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Heat-Pulse Method for Soil Water Content Measurement: Influence of the Specific Heat of the Soil Solids

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ABSTRACT

The heat-pulse method measures soil volumetric water content (θ) based on the linear relationship between soil volumetric heat capacity (C) and θ. Previous work suggested that this method was more appropriate for determining change of θ rather than its absolute value. In this study, we demonstrate that the heat-pulse method can give accurate θ estimation when values for the specific heat of the soil solids (c_s) are determined using the heat-pulse method. Heat-pulse measurements were performed on packed columns of three soils with a wide range of bulk density (ρ_b) and θ. When the commonly used c_s value (0.725 kJ kg^{-3} K^{-1}) was used, the heat-pulse method overestimated θ by 0.052 m^3 m^{-3} on average. However, when c_s values determined from heat-pulse measurements on oven-dried soil were used, the heat-pulse method provided accurate θ results (-0.006 m^3 m^{-3} average error). Using soil-specific, heat-pulse determined c_s values also reduced the average root mean square error (RMSE) in θ for the three soils from 0.061 to 0.039 m^3 m^{-3}.

RECENTLY, the heat-pulse method has been used to measure θ. Laboratory and field studies (Bristow et al., 1993; Tarara and Ham, 1997; Song et al., 1998) indicated that the method offers the benefits of low cost, less soil disturbance, and automatic and frequent in situ readings. The small sample volume also makes this method suitable for detailed measurements of the spatial variability of θ.

Several factors, including probe spacing (Bristow et al., 1993), soil bulk density (Tarara and Ham, 1997), and soil mineralogy (Bristow, 1998) may affect the accuracy of θ measurement using the heat-pulse method. Bristow et al. (1993) and Tarara and Ham (1997) concluded that this method could provide accurate measurements of changes in θ. In this note, we demonstrate that the accuracy of θ measurement with the heat-pulse method is improved by using soil-specific values for c_s.

THEORY

The measurement of C with the heat-pulse method relies on the theory of radial heat conduction of a short-duration heat pulse away from an infinite line source. In an infinite medium, the temperature change as a function of time at a radial distance from the heat-pulse source is given by (de Vries, 1952; Kluitenberg et al., 1993),

$$\Delta T(r,t) = \frac{q}{4\pi\alpha C}\left[Ei\left(\frac{-r^2}{4\alpha(t-t_0)}\right) - Ei\left(\frac{-r^2}{4\alpha t}\right)\right] \quad t > t_0 \quad [1]$$

where ΔT is the temperature change (°C), t is time (s), t_0 is the duration of the heat pulse (s), r is the radial distance (m), q is the rate of heating (W m^{-1}), α is the soil thermal diffusivity (m^2 s^{-1}), C is the volumetric heat capacity (J m^{-3} K^{-1}), and $-$Ei($-x$) is the exponential integral (Abramowitz and Stegun, 1972). Once the $\Delta T(r, t)$ data are obtained from the probe, Eq. [1] is used to determine α and C by means of nonlinear regression (Bristow et al., 1995; Welch et al., 1996).

The volumetric heat capacity can also be estimated by summing the contributions of the individual components (Campbell et al., 1991):

$$C = \rho_b c_s + \rho_w c_w \theta \quad [2]$$

where ρ_w is the density of water (Mg m^{-3}), c_w is the specific heat capacity of water (kJ kg^{-1} K^{-1}), and ρ_b is soil bulk density (Mg m^{-3}). The contribution of soil air to C is ignored because the density and specific heat of air are very small relative to the other terms.

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Abbreviations: C, soil volumetric heat capacity; c_s, specific heat of soil solids; RMSE, root mean square error; θ, soil volumetric water content; ρ_b, bulk density; ρ_w, density of water.

Table 1. Selected properties of the soils.

Soil	Organic matter	Particle-size distribution		
		Sand	Silt	Clay
	%			
Sand	0.0	97.5	0.2	2.3
Silt loam	0.9	23.5	63.5	13.0
Silty clay loam	1.1	12.1	55.5	32.4

Table 2. Particle density (ρ_s), specific heat (c_s), and volumetric heat capacity ($\rho_s c_s$) of the soil solids. The values are means and standard errors of three replicates.

