

Evaluation of the Effects of Soil Properties and Electrical Conductivity on the Water Content Reflectometer Calibration for Landfill Cover Soils

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Abstract

Kim K., Sim J., Kim T.-H. (2017): Evaluations of the effects of soil properties and electrical conductivity on the water content reflectometer calibration for landfill cover soils. *Soil & Water Res.*, 12: 10–17.

This study presents soil-moisture calibrations using low-frequency (15–40 MHz) time domain reflectometry (TDR) probe, referred to as water content reflectometer (WCR), for measuring the volumetric water content of landfill cover soils, developing calibrations for 28 different soils, and evaluating how WCR calibrations are affected by soil properties and electrical conductivity. A 150-mm-diameter PVC cell was used for the initial WCR calibration. Linear and polynomial calibrations were developed for each soil. Although the correlation coefficients (R^2) for the polynomial calibration are slightly higher, the linear calibrations are accurate and pragmatic to use. The effects of soil electrical conductivity and index properties were investigated using the slopes of linear WCR calibrations. Soils with higher electrical conductivity had lower calibration slopes due to greater attenuation of the signal during transmission in the soil. Soils with higher electrical conductivity tended to have higher clay content, organic matter, liquid limit, and plasticity index. The effects of temperature and dry unit weight on WCR calibrations were assessed in clayey and silty soils. The sensor period was found to increase with the temperature and density increase, with greater sensitivity in fine-textured plastic soils. For typical variations in temperature, errors in volumetric water content on the order of 0.04 can be expected for wet soils and 0.01 for drier soils if temperature corrections are not applied. Errors on the order of 0.03 (clays) and 0.01 (silts) can be expected for typical variations in dry unit weight ($\pm 2 \text{ kN/m}^3$).

Keywords: soil electrical conductivity; soil index properties; time domain reflectometry; volumetric water content; WCR calibration

The time domain reflectometry (TDR) method is used widely for measuring volumetric water content (θ) and bulk electrical conductivity (σ_e) of soil. Although TDR has become widely used, the method has some practical disadvantages. First, conventional TDR, which operates at frequencies in the GHz range, is costly. Special instruments, coaxial multiplexers, and coaxial cable are required. Second, cable lengths in conventional TDR are required to be relatively short (typically 20 to 30 m) due to signal attenua-

tion (OR & WRAITH 1999; JONES & WRAITH 2002; MUNOZ-CARPENA 2012; STANDER *et al.* 2013). As a result, operating TDR systems at large field sites can be costly and cumbersome (SKIERUCHA *et al.* 2008; COPPOLA *et al.* 2013; REDER *et al.* 2014; VISCONTI *et al.* 2014; FAN *et al.* 2015).

An alternative approach is to employ a probe that operates in a lower frequency range, such as the water content reflectometer (WCR). WCRs employ lower frequency electromagnetic energy (15–40 MHz)

doi: 10.17221/158/2015-SWR

and incorporate all of the electronic components directly into the probe (SEYFRIED & MURDOCK 2001). WCRs can be also connected to a datalogger using conventional shielded data cable. However, because WCRs operate in the MHz range, the calibration between volumetric water content and dielectric constant is more strongly affected by soil bulk electrical conductivity than in conventional TDR (CSI 1996; CAMPBELL & ANDERSON 1998). For this reason, soil specific calibrations are generally required (KIM & BENSON 2002; KIM *et al.* 2005; SKIERUCHA *et al.* 2008; STANGL *et al.* 2009; REDER *et al.* 2014).

