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Temperature-Compensating Calibration Procedure for Water Content Reflectometers

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Abstract

Data are presented showing how the response of CS616 water content reflectometers (WCRs) manufactured by Campbell Scientific, Inc. is affected by temperature and soil type. The sensitivity illustrates that soil-specific calibrations with temperature compensation are needed when using CS616 WCRs if accurate predictions of volumetric water content are to be made, particularly in fine-grained soils that are more electrically conductive. A procedure to develop soil-specific calibrations with temperature compensation is presented. The procedure consists of six steps and requires two sets of regressions. Application to a field site is also presented to illustrate the difference in volumetric water contents obtained with and without a soil-specific calibration and temperature compensation.

Key Words time domain reflectometry, water content reflectometer, calibration, temperature, electrical conductivity, landfill final cover

Introduction

Time domain reflectometry (TDR) is the most commonly used method for measuring in situ volumetric water content repetitively and non-destructively. A wide-variety of TDR systems are now available and are being used for water content monitoring in research and practice. Conventional TDR (i.e., GHz frequency) remains the most reliable method for measuring volumetric water content. However, conventional TDR can be cumbersome to deploy, has physical limitations, can require special interfaces for data logging, and can be expensive. Consequently, many of the more recent commercial developments have focused on smaller, simpler, and less costly TDR systems that can be readily coupled with commercial data loggers.

Many of the newer TDR systems incorporate all of the electronics in the head of a probe, thereby eliminating the need for specialized electronic interfaces or multiplexers. However, these newer TDR probes may also operate at lower frequency (MHz range) than conventional TDR, making the water content measurements more sensitive to factors such as temperature, soil type, and conductivity of the pore water (Campbell, 1990[1]; Campbell and Anderson, 1998[2]; Seyfried and Murdock, 2001[3]; Kim and Benson, 2002[4]; Stenger et al., 2005[5]; Blonquist, et al., 2005[6]). This sensitivity is often ignored in practice, which can lead to significant errors. These errors can largely be eliminated by developing soil-specific calibrations that account for temperature effects (Seyfried and Murdock, 2001[3]; Kim and Benson, 2002[4]; Czarnomski et al., 2005[7]).

Water content reflectometers (WCRs) manufactured by Campbell Scientific Inc. are the most commonly deployed TDR probes that function in the MHz frequency range (Seyfried and Murdock, 2001[3]; Czarnomski et al., 2005[7]; Plauborg et al., 2005[8]; Stenger et al., 2005[5]; Hansson and Lundin, 2006[9]). The authors have used WCRs extensively for repetitive in situ measurements of volumetric water content and currently are monitoring more than 300 WCRs at sites throughout the United States (US). This experience has shown that WCRs must be calibrated for soil-specific conditions and that a temperature correction should be applied when interpreting volumetric water contents obtained from WCRs. This paper describes how CS 616 WCRs are affected by temperature, illustrates how the sensitivity depends on soil type, and provides an empirical method to develop a soil-specific calibration with temperature-compensation. An example from a field site is provided that illustrates the error that can be incurred by ignoring temperature effects when monitoring volumetric water contents in the field.

Materials and Methods

Water Content Reflectometer

A CS616 WCR manufactured by Campbell Scientific Inc. (Logan, UT, USA) was used for this study. A photograph of a WCR in a calibration cell is shown in Fig. 1. The CS616 WCR consists of two metallic rods affixed to a circuit board that is encapsulated in epoxy (white "head" in Fig. 1). The circuit board contains the electronics needed to generate the electromagnetic energy that is propagated along the rods and through the surrounding soil (Fig. 1) and to detect the reflection from the rod ends. The rods are 300 mm long, 3.2 mm in diameter, and have a center-to-center spacing of 32 mm.

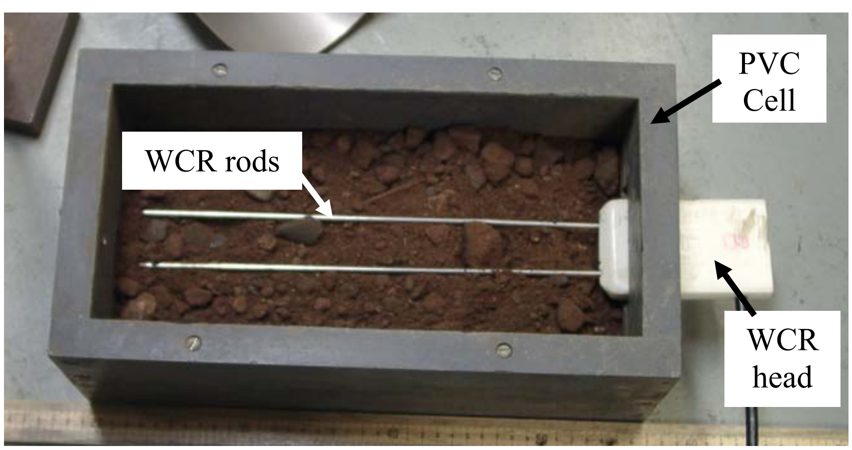

Fig. 1. Calibration cell containing CS616 WCR. Meter stick is shown below cell for scale.

