Evaluation of the Heat-Pulse Technique for Measuring Soil Water Content with Thermo-TDR Sensor

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Abstract

The heat-pulse technique is emerging as a useful technique for measuring soil water content (θw) with the advantages of automated, rapid, and minimal destructive. The purpose of this study is to evaluate the performance of the Liu et al. (2008) thermo-TDR (time domain reflectometry) sensor for measuring soil water content using the heat-pulse technique. For this sensor, the root mean square errors (RMSE) of heat-pulse soil water content estimates compared with gravimetric measures in laboratory evaluations was 0.011 m3 m-3 and was 0.018 m3 m-3 in a field evaluation. The results indicated that the sensor with a needle diameter of 2 mm, needle length of 40 mm, and needle-to-needle spacing of 8 mm can provide accurate, nondestructive, repeated estimates of soil water content.

Keywords: Heat-pulse, Time Domain Reflectometry, TDR, Soil Volumetric Water Content, Thermo-TDR

1. Introduction

Volumetric water content (θw) is an important part of soil, influencing the many biological, physical, and chemical processes. Measurements of θw in vadose zone are often needed by researchers or irrigation managers in agriculture and horticulture. The heat-pulse technique is emerging as a useful technique for measuring soil θw, with the advantages of automated, rapid, and minimal destructive [1-7]. However, laboratory and field studies concluded that the heat-pulse method tended to overestimate θw. Needle deflection has been shown theoretically and experimentally to be the key factor that influences the accuracy of the heat-pulse technique [10, 11]. On the base of Ren et al. (1999) thermo-TDR sensor, Liu et al. (2008) altered the sensor length, diameter and needle-to-needle spacing to reduce the needle deflection during sensor insertion. Experimental results from laboratory and field studies indicated that the redesigned sensor can provide accurate, nondestructive, repeated estimates of soil bulk density (ρb) [12].

The objective of this study is to evaluate the performance of the Liu et al. (2008) thermo-TDR sensor for measuring soil water content using the heat-pulse technique and the time domain reflectometry (TDR) method under both laboratory and field conditions.
2. Theory

De Vries (1963) proposed that the volumetric heat capacity of the soil can be calculated by summing the heat capacities of the solids, water, and air [13]. Since the density and specific heat capacity of air are very small relative to the other terms, the contribution of soil air is neglected [14].

\[ \rho c = \rho_s c_s + \rho_w c_w \theta \]  

[1]

The volumetric heat capacity of the soil can be determined from the measured temperature change as a function of time using a nonlinear regression method [15]. The heat-pulse soil water content (\( \theta_{HP} \)) can be estimated by

\[ \theta = \frac{\rho c - \rho_s c_s}{\rho_w c_w} \]  

[2]

where \( \rho_w \) (1.0 Mg m\(^{-3}\)) and \( c_w \) (4.18 kJ kg\(^{-1}\) K\(^{-1}\)) are the density and the specific heat capacity of water, respectively, and \( c_s \) (kJ kg\(^{-1}\) K\(^{-1}\)) is the specific heat capacity of soil solids. Because \( c_s \) is related to soil texture and organic matter content, the accuracy of \( c \) can be improved using specific \( c_s \) values determined from heat-pulse measurements on dry soils [16]. In this study, the \( c_s \) values were measured on oven-dried soil samples and the results were presented in Table 1.

3. Materials and Methods

3.1 The thermo-TDR Sensor

Combined the design criteria for the TDR probe and the dual-probe heat pulse device, Liu et al. (2008) modified the Ren et al. (1999) thermo-TDR sensor focuses on three aspects. Experimental results from laboratory and field studies indicated that the redesigned sensor increased the accuracy of heat capacity estimates. In this study, the redesigned thermo-TDR sensor was used to measure the soil water content. The configuration of the sensor was described in detail in the paper of Liu et al. (2008)[12].

3.2 Sensor Calibration

The heater-to-thermocouple spacing (\( r \)) was calibrated using agar-immobilized water (5 g L\(^{-1}\)) in a temperature-regulated room (20±1°C), assuming the volumetric heat capacity of the agar-water solution is equal to the volumetric heat capacity of water (4.18 MJm\(^{-3}\)C\(^{-1}\)) [14, 17]. A 15s-length heat pulse was generated by a DC power supply and a datalogger (Model CR23X, Campbell Scientific, Logan, UT) was connected to control the heat input and measure the temperatures of the thermocouples for 1s interval. The value \( r \) was calculated to fit the temperature increase as a function of time using a nonlinear regression method. The measurements were repeated 10 times at a 60-min interval, and the mean of the 10 measurements was used for thermal property calculation.

3.3 Laboratory Evaluation

A laboratory experiment was conducted on three soils: a sand, a silt loam and a clay loam (Table 1). The sand was collected from a reservoir bed (0-30 cm) nearby Beijing, China; the clay loam soil was sampled from the 200-220 cm soil horizon in the experimental farm of China Agricultural University, Beijing, China; and the silt loam soil was sampled from the surface layer (0-15 cm) of a tillage study plot.
in the Luancheng Agricultural Ecosystem Experimental Station, located in Hebei Province of China. Table 1 lists the bulk density and water content ranges of the packed soil columns. Particle size analysis was performed using the pipette method [18], organic matter content of the soil was measured using the Walkley-Black titration method [19], and the $c_s$ values were obtained by performing heat pulse measurements on oven-dried samples.