Applications of the WCR have been increasingly used in field and laboratory experiments to monitor plant water use, irrigation, movements of chemicals and ions, embankment infiltration, subgrade moisture variation of airfield and highway pavement, and water balance in soils and rocks (SEYFRIED & MURDOCK 2001, 2004; KIM & BENSON 2002; ORTON 2002; CHANDLER *et al.* 2004; WALKER *et al.* 2004; KELLENNERS *et al.* 2005; ANDERSON *et al.* 2009; LIU & SHALABY 2013; SOTELO *et al.* 2014). However, limitations with the WCR have been reported for measuring water contents in soils and rocks. QUINONES *et al.* (2003) reported that the WCR default calibrations, given by CSI, were unsatisfactory for various soils, resulting in requiring soil specific calibration. According to SEYFRIED and MURDOCK (2001, 2004), the WCR produces high-quality data with easy measurement at low cost. However, the WCR calibration shows varying output responses in different soils at the same water contents. Only sandy soil agreed with the manufacturer's calibrations. It was also noted that high clay contents strongly affect sensor output period, which impedes data interpretation and requires soil specific calibration (STENGER *et al.* 2005; STANGL *et al.* 2009). Correspondingly, WCRs emit lower frequency pulse which causes output period to be more sensitive to differences in soil physical properties such as bulk dry density, fine content proportions, and soil ionic concentration. WESTERN and SEYFRIED (2005) reported the WCR to be significantly influenced by temperature at high water contents. Similar results can be found in STANGL *et al.* (2009) and UDAWATTA *et al.* (2011). FRANCESCA *et al.* (2010) and ARSOY *et al.* (2013) confirmed that WCRs were impacted by bulk electrical conductivity and temperature to a greater extent than by dielectric relaxation. Therefore, site and soil specific calibration equations are required for accurate estimation of water contents in soils.

The objective of this study was to evaluate how soil electrical conductivity and soil index properties affect WCR calibrations. For that purpose, soil-moisture WCR calibrations were developed for 28 landfill cover soils. Electrical conductivity of the soils was measured using high frequency TDR. This paper also focuses on the effects of temperature and density of soils on WCR calibration.

MATERIAL AND METHODS

Soils and specimens. A set of 28 soils was used in the present experiment, out of which twenty-three are derived from field sites enrolled in the Alternative Cover Assessment Program (ACAP) funded by the US Environmental Protection Agency (USEPA) and five come from other landfill sites (Table 1). The soils represent a variety of soil types ranging from sand to clay. Most of the fine textured soils are of low to moderate plasticity. The exception is the highly plastic soil from Helena, MT.

The CS 615 water content reflectometers (Campbell Scientific, Inc., Logan, USA) used in this study employ TDR principles for measuring volumetric soil water content. A PVC cell having a diameter of 150 mm and height of 500 mm was used for the WCR calibrations. The cell diameter of 150 mm was selected for pragmatic reasons, because less effort was required to prepare the test specimens (KIM *et al.* 2005). Approximately 10 kg of soil was air-dried, crushed to break up agglomerates, and then sieved through an US No. 4 sieve (4.75 mm openings). The water content in the sieved soil was adjusted by spraying the soil with the required amount of tap water, while continuously mixing the soil to ensure the water content was uniform. The moistened soil was compacted into the calibration cell using the impact hammer for standard Proctor compaction. A PVC cell having a diameter of 150 mm and height of 200 mm was used for measuring soil electrical conductivity with TDR. Approximately 1.5 kg of soil was used for preparing specimens for measuring soil electrical conductivity. The soil was compacted into lifts 30 mm thick, with the number of blows per lift varying between 10 and 15 to reach the target dry unit weight (i.e. field dry unit weight). Then the WCR calibrations were conducted at room temperature (20°C).