Soil	ρ_s	c_s	$\rho_s c_s$
	Mg m^{-3}	kJ kg^{-1} K^{-1}	MJ m^{-3} K^{-1}
Sand	2.74 ± 0.006	0.881 ± 0.020	2.413 ± 0.054
Silt loam	2.67 ± 0.022	0.913 ± 0.009	2.439 ± 0.024
Silty clay loam	2.69 ± 0.000	0.973 ± 0.010	2.617 ± 0.027

Rearranging Eq. [2] yields a simple expression for determining θ from the heat-pulse method (Campbell et al., 1991):

$$\theta = (C - \rho_b c_s)/(\rho_w c_w) \quad [3]$$

MATERIALS AND METHODS

The heat-pulse function of a thermo-TDR probe (Ren et al., 1999) was used to measure C. The probe consists of three parallel stainless steel needles, each enclosing a line heater and a thermocouple. The rods are 1.3 mm in diameter and 40 mm in length and spaced 6 mm apart. The heaters are made from 75-μm diam. enameled Evanohm wire (Wilbur B. Driver Co., Newark, NJ), and the thermocouples were chromel constantan. The resistance of the completed heater is 887.6 Ω m^{-1}. See Ren et al. (1999) for additional details regarding the probe design and construction.

The heater-to-thermocouple spacing was calibrated using agar-immobilized water (5 g agar L^{-1}), taking heat capacity of the water as 4.18 MJ m^{-3} K^{-1} (Campbell et al., 1991). The heat pulse was generated by applying a DC current to the central heater with a direct current supply (Model HY1791-3S, Huaiyin Electronics Equip. Corp., Huaiyin, China) for 15 s. A data logger (Model CR10X, Campbell Scientific, Logan, UT) controlled the heat input, monitored the temperatures of the thermocouples every second, and recorded the voltage drop across a precision resistor that was used to determine the current applied to the heater. The heater-to-thermocouple spacing was calculated by using a nonlinear regression method (Welch et al., 1996) to fit the temperature-by-time data.

The heat-pulse method was evaluated in the laboratory on three soils: a sand, a silt loam, and a silty clay loam. Table 1 lists the major physical characteristics of the three soils. Particle-size analysis was performed using the hydrometer method (Gee and Bauder, 1986) and the soil organic matter was measured using the Walkely–Black titration method (Nelson and Sommers, 1982). The soils were air-dried, ground, sieved through a 2-mm screen, moistened with distilled water, and packed into soil columns (5.2-cm i.d. and 6.0 cm in height) with different water contents and bulk densities. Three columns with different ρ_b values were packed at each value of θ. The ρ_b of the soil columns ranged from 0.95 to 1.45 Mg m^{-3} and θ varied from air dry to saturation. All of the columns were tightly covered and placed in a temperature-regulated room (20 ± 1.2°C) for 48 h before measurements. After the probe was inserted into a soil column from the surface, a constant current was then applied from the direct current supply to the central heater for 15 s to generate the heat pulse. The data logger recorded the heating power by measuring the voltage drop across the precision resistor and measured the temperature in the outer rods as a function of time for 300 s. The soil volumetric heat capacity was calculated by analyzing the temperature increase versus time data at the sensor needles using a nonlinear curve-fitting technique (Welch et al., 1996). In each column, the heat-pulse measurements were repeated three times at 60-min intervals. The volumetric heat capacity was taken as the mean of the three replicate measurements. Finally, gravimetric water contents of the soils were determined by oven drying the samples at 105°C, and ρ_b of the soil columns was also determined.

To estimate c_s in Eq. [2] and [3], we performed heat-pulse measurements for oven-dried samples of all three soils. The c_s values were then calculated from the relationship $C = \rho_b c_s$. Table 2 presents the measured results. Particle density was also determined using the pycnometer method and was used to calculate the volumetric heat capacity of the soil solids shown in Table 2.