The WCR employs a line driver that sets the output at one of two discrete values. When the circuit switches state, the electromagnetic energy of the transition is propagated along the rods. The signal is reflected from the end of the rods, and travels back to the line driver circuit. A section of the circuit detects the returning signal, and switches the line driver to the other state which launches another electromagnetic wave down the rods. This process continues as long as the WCR is enabled. The time between line driver transitions (T_r) represents a combination of travel time along the rods and time delays in the circuitry (Bilskie, 1997[10]):

$$T_r = 2[t_{ct} + 2\frac{L\sqrt{K_a}}{c}] \tag{1}$$

where t_{ct} is the propagation time for the line driver and other circuit board components, L is the length of the probe rods, K_a is the apparent dielectric permittivity of the soil, and c is the velocity of an electromagnetic wave in free space (Bilskie, 1997[10]; Campbell and Anderson, 1998[2]; Kelleners et al. 2005[11]). The factor 2 in Eq. 1 accounts for the two trips along the rods and through the circuit (i.e., the two states of the line driver) corresponding to a complete cycle.

The frequency of the CS616 WCRs is approximately 70 MHz in free air and about 24 MHz in free water. To permit data recording using low cost data loggers, the final output transmitted by a WCR is a square wave with the period scaled by 2^{10}. The data logger records the average scaled period of the wave (P), which is related to volumetric water content via a calibration curve (Campbell Scientific, 2004[12]).

Calibration Cell

The calibration cell is a box constructed of polyvinyl chloride (PVC) plate that has inside dimensions of 330 x 152 x 127 mm (Fig. 1). The size of the box is based on experiments conducted by Kim and Benson (2002)[4], where PVC calibration cells of various sizes were tested to determine the minimum size needed to ensure that the cell did not influence the response of the WCR. The calibration cell has a volume of 6.3 L, which is considerably larger than the sampling volume for CS616s computed theoretically (0.04 L) by Blonquist, et al. (2005)[6].

Soil used for the calibration is compacted directly in the box in three lifts of equal thickness. The WCR is inserted through a slot at one end of the box when placing the soil for the second lift. This lift is compacted directly on top of the WCR, ensuring good contact between the rods and soil. The third lift of soil is then placed, and afterwards the box is sealed in plastic. A standard Proctor hammer (ASTM D698, 2000[13]) is used to compact the soil, with the number of tamps adjusted to achieve the target density.

A thermocouple is placed in the center of the box when the second lift of soil is placed. The WCR and thermocouple are attached to a CR10X data logger (Campbell Scientific Inc., Logan, UT) to record the WCR period and the temperature. At least 10 measurements of the period are made at each calibration point, with the average of these measurements recorded.

To achieve different soil temperatures, the calibration cell is placed in a temperature-controlled chamber, with the period recorded after thermal equilibration is achieved at each temperature. An automated chamber controlled by a PC was used in this study that permitted temperatures between -22 and 36 ^{o}C.

Soils

Four soils were used in this study that varied in composition and electrical conductivity. Physical properties of the soils are summarized in Table 1 and the major minerals in each soil are summarized in Table 2. X-ray diffraction was used to determine the mineralogical composition. Particle size distribution curves for the soils are shown in Fig. 2. All four soils are being used to construct water balance covers for waste containment facilities in different regions of the western US.

Table 1. Physical Properties of Soils A-D.

Soil	Max. Dry Density (Mg/m^3)	Opt. Water Content (%)	Specific Gravity (-)	Liquid Limit (-)	Plasticity Index (-)	Percent Fines (-)	USCS Classi-fication	Elec. Conductivity at Saturation (mS/m)
A	1.84	14.5	2.68	24	4	77	ML	71.4
B	2.20	6.2	2.80	27	NP	14	SM	12.4
C	2.10	9.0	2.70	26	NP	30	SM	46.9
D	1.61	17.0	2.60	-	-	17	SM	9.55

Notes: Maximum dry density and optimum gravimetric water content correspond to standard Proctor compaction determined by ASTM D 698 (2000)[13]; fines defined as particles finer than 75 μm; 0.1 kHz electrical conductivity measured at saturation using AASHTO T 288 (2000) [14].

Table 2. Major Minerals in Soils A-D (Percent by Weight).

Soil	Quartz	Feldspars	Calcite	Dolomite	Chlorite	Illite	Smectite
A	34.0	41.3	2.3	-	2.7	10.0	5.9
B	24.3	55.7	-	-	1.4	12.4	-
C	24.5	54.2	-	-	2.1	10.9	-
D	64.8	4.5	3.0	7.2	3.0	17.5	-

Notes: Analysis by K/T GeoServices Inc. (Argyle, TX, USA). Hyphen indicates < 1%.

The particle size distributions of the soils vary widely, from a narrow distribution of sand-sized particles (Soil D) to a broad range of particles spanning gravel to clay (Soil B). One of the soils classifies as silt (A), another is a silty sand (D), and two are silty sands with gravel (Soils B and C). Only the silt (Soil A) exhibits plasticity, and only to a minor degree. The other four soils are non-plastic. The soils are comprised primarily of quartz and feldspars (69.3-80.0%), but also contain small amounts of calcite and dolomite rock flour (Soils A and D) and clay minerals

(13.0-20.5%). Soil A is the only soil that contains an appreciable amount of smectite clay mineral.