Soil specific calibrations. WCR calibrations were performed for a set of 28 soils. Figure 1 shows soil specific calibration for Omaha soils. Linear and polynomial relationships between volumetric water

Table 1. Summary of soil properties, electrical conductivities at saturation, and slopes of linear WCR calibrations

Location	Soil type	USCS	$\frac{Y_{df}}{Y_{dm}}$ (kN/m ³)	W_{opt} (%)	LL	PI	G_s	Sand ¹	Silt ¹	Clay ¹	LOI ¹	σ_{es} (dS/m)	α (m/s)
Sacramento, CA	gravelly clay	SC	15.8	15.8	31	17	2.70	30.1	26.9	17.8	0.40	0.81	0.2585
	clayey silt	CL	15.4	15.5	38	22	2.72	20.1	60.2	18.1	1.02	1.09	0.2843
	silty sand	SM	13.6	14.7	47	19	2.63	48.5	31.4	9.5	N/A	0.66	0.3031
Monticello, UT	clayey silt	CL	15.5	17.5	34	20	2.66	21.5	50.3	27.6	N/A	0.92	0.2972
	silty clay	CL	15.4	16.4	44	25	2.60	5.1	61.1	33.8	0.00	1.30	0.2883
Omaha, NE	sand	SP	15.8	N/A	NP	NP	2.64	100.0	0.0	0.0	0.00	0.05	0.9477
	clayey sand	CL	14.7	16.2	45	27	2.59	1.2	63.6	35.2	0.88	1.17	0.2639
Helena, MT	clayey sand	SC	15.1	15.5	72	49	2.54	50.3	16.6	30.5	0.79	2.48	0.2159
	silty sand	SC	16.4	18.5	32	14	2.60	51.8	16.0	10.9	0.79	0.71	0.2898
Polson, MT	silt	CL-ML	15.8	16.7	26	6	2.68	6.5	75.7	17.2	2.14	0.94	0.3939
	silty sand	SM	15.7	16.9	NV	NP	2.66	50.4	35.3	6.4	0.96	0.48	0.3962
	silty sand	SM	15.8	16.7	NV	NP	2.63	54.6	37.4	5.8	1.88	1.02	0.3210
Boardman, OR	sandy silt	ML	14.9	17.2	22	1	2.73	24.1	65.8	10.1	1.45	0.46	0.4122
	clayey sand	SC	17.6	18.1	28	13	2.66	65.8	8.4	22.0	2.12	0.64	0.3725
Albany, GA	clayey sand	SC	15.1	15.8	27	14	2.65	64.4	8.1	25.0	6.90	1.63	0.2242
	claystone	CL	17.0	18.1	44	20	2.69	11.5	52.2	35.9	3.21	2.76	0.2583
Cedar Rapids, IA	silty sand	SC	19.1	19.7	28	15	2.72	56.1	22.3	17.7	1.13	NA	0.3017
	sandy clay	CL	17.6	17.6	43	25	2.59	40.8	32.2	25.7	3.93	1.24	0.2482
	clay	CL	17.6	19.5	33	19	2.76	45.7	32.3	20.5	N/A	0.67	0.3582
Monterey, CA	clayey silt	CH	11.2	13.7	61	22	2.60	20.1	51.9	28.0	1.13	1.76	0.2845
	sand	SP-SM	16.6	N/A	NP	NP	2.67	91.7	3.8	4.5	0.00	0.19	0.7847
Newberry, CA ²	clay	CH	15.1	15.9	50	29	2.69	15.1	44.9	40.0	N/A	2.60	0.2479
	clayey sand	SC	17.6	19.2	32	18	2.68	57.1	18.8	17.7	2.12	1.50	0.2502
Phelan, CA ²	gravelly sand	SW	17.3	19.7	N/A	N/A	2.68	58.1	3.3	2.0	0.52	0.25	0.6135
	gravelly sand	SW	19.4	20.4	N/A	N/A	2.68	65.0	3.7	1.3	1.33	0.08	0.8513
Apple Valley, CA ²	gravelly sand	SW	18.6	20.7	N/A	N/A	2.68	53.0	9.0	3.5	0.82	0.35	0.5086
	silty clay	ML-CL	17.2	18.3	27	12	2.65	6.3	60.0	30.7	2.15	NA	0.3467
Fernald, OH ²	silty clay	ML-CL	17.1	18.4	29	14	2.66	15.0	58.3	26.7	N/A	NA	0.2974

