASTD D5298 for soil #1.*

Figure 6 plot the measured SFCC curve using the described experimental and analyses procedures. The SWCC measured by the filter paper method is also plotted for comparison. The value and trend of SFCC matches very well with SWCC, particularly for the range of soil suction commonly encountered in practice (from several hundred kilopascals to several megapascals). The observation also implies the conversion factor A (in Eq 7) between the SWCC and SFCC is approximately 1 for this soil.

Experiments were also conducted to validate the applicability of the procedures to specimens of different geometry. For this purpose, the sample of soil #2 with initial gravimetric water content of 16 % was compacted into a steel cylinder consolidometer ring with an inner diameter of 7.1 cm and a height of 20 cm. Soils were compacted into the ring to reach specified maximum density. The prepared specimen was extruded, sandwiched by two pieces of porous stone, wrapped up with a permeable cloth and soaked in water for more than 48 h. The gravimetric water content after soaking was 17.0 %, corresponding to volumetric water content of 31.8 %.

The thermo-TDR was inserted horizontally into the specimen with the rods perpendicular to the axes of the cylindrical soil specimens. Similar thermal procedures were applied to measure the SFCC, i.e., the specimen was frozen under −18°C; it was then subjected to controlled thawing inside a refrigerator; thermo-TDR was used to monitor the degree of thawing and the corresponding temperature. From these, the SFCC was then determined. The ASTM D5298 filter paper method was also conducted to measure the SWCC directly.

Figure 7 plots the measured SFCC and SWCC for soil #2. Again, the two curves coincide in most soil suction range. This good agreement indicates the satisfactory performance of this new method to estimate SWCC from SFCC.

The procedures of ASTD D5298 filter paper method took weeks to perform, while the SFCC by this new method takes only around 15 h. Another note is the SFCC was determined with more densely distributed data than by than filter paper method. This is because each data point on the SWCC by the filter paper method requires at least one week to obtain equilibrium, while more data points can be obtained on the SFCC curve by simply changing the time interval for TDR signals and temperature data.

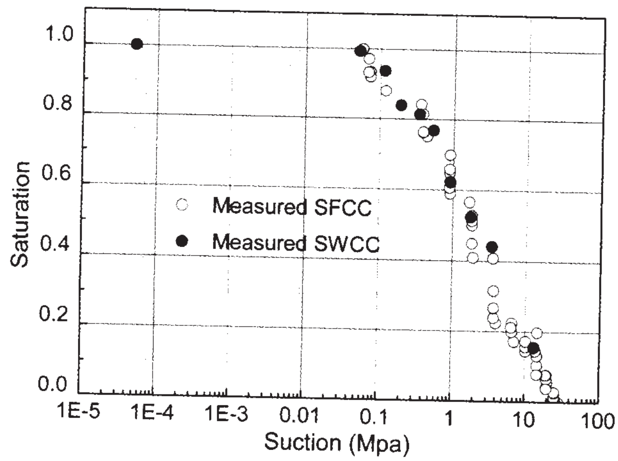


FIG. 7—*Comparison of SWCC by the ASTM D 5298 and SFCC for Soil #2.*

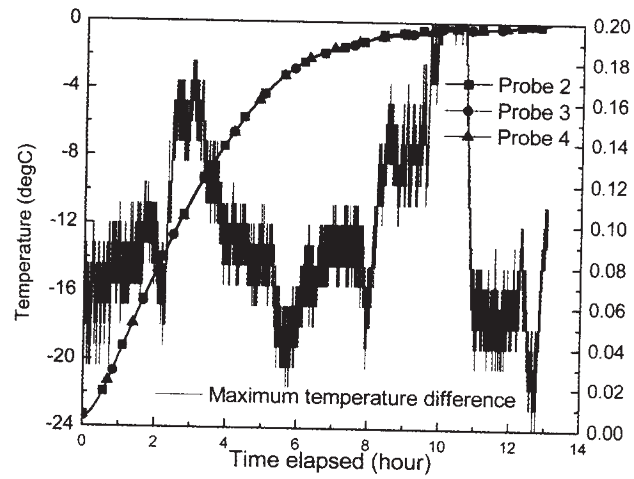


FIG. 9—*Measured temperature process at different locations in soil and the max differences in temperature values at different time.*

Discussion

The theoretical basis of this new method requires (1) equilibrium conditions at the water/ice interface; (2) accurate temperature measurement representing the behavior of the bulk specimen. The first requirement is because the proposed method for SFCC measurement utilizes the Clapeyron equation. The Clapeyron equation describes the thermal equilibrium conditions at the interfaces of different phases. During the thawing procedure, exchange of energy with external system inevitably occurs. Therefore, the thermal equilibrium can only be approximated or only quasi-equilibrium conditions are achieved. Therefore, the rate of freezing/thawing needs to be controlled for accurate SFCC measurement. Specially, the thermal exchange (thawing) needs to be sufficiently slow to approximate quasi-equilibrium conditions. So the Clapeyron equation can be extended and applied without causing significant amount of error.