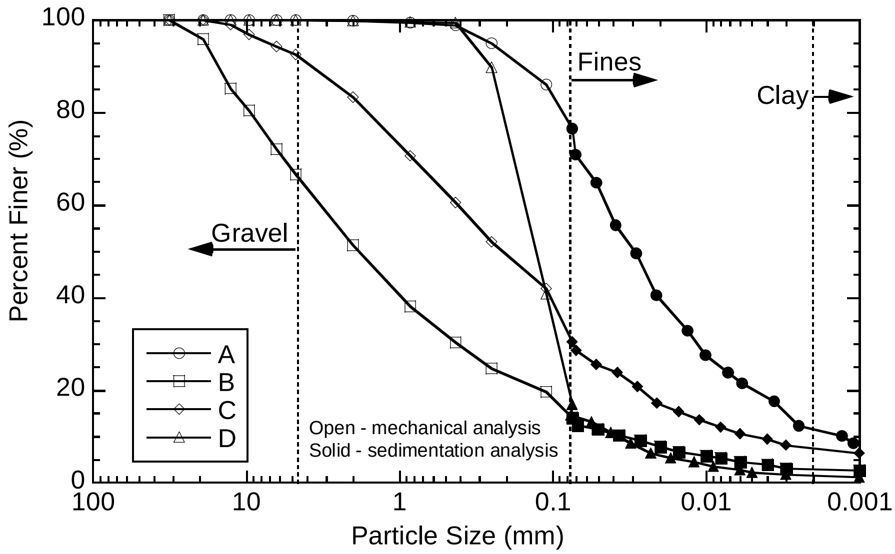

Fig. 2. Particle Size Distribution Curves for Soils A-D.

Temperature Sensitivity

Several factors affect the temperature response of dielectric sensors such as WCRs. These include the temperature-dependent dielectric permittivity of water (ε_w), the temperature-dependent electrical conductivity of the soil (σ_e), and potentially the amount of water bound to the mineral surface. Response of electronic components within the sensor may also be affected by temperature. Increasing the temperature causes ε_w to decrease, σ_e to increase, and may release bound water (Wraith and Or, 1999[15]; Rhodes et al., 1976[16]; Abu Hassanein et al., 1996[17]; Drnevich et al., 2001[18]; Jones et al., 2005[19]). For clean coarse-grained soils with lower σ_e and minimal bound water, temperature effects on K_a are controlled primarily by the effect of temperature on ε_w (i.e., for a given volumetric water content, θ, increasing the temperature causes a decrease in K_a). In contrast, for finer grained soils having higher σ_e and a greater fraction of bound water, temperature effects on K_a are controlled primarily by the effect of temperature on σ_e and perhaps by the release of bound water (i.e., for a given θ, increasing the temperature causes an increase in K_a) (Seyfried and Murdock, 2001[3]; Kim and Benson, 2002[4]; Drnevich et al., 2001[18])

Response of the CS616 WCR embedded in Soil A is shown in Fig. 3 for five volumetric water contents ranging from 0.06 to 0.41 and for temperatures between -22 and 36 ^{o}C. The period decreases with decreasing temperature (i.e., K_a is decreasing, Eq. 1), which is attributed primarily to a decrease in bulk electrical conductivity of the soil due to reduced mobility of ions in the pore water and on the mineral surfaces (Rhodes et al., 1976[16]; Abu Hassanein et al., 1996[17]). The sensitivity to temperature is greater at higher volumetric water content, reflecting the greater contribution of the pore water to the bulk electrical conductivity of the soil.

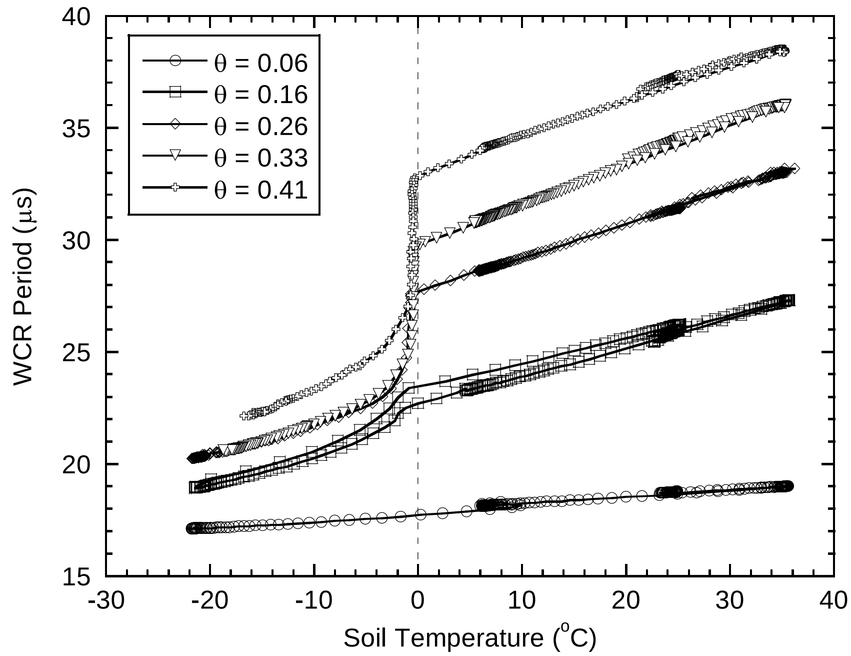

Fig. 3. WCR Period as a Function of Soil Temperature for Soil A at Volumetric Water Contents (θ) of 0.06, 0.16, 0.26, 0.33, and 0.41. Data at θ = 0.16 Include Hysteresis Loop.