Y_{df} – field dry unit weight; Y_{dm} – maximum dry unit weight; w_{opt} – optimum water content; LL – liquid limit; PI – plastic index; G_s – specific gravity of solids; USCS – Unified Soil Classification System; LOI – loss of ignition; σ_{es} – electrical conductivity; α – slope of calibration; N/A – not available; NP – non-plastic; NV – non-viscous; ¹based on size definitions in the USCS; ²non-Alternative Cover Assessment Program site

doi: 10.17221/158/2015-SWR

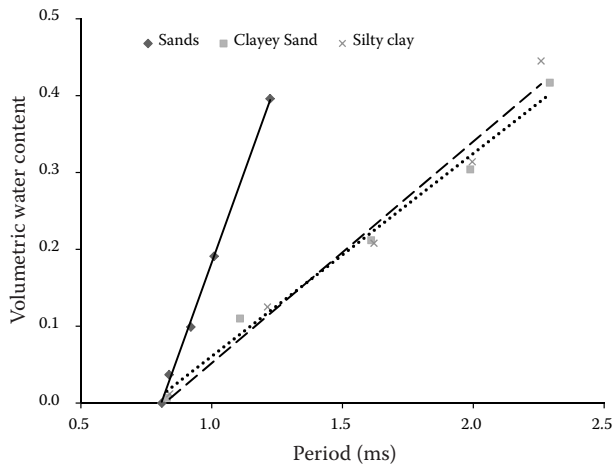


Figure 1. Soil specific water content reflectometer (WCR) calibration for Omaha soils

content (θ) and period (T) were fit to each WCR calibration. In linear function, a is the slope of calibration and T_{\min} is the period corresponding to $\theta = 0$. The coefficient of determination (R^2) for polynomial WCR calibrations ranges between 0.9718 and 0.9989. For linear WCR calibrations, R^2 ranges between 0.9581 and 0.9995. Thus, a strong correlation exists in the data and reliable calibrations were obtained from both equations. Although the R^2 for the polynomial calibrations are slightly higher, the linear calibrations are accurate and simple to use. Thus, the linear calibrations are used in the remainder of this study. The parameter a in the linear calibrations ranges between 0.2159 and 0.9413 (Table 1). Most calibrations have T_{\min} near 0.8 ms.

Soil electrical conductivity. Soil electrical conductivity (σ_e) can be determined from attenuation of

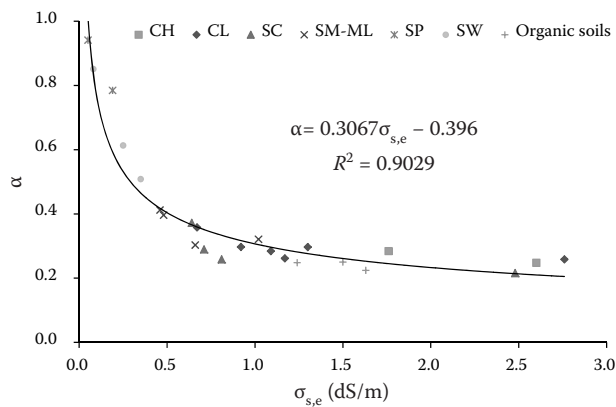


Figure 2. Effect of electrical conductivity at saturation on slope of the water content reflectometer (WCR) calibration curve

the conventional TDR waveform (TOPP *et al.* 1988). Free ions in the soil solution provide a path for electrical conduction, which results in attenuation of the signal applied to the probe. Attenuation reduces the amplitude and affects the shape of the reflected signal displayed on the oscilloscope (CSI 1996; JONES *et al.* 2002). Several models exist for computing electrical conductivity from the TDR waveform. ZEGELIN *et al.* (1989) evaluated the electrical conductivity models, and found that the Giese-Tiemann (G-T) method is the most accurate method for measuring soil electrical conductivity. The Giese-Tiermann (G-T) equation can be written as:

$$\sigma_e = \frac{K_p}{Z_c} \left(\frac{1 - \rho_f}{1 + \rho_f} \right) = \frac{K_p}{Z_c} \left(\frac{2V_0}{V_f} - 1 \right) \quad (1)$$

where:

K_p – probe constant

Z_c – cable impedance (usually 50 Ω)

ρ_f – final reflection coefficient ($\rho_f = V_f/V_0 - 1$)

V_0 – incident pulse voltage

V_f – return voltage at a long distance from the end of probe ($> 10 L_a$; JONES *et al.* 2002)

RESULTS AND DISCUSSION

Electrical conductivity. The electrical conductivity at saturation ($\sigma_{s,e}$) varies between 0.05 and 2.76 dS/m, at volumetric water contents ranging between 0.38 and 0.42. The effect of $\sigma_{s,e}$ on the slope (α) of the WCR calibration curve is shown in Figure 2. The slope decreases as $\sigma_{s,e}$ of the soil increases. A power function was fit to the data using least squares regression. The coefficient of determination (R^2) is 0.9029, indicating that a strong correlation exists between WCR calibration slope and $\sigma_{s,e}$. The lower slopes correspond to soils with a greater clay content, or organic content, which have higher electrical conductivity. In contrast, the soils with higher slope are primarily silts and sands, which have lower electrical conductivity.

Clay content and fines. Table 2 shows the influence of clay content and fines (i.e. silt and clay) on the calibration curves and the relationships between clay content or fines and electrical conductivity. Functions were fit to the data sets using least squares. The slope of the calibration curve decreases as clay/fines content increases because the electrical conductivity of the soil increases as the clay/fines content increases. The clay fraction appears to be

Table 2. Summary of relationships between the slope of calibration (α) and electrical conductivity ($\sigma_{e,s}$), and soil index properties and particle fractions

Description	Trend line	R^2
Clay and fines contents	$\alpha = -0.101\ln(C) + 0.6185$	0.7366
	$\alpha = -0.089\ln(F) + 0.6828$	0.6822
	$\sigma_{s,e} = 0.0517(C) + 0.1042$	0.6939
	$\sigma_{s,e} = 0.0157(F) + 0.2743$	0.3861
Atterberg limits	$\alpha = -0.0028\ln(LL) + 0.4126$	0.5109
	$\alpha = -0.004\ln(PI) + 0.3797$	0.6204
	$\sigma_{s,e} = 0.0517(LL) + 0.1042$	0.5299
	$\sigma_{s,e} = 0.0157(PI) + 0.2743$	0.4479

C – 2- μm clay contents (%); F – fines (%); LL – liquid limit; PI – plasticity index

more important than the silt fraction, as shown by the stronger relationships between α and clay content, and electrical conductivity at saturation and clay content. These relationships exhibit much less scatter than the comparable relationships with fines, which include silt and clay particles. Thus, clay content is believed to be the main factor affecting WCR calibration curves. Three of the clayey sands (Albany, Cedar Rapids, and Monterey) that were evaluated have appreciable organic content (loss of ignition (LOI) 2–7%). Each of these soils is classified as clayey sand (SC) in the Unified Soil Classification System (USCS). Their calibration falls close to that for clays, and below that for silty and clayey sands. The organic fraction causes a longer period, as suggested by CAMPBELL and ANDERSON (1998),

resulting in a smaller slope than that typical of silty and clayey sands.

Atterberg limits. The Atterberg limits are indicators of soil composition and mineralogy. Thus relationships between α and the liquid limit (LL) and plasticity index (PI) were examined. Relationships between the Atterberg limits and α and electrical conductivity are shown in Table 2. $\sigma_{s,e}$ increases and α decreases as LL and PI increase. Soils that are more plastic have greater clay content and more active clay minerals, and thus have greater electrical conductivity. Thus, smaller α is expected for higher LL or PI.