The slow rate of thermal exchange achieved in our experiments ensures relative uniform temperature distribution inside the specimen. For example, the temperature process as well as the maximal differences between measured temperatures inside the specimen is plotted in Fig. 9. It can be seen that the maximum temperature difference between sensors is mostly lower than 0.1°C and the maximum difference is around 0.2°C. The corresponding differences in estimated suction values are no more than 20 kPa. The extent of error was further reduced by taking average of the temperature data.

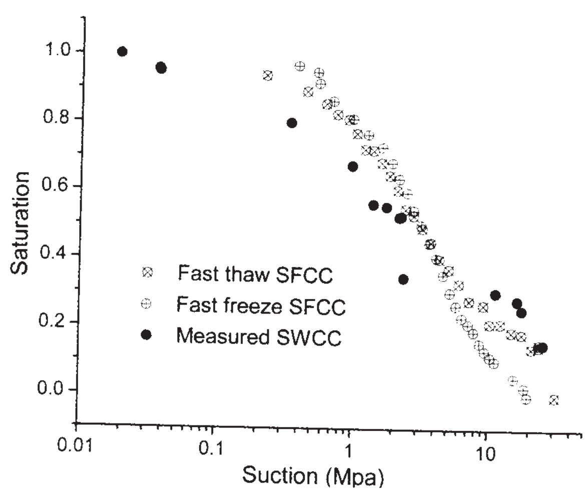


FIG. 8—*Measured SWCC by filter paper method and measured SFCC with fast thawing and freezing procedures.*

The approximation of the thermal equilibrium condition is dependent upon the rate of thawing. Typically the faster the thawing process, the further away the soil to the equilibrium conditions. To investigate the effects of thawing rate on the SFCC measurements, experiments were conducted using a fast thawing procedure by directly exposing the frozen soil specimen to the room temperature. The SFCC was also measured under a fast freezing procedure involved by directly placing the specimen in a −18°C freezer. Figure 8 plots the SFCC from the fast thawing/freezing procedures. The SWCC by ASTM D5298 filter paper method is also plotted as comparison. The comparison shows that the suction values by SFCC under fast freezing/thawing procedures is lower in the low suction range and higher at higher suction range compared to the SWCC. The discrepancy between SWCC and SFCC is likely due to the non-equilibrium conditions under the fast freezing-thawing procedures.

The observations above indicate maintaining thermal-equilibrium conditions are necessary to estimate SWCC from SFCC measurement. To reduce the rate of thawing, the thawing process in this experiment was conducted inside a refrigerator. The specimens were frozen in the refrigerator to −18°C (the lowest temperature the refrigerator can achieve). It was found that more than 15 h were required for completing the thawing process, while it only takes around 30 min to thaw the specimen completely when directly exposing it to the room temperature of 22°C. Due to good thermal insulation provided by the refrigerator, the temperature difference between air temperature of refrigerator and the coldest location in the soil sample stayed within 4°C. According to the Newton's law of cooling, the rate of thermal energy exchange is controlled by the difference of temperature with the environment as Eq 10

$$\dot{Q} = h \cdot A(T_{\text{env}} - T) \tag{10}$$

where $\dot{Q}$ is the rate of thermal energy exchange (J/s), h is the heat transfer coefficient, A is the surface area, T_{env} is the environmental temperature, T is the surface temperature of the specimen.

For static air, a conservative assumption of the convective heat transfer coefficient is 5 $W/m^2 \cdot K$ (Burmeister 1993). A maximum 4°C difference between surface temperature and environmental temperature (which is measured during the experiments) corresponds to a rate of 20 W/m2 heat flux into the specimen. The reasonable agreement of measured SFCC and SWCC in Fig. 6 indicate that this rate of energy exchange might be sufficient to approximate thermo-equilibrium conditions inside the soil specimens. Therefore, heat flux of less than 20 W/m^2 on thawing is recommended for application of the developed method. This might set the criteria to ensure the quasi-equilibrium conditions while thawing a frozen soil specimen. Further validation of this criterion is needed for different sized specimens.

Conclusion

This paper describes a new procedure to estimate the SWCC based on the SFCC. This method is based on the similarity between the freezing and drying processes. The paper first presents the theoretical basis for this method. The experimental measurements for SFCCs were carried out by use of a thermo-TDR sensor. The thermo-TDR simultaneously measured the unfrozen water content (or saturation) and soil temperature. The soil temperature was converted to soil suction by use of the Clapeyron equation, which describes the pressure-temperature relationship at interfaces of solid and liquid water under thermal-equilibrium condition. Therefore, the SFCC of soil can be obtained by subjecting the soil to proper freezing or thawing procedure. The rate of thermal exchange while thawing was controlled so that a thermal equilibrium condition was approximated inside the soil specimen. The SFCCs obtained from this procedure were found to match the SWCCs directly measured by the ASTM D5298 filter paper method. Therefore, SFCC is a potential alternative procedure for SWCC measurement. On the scientific side, this study provided another evidence on the similarities between freezing/thawing processes and desorption/sorption processes.

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