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CALIBRATION OF CAPACITANCE SENSORS FOR COMPACTED SILT IN NON-ISOTHERMAL APPLICATIONS

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ABSTRACT: This study investigates how temperature affects the response of capacitance sensors used to measure the dielectric permittivity of unsaturated soils. The dielectric permittivity is strongly correlated with the volumetric water content, an important variable in understanding water flow processes in unsaturated soils. Although capacitance sensors have been used widely in laboratory and field applications, they have only recently been used to characterize thermally-induced water flow in unsaturated soils during geothermal heat exchange processes. To date, no studies have characterized the effects of temperature on capacitance sensor output for dense, compacted soils. This paper describes a calibration methodology that was used to isolate the effects of temperature on the response of capacitance probes in compacted soils having different initial conditions (i.e., compaction water content and dry density). It was observed that changes in temperature of 26 °C can lead to an increase in the measured dielectric permittivity of up to 24% with no changes in volumetric water content of the soil. In addition to defining a soil-specific calibration equation to relate volumetric water content and dielectric permittivity under ambient temperature conditions, a correction equation was proposed for temperature effects. The capacitance sensor's response to changing temperatures was observed to be sensitive to both the initial volumetric water content and the initial density of the soil, and parameters were defined for both of these terms in the correction equation.

KEYWORDS: Capacitance sensors, calibration, temperature effects, thermally-drive water flow

26 INTRODUCTION

27 Thermally-active geotechnical systems are created by incorporating geothermal heat
28 exchangers into civil engineering infrastructure such as building foundations (Laloui et al. 2006;
29 Brandl 2006; Murphy et al. 2014), embankments (Coccia and McCartney 2013; Coccia et al.
30 2013), retaining walls (Stewart et al. 2014), or borehole thermal energy storage systems (Başer et
31 al. 2014). If the compacted soil backfill used in these systems is unsaturated, heating and cooling
32 of the soil may lead to thermally-driven water flow (Philip and DeVries 1957). This thermally-
33 driven water flow process may have significant effects on both the thermal properties (Smits et
34 al. 2013; Başer et al. 2014) and the mechanical response of unsaturated soils (Coccia and
35 McCartney 2013; Coccia et al. 2013; Stewart et al. 2014). Accordingly, it is important to have a
36 technique to infer transient changes in volumetric water content of unsaturated soils in physical
37 models and field applications of thermally-active geotechnical systems. An accurate assessment
38 of thermally-induced changes in volumetric water content of unsaturated soils is needed to
39 calibrate and validate numerical simulations of heat and water flow processes. Calibration and
40 validation of these numerical simulations is particularly necessary due to coupling between
41 changes in temperature and volumetric water content, the potential for phase change between
42 liquid water and water vapor, and the potential for soil deformations (Pruess 1991; Thomas and
43 King 1994; Thomas and Sansom 1995; Thomas and He 1997).

44 Dielectric sensors have been used for many years to infer the volumetric water content of
45 unsaturated soils at a point by inferring the bulk dielectric permittivity of the soil, which is
46 closely related with the amount of water in the soil on a volumetric basis (Topp et al. 1980).
47 Although dielectric sensors come in many forms (time domain reflectometry, frequency domain
48 reflectometry, water content reflectometers, capacitance sensors, etc.), capacitance sensors are

cost-effective, have low power requirements, and have a simple data acquisition system. Despite these advantages, it is well known that changes in temperature may affect the response of capacitance sensors (Baumhardt et al. 2000; Czarnomski et al. 2005; Evett et al. 2006; Bogena et al. 2007; Cobos and Campbell 2007; Seyfried and Grant 2007; Kizito et al. 2008; Assouline et al. 2010; Rosenbaum et al. 2011). Although it is possible to correct for these temperature effects (Evett et al. 2006; Cobos and Campbell 2007; Seyfried and Grant 2007; Rosenbaum et al. 2011), most of the previous studies on thermal effects on capacitance sensors have focused on soils in agricultural or soil science applications where the compaction conditions were not reported (i.e., the combination of initial gravimetric water content and dry density), often with high salinity levels. Although thermal effects on capacitance sensors have been characterized in some studies by heating of the sensors while in different liquids (Bogena et al. 2007; Rosenbaum et al. 2011), it is possible that the soil structure associated with a given initial compaction water content and dry density may affect the thermal effects. Further, new sensors are regularly being introduced that may have a differing response than observed in the studies mentioned above, emphasizing the need for a general methodology to consider their temperature effects for a given soil.