Effect of dry unit weight. WCR calibration curves are typically prepared at a single dry unit weight whereas dry unit weight is spatially variable in the field. To evaluate the error that can be incurred by variations in dry unit weight, WCR measurements were made on Sacramento gravelly clay and Boardman silt at a volumetric water content of 0.3 and at four different dry unit weights (12.35, 14.11, 15.88, and 17.64 kN/m^3). The relationship between period and dry unit weight for Sacramento gravelly clay and Boardman silt is shown in Figure 3a. The period is more sensitive to dry unit weight for the clay than the silt, which reflects the greater sensitivity of electrical conductivity to dry unit weight as plasticity increases.

The potential error in volumetric water content was calculated for Sacramento gravelly clay and Boardman silt assuming that the field dry unit weight differed by as much as 2 kN/m^3 from the dry unit weight used for calibration. Variations of this magnitude are typical in alternative cover soils. The error is shown as a function of the deviation in dry unit weight in Figure 3b. For typical variations in dry unit weight

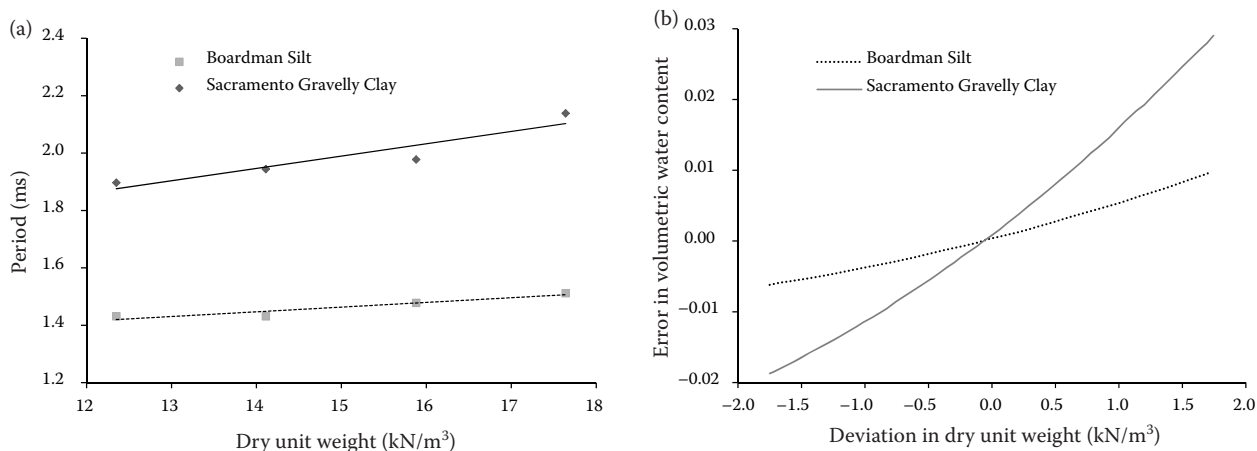


Figure 3. Effect of dry unit weight on water content reflectometer (WCR) period at a volumetric content of 0.3 (a), error in volumetric water content as a function of deviation in dry unit weight for Sacramento gravelly clay and Boardman silt (b)

doi: 10.17221/158/2015-SWR

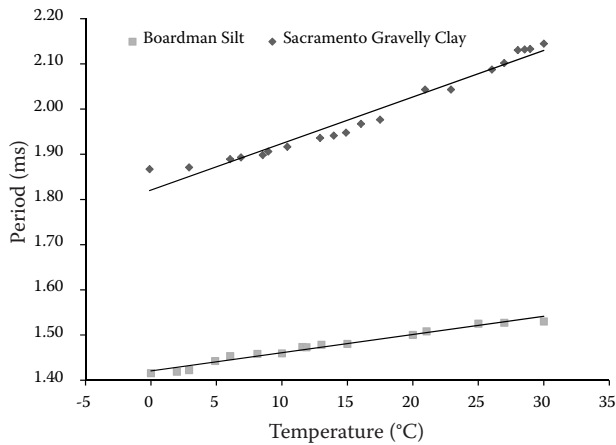


Figure 4. Effect of temperature on water content reflectometer (WCR) period for Sacramento gravelly clay and Boardman silt at a volumetric water content of 0.33