The period changes rapidly as the temperature drops below 0 ^{o}C due freezing of the pore water. Ice has considerably lower relative dielectric permittivity (~ 3) compared to liquid water (~ 80) (CRC, 2006[20]), which results in lower K_a and lower P (Eq. 1). At lower volumetric water contents, a smaller drop in P occurs when the soil freezes because water contributes a lesser amount to K_a at lower volumetric water contents.

The response of the WCR also exhibits a slight amount of hysteresis as the temperature is cycled, as illustrated in Fig. 3 for θ = 0.16. The mechanism responsible for this hysteresis is not known. However, hysteresis has also been observed with other soils and for conditions where the soil was not cycled through conditions below 0 ^{o}C.

The effect of temperature on the WCR calibration curve for Soil A is shown in Fig. 4 for temperatures of 5, 20, and 35 ^{o}C. Curves are not shown for temperatures below 0 ^{o}C because the unfrozen volumetric water content was not determined in this range. The slope is shallower and the period increases as the temperature increases, which can have a significant effect on the inferred volumetric water content. For example, if a CS616 WCR was calibrated with Soil A at 20 ^{o}C, a period of 30 μs would correspond to θ = 0.25. However, if the soil temperature was 5 ^{o}C or 35 ^{o}C (a common range of temperatures at the near surface), θ would could be as low as 0.21 or as high as 0.31 (Fig. 4). That is, for Soil A, the error in θ could be on the order of 0.10.

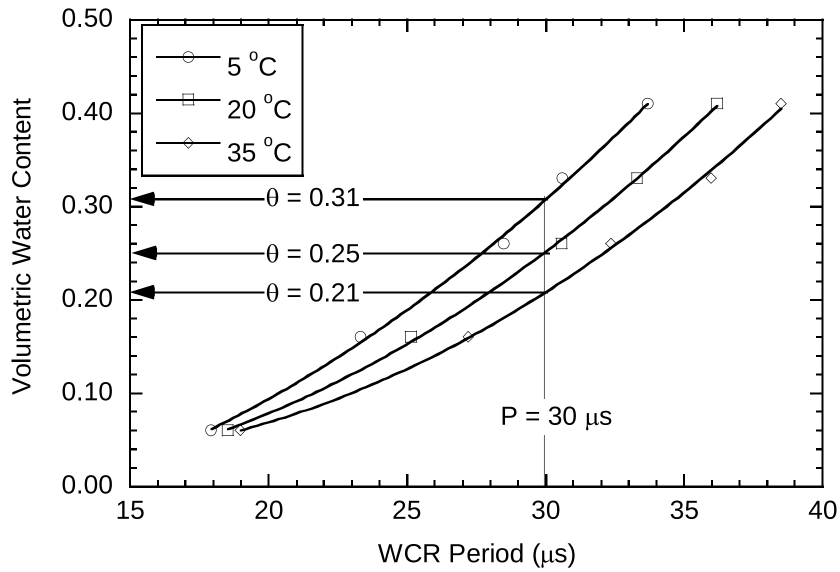

Fig. 4. WCR Calibration Curves for Soil A at Temperatures of 5, 20, and 35 °C.

Calibration with Temperature-Compensation

An empirical method was developed that can be used to develop a temperature-compensating calibration for the CS616 WCR. The method is based on the nearly linear relationship between P and soil temperature (T) for T > 0 °C, as shown in Fig. 5a for Soil C and in Fig. 3 for Soil A (as will be shown subsequently, P varied linearly with T for all four soils that were tested).

The linear relationship illustrated in Fig. 5a can be written as:

$$P = \alpha_\theta T + \beta_\theta \tag{2}$$

where α_θ and β_θ are empirical parameters that vary systematically with θ (Fig 5b). The relationship between α_θ and θ typically follows a second order polynomial (Fig 5b):

$$\alpha_\theta = a_0 + a_1\theta + a_2\theta^2 \tag{3}$$

whereas β_θ varies linearly with θ (Fig. 5b):

$$\beta_\theta = b_0 + b_1\theta \tag{4}$$

An expression relating θ, P, and T is then obtained by combining Eqs. 2-4 and solving for θ as a function of T and P. This expression has the form:

$$\theta = \frac{-(b_1 - a_1T) + \sqrt{(b_1 + a_1T)^2 - 4a_2T(a_0T + b_0 - P)}}{2a_2T} \tag{5}$$

The parameters a_o, a_1, a_2, b_o, and b_1 in Eq. 5 are obtained by least squares regressions on the α_θ-θ and β_θ-θ data (i.e., as shown in Fig. 5b) using expressions having the forms shown in Eqs. 3-4.