Accordingly, this study focuses on the development of a temperature correction equation for capacitance sensors in compacted soils. Specifically, the objectives of this study are to better understand the influence of temperature on the 5TM capacitance sensor from Decagon Devices of Pullman, WA when used in a low-plasticity, compacted silt, and to develop a practical methodology that can be used to define thermal correction equations to consider the role of initial compaction water content and dry density on the response of this specific sensor during temperature changes. Throughout this paper, this sensor is referred to as a capacitance sensor even though it is capable of measuring both the temperature and dielectric permittivity. The

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methodology involves isolating the effects of temperature on the response of a capacitance sensor in a soil layer having a given set of initial compaction conditions by preventing thermally-induced water flow. The temperature correction equation can then be used to analyze data from the capacitance sensors in applications where thermally induced water flow occurs.

BACKGROUND

Volumetric Water Content

Unsaturated soils are generally a three phase medium consisting of air, water and soil particles. The soil matrix is comprised of mineral particles that play an important role in both soil behavior and classification, and in geotechnical applications organics are typically removed. Water exists within the matrix in one of three phases: water vapor, free water (pore water) and bound water (attracted to the surface of soil particles and exchangeable cations). The amount of water in soils can be described using different terms that are derived from the phase diagram, using the gravimetric water content (w_{grav}), the volumetric water content (θ_w or VWC), or the degree of saturation (S_r). Although the gravimetric water content is typically used in compaction specifications, the volumetric water content is typically used in water flow analyses in unsaturated soils using Richards' equation (McCartney 2007). Further, because the dielectric permittivity of soils depends on the amount of water in the soil on a volumetric basis, the volumetric water content is used in dielectric sensor calibration equations (Topp et al. 1980). The maximum value of the volumetric water content occurs when the soil is saturated, in which case it is equal to the porosity (n). The porosity is equal to the ratio of the volume of voids to the total volume.

Unfortunately, it is not straightforward to directly determine the volumetric water content in the laboratory. The phase diagram can be used to calculate the volumetric water content from other variables, as follows:

$$VWC = \theta_w = \frac{\rho_d}{\rho_w} w_{grav} = \frac{\rho_t}{\rho_w (1 + w_{grav})} w_{grav} \quad (1)$$

where ρ_t is the total density of the soil, ρ_d is the dry density of the soil, and ρ_w is the density of water. While the gravimetric water content is can be determined using oven drying (ASTM D2216), determination of the volumetric water content requires consideration of the total density of the soil (the ratio of the total mass to the total volume of a soil specimen). Estimation of the total density may be difficult for some soils. Although gravimetric water content measurements are reliable, samples need to be extracted from a soil layer and the measurement requires at least 24 hours to make, which may not be convenient in characterizing water flow processes. Nonetheless, gravimetric water content measurements are useful in calibrating non-destructive methods of water content determination such as dielectric sensors.

Electromagnetic Properties of Soils

The electromagnetic properties of soils of primary interest when inferring the volumetric water content are the electrical conductivity and dielectric permittivity. The electrical conductivity (σ) is a measure of a material's ability to conduct an electrical current. Soil particles typically exhibit relatively low electrical conductivity, so the electrical conductivity of a soil is predominately affected by its water content. In clays, the cations in the bound water have a significant effect on the electrical conductivity, and they may remain electrically conductive over a wide range of degrees of saturation. The dielectric permittivity (ϵ) is a measure of the flux density generated by an electric field in a given material. It is commonly expressed as the

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relative permittivity, which is the ratio of the absolute permittivity to the permittivity of a vacuum and is dimensionless. While the permittivity of a vacuum is a constant ($\epsilon_0 = 8.85 \times 10^{-12}$ F/m), the absolute permittivity of most materials is dependent on the frequency of the electromagnetic wave applied to the sensor and is therefore a complex number comprised of “real” and “imaginary” parts. The “real” part (ϵ') is related to the permittivity of the soil materials themselves (air, water and soil minerals). The “imaginary” part (ϵ'') is related to the dielectric losses, or the energy that is lost during application of an electromagnetic pulse, and the electrical conductivity of the soil. The equation for the complex dielectric permittivity that characterizes both the polarization effect and energy losses is given below (Jones et al. 2005):

$$\epsilon = \epsilon' - j \left(\epsilon'' + \frac{\sigma_{dc}}{2\pi f \epsilon_0} \right) \tag{2}$$

where ϵ' and ϵ'' are the real and imaginary components of the dielectric permittivity, σ_{dc} is the electrical conductivity in a direct current system, f is the frequency of the electromagnetic wave and ϵ_0 is the dielectric permittivity of vacuum. The role of the imaginary part of Equation (2) has been observed to decrease with increasing frequency (Robinson et al. 2005).