(i.e. $\pm 2 \text{ kN/m}^3$ from the mean), errors in volumetric water content on the order of 0.03 can be anticipated for clayey soils and 0.01 for silty soils.

Effect of temperature. Tests were conducted on Sacramento gravelly clay (CL) and Boardman silt (ML) to evaluate the effect of temperature on the calibration curve. Experiments were conducted at a nearly saturated ($\theta = 0.33$) condition for both soils. The specimens were prepared at the target densities tabulated in Table 1. The tests were conducted for temperatures ranging 0–30°C. Results of the tests are shown in Figure 4. The period increases almost linearly as the temperature increases. Following the method in CAMPBELL and ANDERSON (1998), temperature sensitivities were obtained from the slopes of the lines in Figure 4 and the soil specific calibration curves for the Sacramento and Boardman soils (Table 1). The temperature sensitivities

Table 3. Temperature sensitivities of Sacramento clay and Boardman silt

Media	$\delta\theta/\delta T \text{ (m}^3/\text{m}^3/^\circ\text{C)}$
Sacramento clay at $\theta = 0.33$	2.94×10^{-3}
Boardman silt at $\theta = 0.33$	1.66×10^{-3}
Silt loam at $\theta = 0.28$ (CAMPBELL & ANDERSON 1998)	1.60×10^{-3}

$\delta\theta/\delta T$ – the change in water content per degree change in soil temperature; θ – volumetric water content

summarized in Table 3 are similar or slightly larger than that for silt loam reported by CAMPBELL and ANDERSON (1998). In addition, the temperature sensitivity of Sacramento gravelly clay is two times larger than that of Boardman silt. Thus, the effect of temperature depends on soil type.

Daily soil temperature data from field sites in Boardman, OR and Sacramento, CA were used to assess the error that could be incurred without a temperature correction. The temperature data correspond to a depth of 300 mm in the landfill final covers. Temperature specific calibration curves for both soils were created by computing the slope a for each of the temperatures shown in Figure 4. The parameter T_{\min} was assumed to be independent of temperature. Calibrations were made for volumetric water contents of 0.1, 0.2, and 0.3.

The error was computed in the following manner. First, the WCR period was computed for each day of the temperature record for each specified volumetric water content ($\theta = 0.1, 0.2, \text{ and } 0.3$) using the soil specific calibration curve in Table 1, which corresponds to 20°C. Second, the apparent volumetric water content (θ_a) was computed for each period