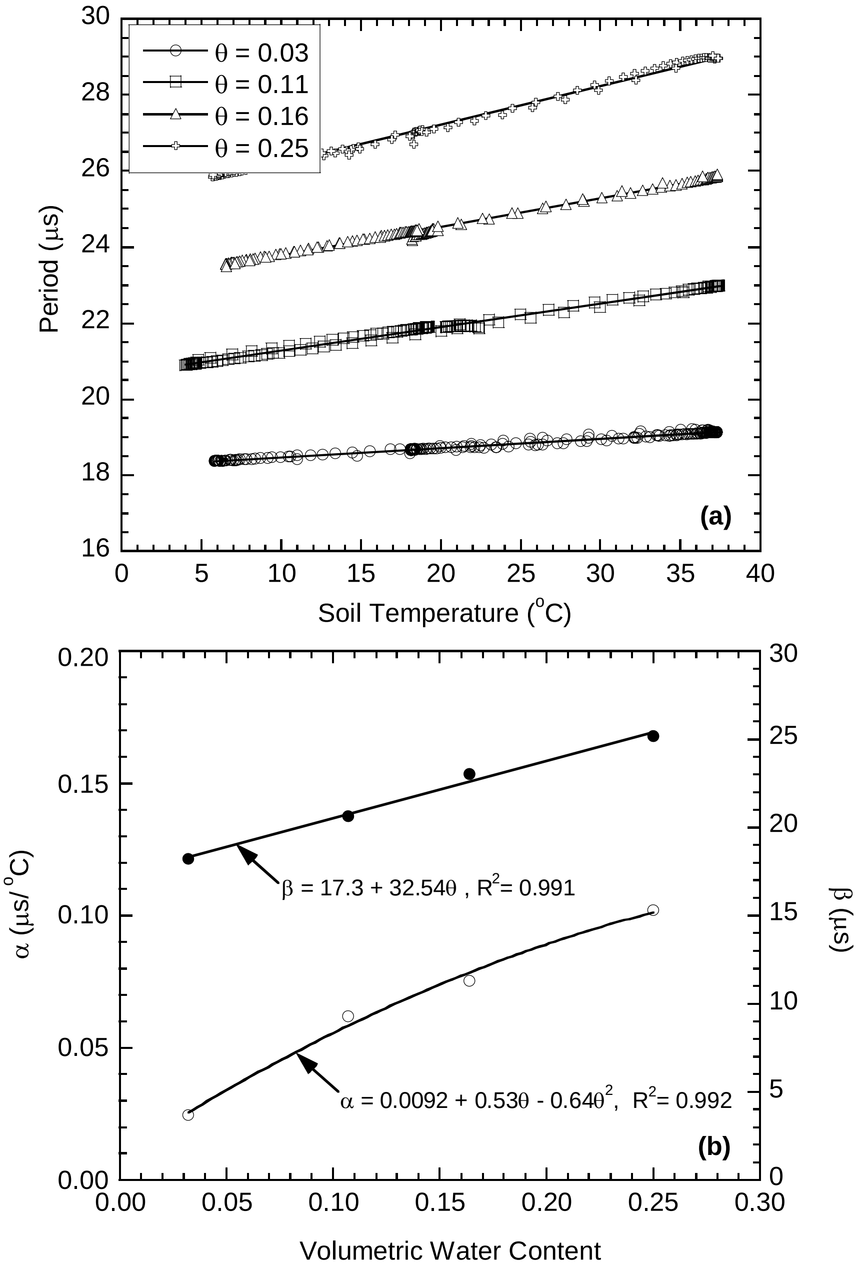

Fig. 5. Graphs Illustrating Method to Develop Temperature-Compensating Calibration for Soil C: (a) WCR Period (P) as a Function of Temperature for Four Volumetric Water Contents (θ) with Regressions Lines to Define α_θ and β_θ, (b) Calibration Parameters α_θ and β_θ for Soil C as a Function of Volumetric Water Content (θ).

Summary of Temperature-Compensating Calibration Procedure

The procedure to develop a temperature-compensating calibration can be summarized as follows:

1. Prepare 4-6 specimens in a calibration cell corresponding to volumetric water contents spanning the range of interest in the field.

2. Subject each specimen to 4-6 temperatures within the range of temperatures expected in the field. After establishing equilibrium at each temperature, record P corresponding to that temperature and θ.

3. Determine the parameters α_θ and β_θ for each θ by linear least-squares regression of P on T.

4. Determine the parameters a_o, a_1, and a_2 by least-squares regression of α_θ on θ using a second order polynomial.

5. Determine the parameters b_o and b_1 by linear least squares regression of β_θ on θ.

6. Define the θ-P calibration by inserting the parameters a_o, a_1, and a_2 from Step 4 and b_o and b_1 from Step 5 into Eq. 5.