RESULTS AND DISCUSSION

A survey of the published data indicates a relatively wide range of values for c_s (Table 3), from 0.644 kJ kg^{-1} K^{-1} (Johnston, 1937) to 0.939 kJ kg^{-1} K^{-1} (Campbell et al., 1991). Bristow (1998) showed that errors of >10% can occur in heat-pulse θ measurement when inaccurate values of c_s were used in Eq. [3]. In this study, we first used 0.725 kJ kg^{-1} K^{-1} (de Vries, 1963) for c_s and calculated θ from C measurements using Eq. [3]. Figure 1 presents the heat-pulse results in comparison with the values determined gravimetrically. Good linear relationships exist between the data of the heat-pulse method and the gravimetric method. However, regardless of soil texture, θ, and ρ_b, the heat-pulse method systematically overestimated θ. On average, Eq. [3] overestimated θ by 0.067, 0.040, and 0.050 m^3 m^{-3} for the sand, the silt loam, and the silty clay loam, respectively. Some of the scatter of the data at θ > 0.2 m^3 m^{-3} was caused by the spatial variation of ρ_b within the columns, since we experienced difficulties in packing the soil columns uniformly at higher water contents.

We then used the c_s values determined from the heat-pulse measurements on the oven-dried soils to estimate θ using Eq. [3]. The heat-pulse estimated c_s values were 0.881, 0.913, and 0.973 kJ kg^{-1} K^{-1} for the sand, silty loam, and silty clay loam (Table 2). These values are respectively 21.5, 25.9, and 34.2% higher than the commonly used value of 0.725 kJ kg^{-1} K^{-1} (de Vries, 1963). The results calculated using these soil specific c_s values

Table 3. Literature values of specific heat of soil solids (c_s).

Literature	c_s
	kJ kg^{-1} K^{-1}
Johnston (1937)	0.644
de Vries (1963)	0.725
Hillel (1982)	0.755†
Campbell (1985)	0.804–0.902†
Hanks and Ashcroft (1986)	0.838
Campbell et al. (1991)	0.864–0.939
Ochsner et al. (2001)	0.801–0.895

† Calculated from volumetric heat capacity by taking the soil particle density as 2.65 Mg m^{-3}.

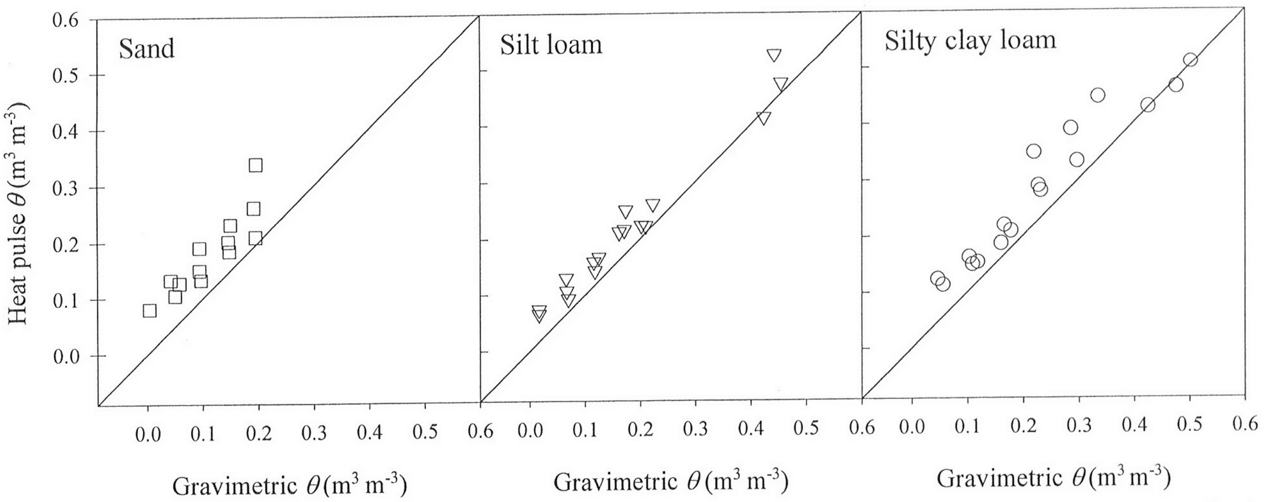

Fig. 1. Heat-pulse water content, θ, vs gravimetrically determined θ. The parameter of specific heat of soil solids, c_s, was 0.725 kJ kg^{-1} K^{-1}. The solid lines are the 1:1 lines.

agreed well with the gravimetrically measured values, and the data were randomly distributed along the 1:1 line (Fig. 2). On average, Eq. [3] overestimated θ by 0.02 m^3 m^{-3} for the sand and underestimated θ by 0.014 and 0.025 m^3 m^{-3} for the silt loam and the silty clay loam, respectively. For each soil the bias of the θ measurement was reduced by using the c_s values determined from the heat-pulse measurements on oven-dried soil.