Changes in temperature primarily affect the values of σ and ϵ'' (Seyfried and Grant 2007). Or and Wraith (1999) found that the electrical conductivity could increase by 2%/°C. Seyfried and Grant (2007) note that temperature causes an increase in ϵ'' . When a dielectric sensor uses a low frequency to measure the dielectric permittivity, the effect of ϵ'' on the value of ϵ may be greater. This is why capacitance probes that operate at frequencies of approximately 70 MHz may show greater temperature effects than time domain reflectometry (TDR), which operates at much higher frequencies of 600 to 1000 MHz. Seyfried and Grant (2007) found that the electrical components within capacitance sensors, which are at the location of the probe, may be

affected by temperature and will primarily change the value of ϵ' . However, this change in ϵ' was found to be negligible compared to the change in ϵ'' with temperature.

The bulk dielectric permittivity of soils is considered a weighted average of the individual permittivity values of soil constituents (particles, water, and air) depending on the volumetric fraction of each constituent. The permittivity is primarily influenced by volumetric water content as water has a relatively high permittivity ($\epsilon = 80$ at 20°C) as compared to that of air ($\epsilon = 1$) and soil minerals ($\epsilon = 5$ to 12 , depending on mineralogy) (Topp et al. 1980; Jones et al. 2005). Any dielectric technique requires a correlation to define the relationship between the dielectric permittivity and volumetric water content. A commonly used calibration equation is that of Topp et al. (1980), given as follows:

$$\text{VWC} = 4.3 \times 10^{-6} \times \epsilon^3 - 5.5 \times 10^{-4} \times \epsilon^2 + 2.92 \times 10^{-2} \times \epsilon - 5.3 \times 10^{-2} \quad (2)$$

where VWC has units of m^3/m^3 , and the dielectric permittivity is dimensionless. This equation was empirically developed using TDR technology for various mineral soils, but it is also used in the calibration of capacitance sensors (Decagon Devices 2014). However, Decagon Devices (2014) recommend the development of soil-specific calibrations to reduce error.

As temperature increases, the dielectric permittivity of distilled water is expected to decrease (Malmberg and Maryott 1956). As the dielectric permittivity values of most soil minerals and air do not appreciably change with temperature (Assouline et al. 2010), it would logically follow that the soil's bulk dielectric permittivity would also decrease with an increase in temperature. When using TDR, the values of ϵ'' and σ are not as relevant due to the high excitation frequency. Topp et al. (1980) observed a negligible effect of temperature on the dielectric permittivity measured using TDR, while Or and Wraith (1999) and Wraith and Or (1999) observed that the dielectric permittivity of soils may increase or decrease depending on an interplay between the

change in dielectric permittivity of the water and the release of bound water from the clay fraction in the soils with temperature. When using capacitance sensors, the role of ϵ'' and σ become more important, and most researchers have observed an increase in water content with temperature (Evelt et al. 2006; Seyfried and Grant 2007; Bogena et al. 2007; Kizito et al. 2008; Cobos and Campbell 2007), while Czarnomski et al. (2005) observed a decrease in water content with temperature.

Pepin et al. (1995) proposed a simple temperature correction in the following form for TDR sensors in different soil types:

$$VWC_{\text{corrected}} = VWC_{\text{measured}} - c_1 \times \Delta T \quad (3)$$

where c_1 is a constant equal to $0.00175 \text{ m}^3/\text{m}^3$ per $^\circ\text{C}$, VWC is the volumetric water content in m^3/m^3 and ΔT is the change in temperature in $^\circ\text{C}$. Seyfried and Grant (2007) studied the effect of temperature on the different components in Equation (2) using a HydraProbe capacitance sensor, and also observed that ϵ'' and σ generally vary linearly with temperature. Cobos and Campbell (2007) used a multi-variable regression to define a calibration equation in the following form:

$$VWC_{\text{corrected}} = C_1 VWC_{\text{measured}} + C_2 T_{\text{soil}} + C_3 \quad (4)$$

where C_1 , C_2 , and C_3 are constants and T_{soil} is the soil temperature in $^\circ\text{C}$. Other studies have found that nonlinear corrections may be necessary. Bogena et al. (2007) used a third order polynomial to correct for temperature effects in EC-5 capacitance sensors from Decagon Devices that were observed when heating the sensor in different types of fluids. Rosenbaum et al. (2011) also heated sensors in different types of fluids and developed a different third order polynomial equation to correct for temperature effects in EC-5 and 5TE sensors from Decagon Devices. They considered the response of multiple sensors on the development of their correction equation. Evelt et al. (2006) evaluated the response of different capacitance sensors from

different manufacturers, and used a nonlinear form of Equation 3 where the actual temperature of the probe was raised to a non-integer power that depended on soil type. Other studies have focused on techniques to extract the impact of diurnal temperature changes on the response of dielectric sensors noted by Baumhardt et al. (2000) using multiple regression analyses or averaging (Assouline et al. 2010; Cobos and Campbell 2007). Rosenbaum et al. (2007) found that the greatest effect of temperature on the response of the EC-5 and 5TE sensors occurred for high-permittivity media (35-42) for temperatures up to 40 °C.

In addition to the water content and temperature, measurements from dielectric sensors in general have been found to be sensitive to salinity, dry density, mineral/clay content, and soil fabric (Topp et al. 1980; Nadler et al. 1999; Baumhardt et al. 2000). Baumhardt et al. (2000) observed that an increase in the pore water salinity will lead to an increase in the apparent volumetric water content measured by a capacitance sensor, likely due to the greater electrical conductivity with greater salinity. However, Nadler et al. (1999) observed that the coupled effects of density and clay fraction may lead to more inconsistent effects of pore water salinity. This indicates that the effects of density may play a similar role in temperature effects on capacitance sensors. Although Topp's equation provides a good estimate of the volumetric water content for low-plasticity soils under loose conditions, it may not consider the role of compaction conditions or temperature effects. Pozzato et al. (2008) presented a modification to Topp's equation for TDR probes to consider the role of dry density for silt.

MATERIALS

Although it is expected that the soil type and mineralogy may play an important role in the effects of temperature on the sensor response, only a single soil was investigated in this study, albeit under a range of compaction conditions that may be encountered in various geotechnical

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3 201 applications. Bonny silt was used in this study to demonstrate the methodology for assessing the
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5 202 impact of temperature on the response of dielectric sensors in unsaturated soils as it is currently
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8 203 being used in several experimental evaluations of thermally-active geotechnical systems (Coccia
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10 204 and McCartney 2013; Coccia et al. 2013; Başer and McCartney 2015). Further, it was also used
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12 205 because its low-plasticity indicates that it has a low amount of active clay minerals, which may
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14 206 be affected by physico-chemical processes that change the characteristics of bound water with
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16 207 temperature (Wraith and Or 1999). Relevant geotechnical properties of Bonny silt are listed in
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22 209 **EXPERIMENTAL METHODS**

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24 210 **Capacitance Sensor**

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27 211 The capacitance sensor evaluated in this study is 5TM sensor manufactured by Decagon
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29 212 Devices of Pullman, WA (Decagon 2014). The overall sensor has a length of 100 mm, a width of
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31 213 32 mm and a thickness of 7 mm, with an active probe length of 52 mm. The capacitance sensor
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33 214 measures the apparent dielectric permittivity of soil by imposing a 70 MHz oscillating
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35 215 electromagnetic wave through its three prongs to charge a capacitor circuit formed by the sensor
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37 216 and the surrounding soil. The magnitude of the stored charge is a function of the electromagnetic
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39 217 properties of soils, which are dependent on the volumetric water content of the soil. The
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41 218 sampling volume of the capacitance sensor is limited to material a distance of approximately 20
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43 219 mm from the prongs, so it provides a point measurement of water content. This small sampling
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45 220 volume may increase the sensor's sensitivity to local heterogeneities in soils such as large
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47 221 particles or voids (Baumhardt et al. 2000). The accuracy of the sensor is $\pm 1 \text{ } \epsilon$ for volumetric
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49 222 water content values ranging from 0.01 to 0.40 m^3/m^3 and $\pm 15\%$ for volumetric water content
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51 223 values exceeding 0.40 m^3/m^3 (Decagon Devices 2014). The soil temperature is monitored via a
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thermistor mounted on the base. Decagon Devices (2014) recommends using the sensor at temperatures less than 60 °C, but they may function at higher temperatures with soil-specific calibration. The sensor is connected to an EM50 data logger manufactured by Decagon Devices and data is collected continuously at 1 minute intervals using the ECH20 Utility Software.