Effect of Soil Type

The parameters α_θ and β_θ are shown as a function of θ in Fig. 6 and the parameters a_o, a_1, a_2, b_o, and b_1 for each soil are summarized in Table 3. The relationship between α_θ and θ varies considerably between soils (Fig. 6a), which suggests that a soil-specific calibration curve is needed for CS616 WCRs, as suggested by the manufacturer (Campbell Scientific, 2004[12]) and by others (Seyfried and Murdock, 2001[3]; Kim and Benson, 2002[4]; Czarnomski et al., 2005[7]). The greatest sensitivity is for Soil A, which exhibits plasticity and has the highest fines content and clay content of the soils that were tested (Fig. 2, Table 1.). Conversely, there is little relationship between α_θ and θ for Soil D, which has the smallest clay fraction of the soils that were tested and exhibits no plasticity (Fig. 2, Table 1). In contrast, the relationship between β_θ and θ is nearly unique, and a single expression relating β_θ and θ is reasonable for all four soil types (Fig. 6b).

Electrical conductivity appears to be the key factor affecting the relationship between α_θ and θ, with soils having greater electrical conductivity exhibiting greater sensitivity. The WCR response is also more sensitive to temperature in soils that are more electrically conductive. For example, Soil B is more sensitive to temperature than Soil D (Fig. 7), and Soil B has an electrical conductivity at saturation (σ_{es}) of 12.4 mS/m compared to 9.55 mS/m for Soil D (Table 1). Similarly, Soil A is the most sensitive to temperature (Fig. 3), and has the highest σ_{es} (71.4 mS/m, Table 1).

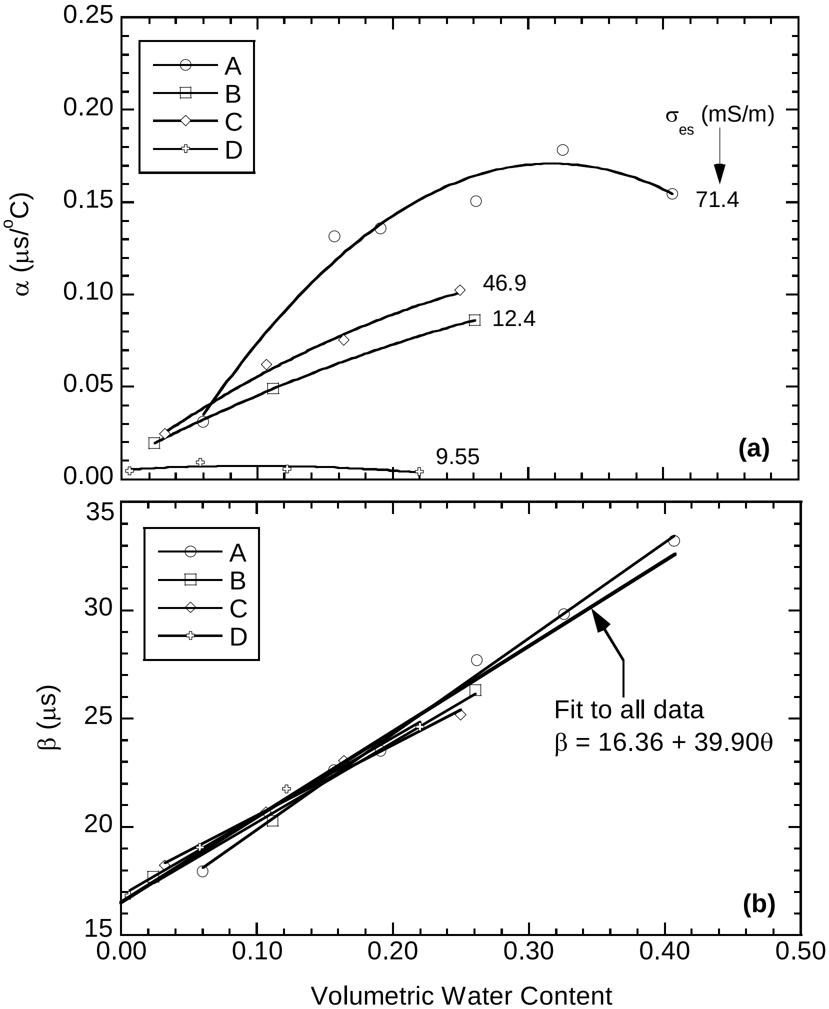

Fig. 6. Calibration Parameters α_θ (a) and β_θ (b) for Soils A-D as a Function of Volumetric Water Content. Trend lines obtained by regression (parameters in Table 3).

Table 3. Temperature-Compensating WCR Calibration Coefficients for Soils A-D.