Using the soil-specific c_s values also led to decreases in the root mean square error (RMSE) of the heat-pulse θ measurements for each soil. The RMSE decreased from 0.073 to 0.041 m^3 m^{-3} for the sand, from 0.046 to 0.029 m^3 m^{-3} for the silt loam, and from 0.062 to 0.048 m^3 m^{-3} for the silty clay loam. We suspect that non-uniformities of ρ_b and θ within the packed columns caused these RMSE values to be larger than they would have been if the columns had been perfectly uniform. If so, then the real precision of the heat-pulse method is likely better than that indicated by these RMSE values.

Previous investigators (Bristow et al., 1993; Tarara and Ham, 1997) concluded that the heat-pulse method could provide accurate measurements of changes in θ. Ours results showed that the heat-pulse method is also able to provide accurate absolute θ for soils with a range of textures and ρ_b, provided appropriate c_s values are used. For the three soils used in this study, the measured c_s values are greater than the commonly employed value, but they are still in the range of literature values (Table 3).

CONCLUSIONS

We demonstrate that using an inappropriate c_s value leads to errors in heat-pulse measured θ. In this study, using the c_s value (0.725 kJ kg^{-1} K^{-1}) from de Vries (1963) resulted in overestimation of θ by 0.040 to 0.067 m^3 m^{-3}. We also illustrated that using c_s values determined from heat-pulse measurements on oven-dried soil samples improves the accuracy of the heat-pulse θ measurements. Again, the focus of this study is on obtaining more accurate θ measurements by the heat-pulse technique. Independent measurements of c_s would be required to determine if the c_s values determined by the heat-pulse method are themselves accurate.

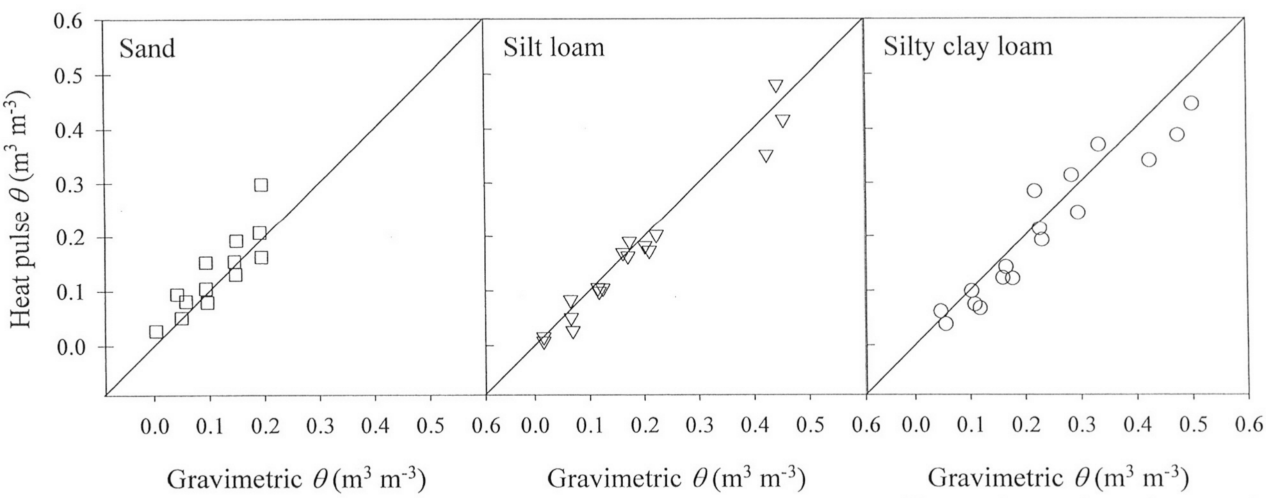

Fig. 2. Heat-pulse water content, θ, vs gravimetrically determined θ. The heat-pulse measured specific heat of soil solids, c_s, for each soil was used. The solid lines are the 1:1 lines.

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