Experimental Setup

The experiments were performed on capacitance sensors that had been placed into soil while it is being compacted into a 152 mm-diameter modified Proctor mold. A cross-section schematic of the mold is shown in Figure 1, which highlights the dimensions, the location of the embedded capacitance sensor and the zone of influence of the capacitance sensor. The base plate and extension collar are constructed of steel and conform to specifications in ASTM D698. The mold itself is a 178 mm-tall section of PVC pipe, identical in inside dimensions of a modified Proctor mold. The reason for using PVC is to avoid any electrical interference between the mold and the dielectric sensor. A 17 mm-diameter hole was drilled into the wall of the mold to allow the cable for the dielectric sensor to exit, which is plugged using a greased rubber stopper having a hole the size of the sensor cable. One of the objectives of this experiment was to minimize any loss of water from the compacted soil layer during heating. The sides of the mold are assumed to be impermeable. Water movement from the top of the specimen was restricted using four layers of low-density polyethylene sheeting (plastic wrap) stretched across the top of the soil layer and sandwiched between the top of the mold and the collar as shown in Figure 1. Further, water movement from the bottom of the mold was restricted using four layers of polyethylene sheeting placed on the bottom of the container and held in place against the side of the mold using an O-ring as shown in Figure 1. Even though the system is closed, it may be possible for water vapor to redistribute within the soil layer due to buoyancy. However, this process will take time to

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3 247 occur, so one of the goals of this study was to evaluate the impact of the duration of heating on
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5 248 the results so that an appreciable temperature change could be applied while still not resulting in
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8 249 a significant change in water content. Further, the impact of differential thermal expansion of the
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10 250 water, air, and solids on the volumetric water content in the soil is assumed to be negligible for
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12 251 the range of temperatures evaluated. A preliminary calculation considering the volumetric
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14 252 thermal expansion of each phase indicates that a change in temperature of 30 °C for initial
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16 253 volumetric water contents of 0.1 or 0.2 m³/m³ will only lead to an increase in volumetric water
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18 254 content of 2.8 or 1.2%. This is much smaller than the temperature effects on the sensor response
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20 255 that will be presented later in the paper.
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24 256 **Experimental Procedures**

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27 257 The Bonny silt was prepared in large batches having different gravimetric water contents so
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29 258 that multiple specimens could be tested under similar conditions. The soil was moisture-
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31 259 conditioned to a target gravimetric water content by misting water with a pressurized spray bottle
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33 260 while hand mixing. After adding a calculated amount of water to oven-dried soil, the moist soil
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35 261 was sealed in a plastic bucket for a minimum of 24 hours for equilibration. Prior to each test,
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37 262 samples were obtained to determine the actual water content of each batch using oven-drying.
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39 263 For each test, soil was statically compacted into the mold in six lifts using a mechanical press,
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41 264 with greater stresses applied with the press to reach higher densities. The sensor was placed in
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43 265 between the third and fourth lifts in the center of the mold. The soil around the sensor was first
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45 266 compressed carefully by hand before using the press to complete the compaction of this lift. This
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47 267 approach was found to minimize the potential for bending of the dielectric sensor during
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49 268 compaction. The same sensor was used for all of the tests in this study to avoid the possibility of
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51 269 sensor variability effects, and the sensor was observed to be undamaged after each test both
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visually and in terms of the measured dielectric permittivity of air at room temperature. Bonny silt does not have large particles, which also helped avoid abrasion of the sensor during repeated compaction. Care was taken during removal of the sensor from the soil layer to avoid damage.