Soil	Porosity	α parameters (μs/°C)				β parameters (μs)		
		a_0	a_1	a_2	R^2	b_0	b_1	R^2
A	0.42	-0.036	1.30	-2.05	0.965	15.5	44.2	0.995
B	0.33	0.010	0.384	-0.361	1.000	16.5	36.8	0.994
C	0.34	0.0092	0.523	-0.635	0.992	17.3	32.5	0.991
D	0.40	0.00503	0.0433	-0.225	0.476	16.9	36.3	0.990

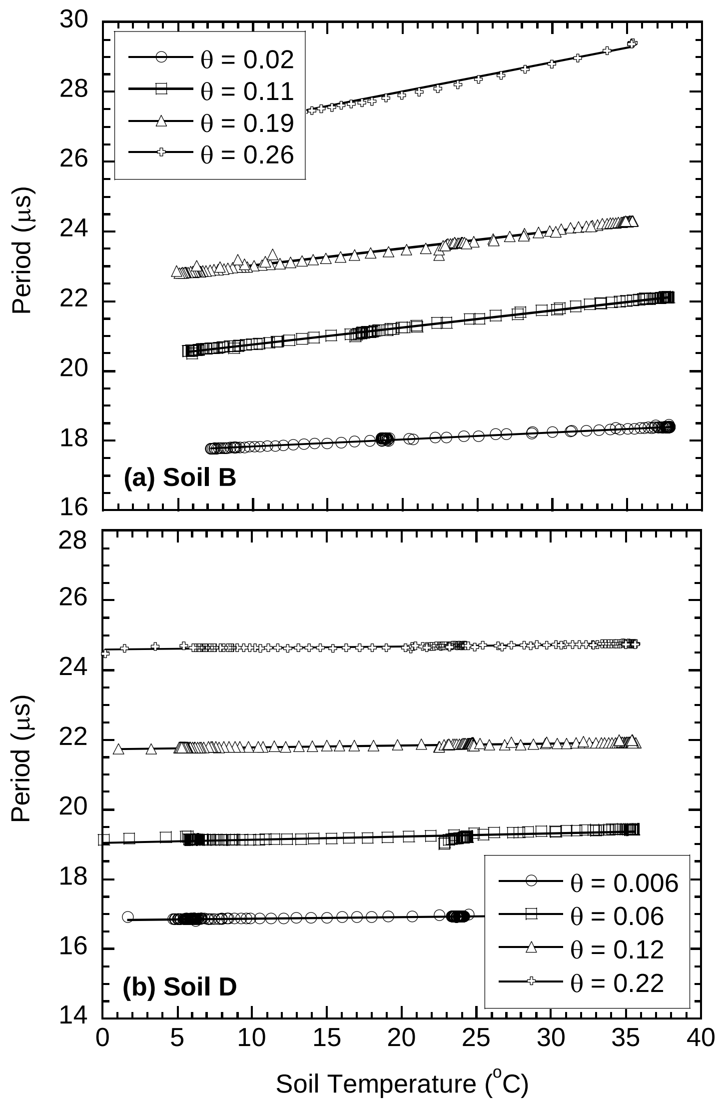

Fig. 7. WCR Period vs. Soil Temperature: (a) Soil B and (b) Soil D. Note Difference in Temperature Sensitivity Between Soil Types.

Example Application

CS616 WCRs were installed in the final cover of the City of Burbank's (CA, USA) Landfill No. 3 in July 2005 to monitor the migration of water in the cover over time. The final cover design consists of a vegetated monolithic water balance cover constructed from Soil C (total thickness ≥ 1220 mm). The WCRs were installed in nests, and each nest consisted of four WCRs stacked vertically at depths of 300, 600, 900, and 1200 mm bgs. A type-T thermocouple was affixed to the head of each WCR to monitor the soil temperature in the vicinity of the volumetric water content measurement. The WCRs and thermocouples were attached to a datalogger for continuous monitoring of volumetric water content and soil temperature. A solid-state multiplexer with on-board temperature reference was used as an interface between the datalogger and the thermocouples. A weather station was also installed for monitoring meteorological conditions on site. Data collected from the site are shown in Fig. 8.