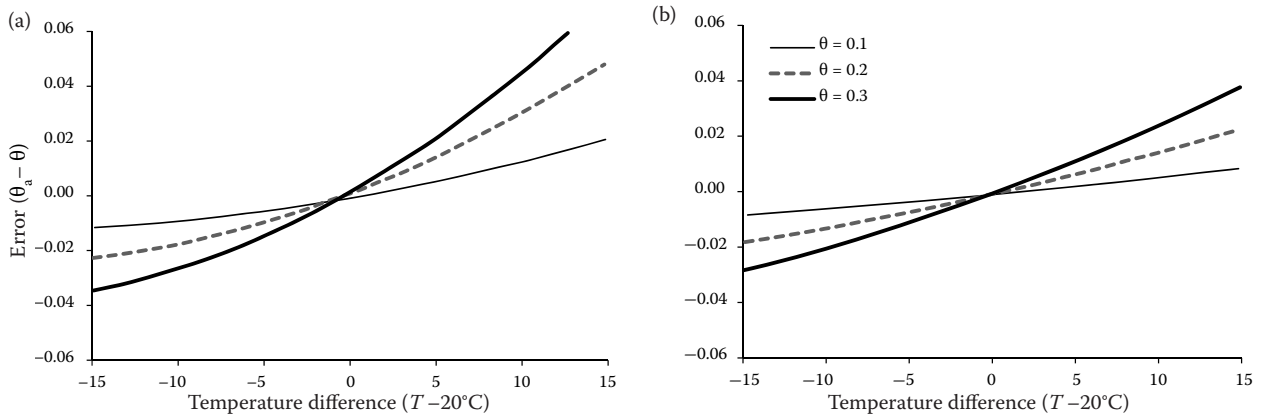


Figure 5. Errors in volumetric water content vs temperature difference ($T - 20^\circ\text{C}$) for three different actual soil water contents: (a) Sacramento gravelly clay and (b) Boardman silt

computed in the first step using the temperature specific calibration curves and the temperature data in the field. That is, three time series of daily θ_a were computed, corresponding to $\theta = 0.1, 0.2,$ and 0.3 . Third, the daily error (e) in each time series was computed as the difference between θ_a and θ (i.e. $e = \theta_a - \theta$).

The error caused by neglecting the temperature effect appears to be the largest in summer and winter, when the greatest difference exists between field temperature and the calibration temperature (20°C). Errors ranging between -0.04 and 0.05 can be expected during the extreme periods (summer and winter), depending on the actual volumetric water content and the composition of the soil. The error is larger for higher water content, and is larger for Sacramento clay than Boardman silt.

The error in volumetric water content is shown in Figure 5 as a function of temperature for Sacramento gravelly clay and Boardman silt. The error increases non-linearly, which reflects the non-linear relationship between soil electrical conductivity and temperature. For temperature differentials of 10°C from the calibration temperature, which are typical in field settings, errors on the order of 0.04 can be expected for moist soils and 0.01 for drier soils.

CONCLUSIONS

This study dealt with calibration of low-frequency ($15\text{--}40$ MHz) WCR for measuring the volumetric water content of 28 landfill final cover soils. The goal was to evaluate how the electrical conductivity and index properties of the soils influence WCR calibrations. Electrical conductivity of the soils was measured using conventional high frequency (GHz) TDR. The linear calibrations are very good fit to the data ($R^2 = 0.9581$ to 0.9995) and are simple to use, although the accuracy for the polynomial calibration is slightly higher.

The slope of the calibration decreases as the electrical conductivity of the soil increases. Lower slopes correspond to soils with greater clay content, organic content, liquid limit (LL), and plasticity index (PI), which typically have higher electrical conductivity. The clay fraction appears to have stronger influence on the calibration slope than the silt fraction. Strong relationships were found between a and clay content, and electrical conductivity and clay content, whereas weaker relationships were found with fines content. The error that can be incurred by variations in dry unit weight and temperature was also evalu-

ated by conducting tests with clay and silt. Greater sensitivity to dry unit weight was found for the clay than the silt, which reflects the greater sensitivity of electrical conductivity to dry unit weight as plasticity increases. For typical variations in dry unit weight, errors in volumetric water content of 0.03 can be anticipated for clayey soils and 0.01 for silty soils. For temperature differentials of 10°C from the calibration temperature, which are typical in field settings, errors on the order of 0.04 can be expected for moist soils and 0.01 for drier soils.

Acknowledgements. The research was supported by the US Department of Energy (DOE) through the Fernald Environmental Management Project (FEMP) and by the National Science Foundation (Grant No. CMS-9713543).

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doi: 10.17221/158/2015-SWR

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Received for publication September 10, 2015

Accepted after corrections May 4, 2016

Published online July 20, 2016