Table 1  Particle-size distributions, organic matter (OM) content, and specific heat ($c_s$) of the laboratory soils.

| Texture   | Particle size distribution | OM  | $c_s$   |
|-----------|---------------------------|-----|---------|
|           | >0.05 mm  | 0.002-0.05 mm | <0.002 mm | g kg$^{-1}$ | kJ kg$^{-1}$ K$^{-1}$ |
| Sand      | 93         | 0             | 7         | 0.64         | 0.791         |
| Silt loam | 15         | 65            | 20        | 14.55        | 0.875         |
| Clay loam | 31         | 39            | 30        | 2.71         | 0.833         |

Soil samples were air dried, ground, sieved through a 2-mm screen, moistened with distilled water, mixed thoroughly and then packed into PVC cylinders (100 mm in diameter, and 80 mm in height) with different water contents and bulk densities. The packed columns were covered tightly and placed in a temperature-regulated room (20±1°C) for 24 hours before obtaining measurements. To perform measurements, the thermo-TDR sensor was inserted into each soil columns vertically from the surface. The heat pulse (15 s) was generated to the central needle by a direct current supply. The datalogger controlled the heat input, monitored the temperatures of thermocouples every second, and recorded the voltage drop across a precision resistor that was used to determine the heat input to the central needle. To maintain the temperature increase in the outer needles in the range of 0.6 - 0.9°C, the magnitude of the heating power was adjusted depending on the soil water content. Soil $c$ was calculated by applying the HPC code to fit the measured temperature change as a function of time. Then the $HPC$ was estimated by Eq.[2]. For a given soil column, three heat-pulse measurements were made on each column at 60-min intervals. Finally, gravimetric water content and bulk density of the soil column was determined by oven-drying the soil sample for 24 h at 105°C.

3.4 Field Evaluation

The field evaluation was conducted on a long-term tillage experimental site at the Luancheng Agricultural Ecosystem Experimental Station of the Chinese Academy of Sciences, located in Hebei Province of China. The soil texture was the same silt loam as listed in Table 1.

Field measurement was conducted after winter wheat harvest. A trench (300-mm long, 200 mm-wide, and 200-mm deep) was made and the sensors were pushed into the soil horizontally at 50 mm depth. To avoid disturbance during the measurement, the spacing between neighboring sensors was about 100-mm spacing. Heat pulse and TDR measurements were then completed. The measurement procedure was same as in the laboratory except that a 12 V battery was used to produce the heating power. To adjust the temperature rise in the outer needles less than 0.9°C, the heat pulse length was 15s for Sensor. Finally, undisturbed soil samples were collected using ring samplers (50-mm long and 50-mm diameter), pushed in horizontally at each location where thermo-TDR sensors were installed. Soil gravimetric water content and bulk density were determined by oven-drying these core samples. The same measurement at the 150-mm depth was completed following the same procedure and four replicated measurements were
made for each tillage treatment.

3.5 Data Analysis

In this study, root mean square error (RMSE) and relative error (RE) of soil water content estimates was used to evaluate the performance of the sensor.

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\theta_{i e} - \theta_{i grav})^2}{n}}
\]  

where \( \theta_{e} \) was estimated water content value by heat-pulse and TDR methods, \( \theta_{grav} \) was the gravimetrically determined water content value, and \( n \) was the number of the data points.

4. Results and Discussion

Comparisons of heat-pulse water contents (\( \theta_{HP} \)) with the volumetric water contents (\( \theta_{G} \)) determined gravimetrically for the three soils in laboratory soil columns and undisturbed soil in field were shown in Fig. 1. In general, the \( \theta_{HP} \) values agreed well with \( \theta_{G} \) values, as indicated by random distribution of the data along the 1:1 lines. The result demonstrated that the redesigned sensor was able to capture the trend of the gravimetric soil water content. The root mean square error (RMSE) of \( \theta_{HP} \) compared with gravimetric measures was 0.011 m\(^3\) m\(^{-3}\).

Figure 1. Heat-pulse estimated water content (\( \theta_{HP} \)) versus gravimetrically measured water content (\( \theta_{G} \)) in laboratory soil columns

The sensors were able to capture the gravimetric water content trends in the field experiment (Fig. 2). However, compared to the laboratory results there was relatively larger scattering of data for field sensor. The RMSE of thermo-TDR estimated \( \theta_{HP} \) compared with gravimetric measures of \( \theta_{G} \) was 0.018 m\(^3\) m\(^{-3}\). The performance on laboratory and field studies indicates that the redesigned sensor could provide accuracy water content values by heat-pulse technique.
Conclusions

In this paper, we evaluated the performance of Liu et al. (2008) thermo-TDR sensor for measuring soil water content by heat-pulse methods. Experimental results from laboratory and field studies indicated that the redesigned Liu et al. (2008) sensor with a needle diameter of 2 mm, needle length of 40 mm, and needle-to-needle spacing of 8 mm increased the accuracy of \( \theta_{HP} \) estimates. The RMSE of \( \theta_{HP} \) from the Liu et al. (2008) sensor was 0.011 and 0.018 m\(^3\) m\(^{-3}\) under laboratory and field conditions. The thermo-TDR technique provides a valuable tool for obtaining soil temperature, water content, and thermal properties, as it allows in situ, direct, rapid, and automated measurements.

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