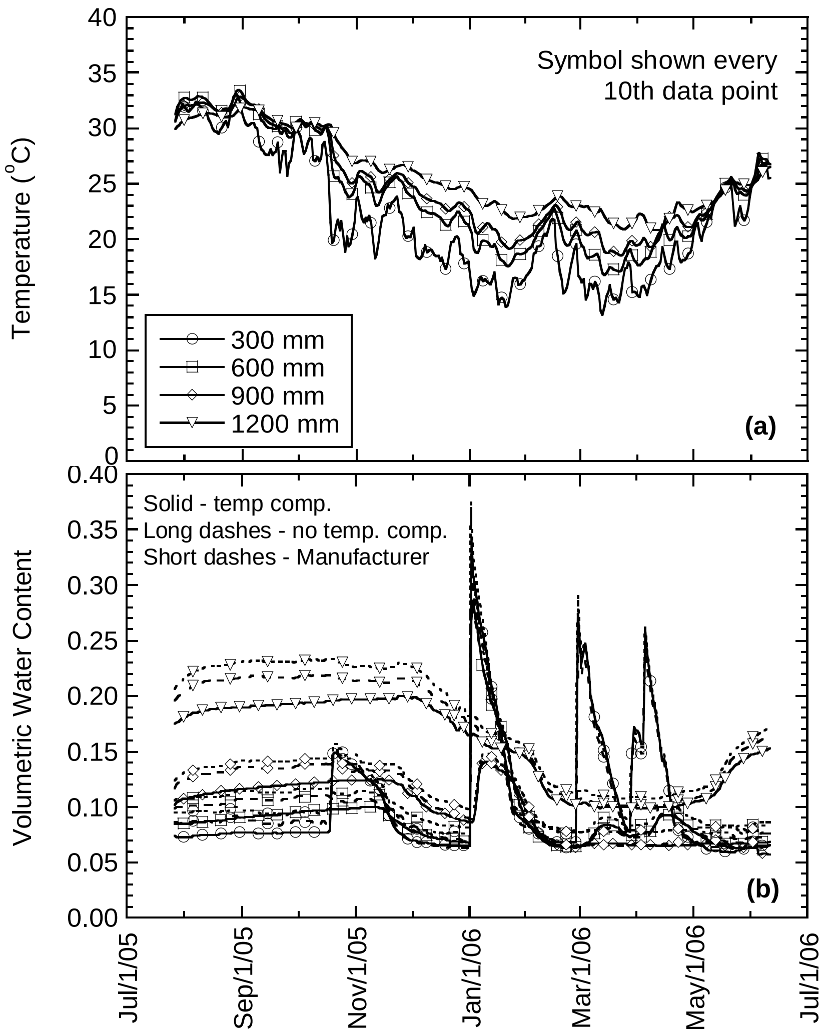

Fig. 8. Example of Volumetric Water Contents Measured with CS616 WCRs in the Final Cover on the City of Burbank's (CA) Landfill No. 3. Solid Lines Correspond to Data with Temperature Compensation. Dashed Lines are for Data without Temperature Compensation.

The temperature record for one of the nests is shown in Fig. 8a. The corresponding record of volumetric water contents measured with the WCRs is shown in Fig. 8b. Volumetric water contents were computed from the WCR periods using the soil-specific calibration with and without temperature compensation using the parameters for Soil C in Table 3. For the computations without temperature compensation, the calibration temperature was assumed to be 20 °C. Additional computations were made using the manufacturer's calibration equation for a sandy clay loam having a porosity of 0.40 and an electrical conductivity of 40 mS/m. Soil C has comparable electrical conductivity to the sandy clay loam cited by the manufacturer, but is more dense (Tables 1, 3). The manufacturer's equation is (Campbell Scientific, 2004[12]):

$$\theta = 0.0950 - 0.0211P + 0.0010\, P^2 \quad (6)$$

Eq. 6 does not include temperature compensation.

The temperature and volumetric water content data reflect the climate in Burbank, CA, with warm and dry conditions during the summer months and milder and wetter conditions during the winter and spring. Sharp pulses occur in the volumetric water contents at the near surface (300 and 600 mm) in response to infiltration from heavy precipitation events in the winter and spring. Much of this infiltration is transmitted back to the atmosphere via evapotranspiration, resulting in smaller changes in volumetric water content near the base of the cover.

Comparison of the volumetric water content records with and without temperature compensation (Fig. 8b) indicates that higher volumetric water contents would be inferred most of the year without temperature compensation, particularly during the hotter months, when soil temperatures in excess of 30 ^{o}C occur. Use of the manufacturer's equation would also have resulted in higher volumetric water contents being inferred, particularly during the warmer months.

The volumetric water contents predicted without temperature compensation also exhibit higher frequency fluctuations, particularly during the warmer months. Using a temperature-compensating equation removes most of these fluctuations, resulting in a smoother variation in volumetric water content during the drier months that is more consistent with the rate of hydrological change expected when volumetric water contents are low and precipitation is infrequent.

Much closer agreement exists between the volumetric water contents computed by all three methods during the wetter winter and spring months, when ambient soil temperatures are closer to 20 ^{o}C (the assumed calibration temperature for the computations made without temperature compensation). The closer agreement during the cooler months is fortuitous for this site, as this is the period when the most significant meteorological conditions are imposed on the cover.

The relatively good agreement between the temperature-compensated and uncompensated data during the wet winter months also suggests that if an isothermal calibration is used, the calibration should be performed at a temperature comparable to the typical temperature at the site or the temperature expected during the most critical portion of the monitoring period. However, the modest electrical conductivity of the cover soil at this site (Table 1) limits the sensitivity of the WCR to temperature effects. Larger temperature effects would be expected at sites where the soil has greater clay content or salinity (resulting in higher electrical conductivity) or at sites where ambient temperatures differ appreciably from the calibration temperature.

Summary and Conclusions

Data have been presented showing that the response of CS616 WCRs manufactured by Campbell Scientific, Inc. is sensitive to temperature and soil type. The temperature sensitivity is greater for soils that are more electrically conductive. For the most electrically conductive soil that was evaluated, the inferred volumetric water content could vary by 0.10 for a given period as the temperature varied over a typical environmental range (5-35 ^{o}C).

These findings indicate that soil-specific calibrations with temperature compensation should be developed when using CS616 WCRs to obtain more accurate predictions of volumetric water content. A procedure to develop this type of calibration has been presented. The procedure consists of six steps and requires two sets of regressions.

An application to a field site has also been presented to illustrate how different volumetric water contents are obtained with and without temperature compensation. This application showed that higher volumetric water contents typically would be inferred if temperature compensation was not applied or if the manufacturer's calibration was used, particularly during warmer and drier periods. Including temperature compensation also removed some of the high frequency variations in the volumetric water contents predicted without temperature compensation, resulting in a more realistic temporal variation in volumetric water content.

Acknowledgement

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