The tests performed in this study involved heating a compacted specimen of Bonny silt containing the capacitance sensor in a forced-air oven having a temperature of 60 °C for a given duration of time. The oven had a port through which the sensor cable could be passed so that the datalogger would remain at room temperature outside the oven. In order to identify the sole effect of temperature on the sensor response in Bonny Silt, the VWC had to be kept constant during heating. The silt specimen within the sealed mold was placed into the oven, during which transient measurements of temperature and apparent dielectric permittivity were made using the capacitance sensor. Before and after heating, the distribution in gravimetric water content was measured using oven drying to observe any potential water migration effects. In addition to the temperature response of the sensors during heating, the correlation between the initial volumetric water content calculated using Equation 1 and the dielectric permittivity measured by the sensor before heating allowed the development of a soil-specific calibration equation for Bonny silt at room temperature.

Three series of tests were performed to characterize the impact of temperature on the capacitance sensor. First, a series of heating tests were performed on Bonny silt specimens compacted to the nearly same conditions to evaluate the impact of the duration of heating (Testing Series A), to make sure there is no significant water flow within the specimens due to the change in temperature. In Testing Series A, each heating test was repeated as a check on the sensor response. Next, a series of heating tests were performed on Bonny silt specimens having the same dry density but different initial volumetric water content values (Testing Series B).

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3 293 These tests were performed to isolate the impact of the quantity of water on the response of the
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5 294 capacitance sensor during heating, but also may reflect changes in the soil structure with
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8 295 compaction water content (Mitchell et al. 1965). The term “initial is used even though the
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10 296 volumetric water content is not expected to change significantly during heating because the
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12 297 volumetric water content is known with certainty after compaction. Testing Series B includes
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14 298 baseline tests on a sensor in oven-dry soil as well as a sensor in air for reference. Finally, a series
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16 299 of heating tests were performed on Bonny silt specimens having different initial dry density
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18 300 values but the same initial gravimetric water content (Testing Series C). Again, the term “initial”
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20 301 is used even though it is not expected that the dry density will change significantly during
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22 302 heating because it is known with certainty after compaction. A summary of all of the compaction
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24 303 data points corresponding to the calibration tests is shown in Figure 2, along with the modified
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26 304 and standard Proctor compaction curves for Bonny silt. For all of the time series, data collection
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28 305 started (i.e., a time of zero) when the experimental mold was placed in the oven and was stopped
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30 306 when it was removed from the oven.
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36 307 **RESULTS**

38 308 **Testing Series A: Evaluation of the Impact of Heating Duration**

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40 309 The purpose of this testing series was to evaluate whether heating of identical soil specimens
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42 310 for different amounts of time would lead to a change in the distribution of volumetric water
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44 311 content within the specimens. In these tests, the initial compaction conditions (dry density and
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46 312 volumetric water content) were kept within 3% of each other, and a specimens were heated for 1,
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48 313 3, 5, and 7 hours. Each test was repeated. The time series for the change in temperature and
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50 314 change in dielectric permittivity at the location of the sensor in these tests are shown in
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53 315 Figure 3(a). The results show that as the temperature increases, the dielectric permittivity
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measured using the sensor also increases. As noted in the background section, the measured value of dielectric permittivity does not directly reflect the actual changes in the dielectric permittivity of the soil with temperature (Seyfried and Grant 2007). Regarding the impact of heating duration, the change in temperature curves and the change in measured dielectric permittivity curves all follow the same trends with time regardless of the duration. The heating duration did not lead to significant changes in the shapes of the time series curves from 1 to 7 hours, except for the fact that higher temperatures were observed in the longer tests.

After heating, the specimens in this testing series were immediately dissected to destructively measure the gravimetric water content at the center and edge of the container at different depths. The purpose of these measurements was not only to provide data points as part of developing a soil-specific calibration for the capacitance sensors, but also to detect whether any water flow occurred in the soils. The destructive samples were obtained as quickly as possible to prevent the soil from decreasing in temperature and possibly counteracting any thermally-induced water flow that may have occurred in the oven. In all cases, there was no significant change in gravimetric water content with depth or radial location from the beginning to the end of the tests, as shown in Figure 4. This confirms that there was no change in water content in the tests, indicating that the effect of temperature on the capacitance sensors was effectively isolated. This observation indicates that the duration of testing up to 7 hours did not lead to water redistribution in the specimens, so in order to obtain a change in temperature of approximately 20 °C, the specimens in Testing Series B and C were heated for three hours. However, it should be noted that it is possible that heating of the specimens for a longer time than evaluated in this testing series may have caused water vapor redistribution in the specimen due to buoyancy. This is

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338 something that should be considered carefully when applying this technique to sandy soils that
339 may have a higher gas permeability than compacted silt.

340 **Testing Series B: Evaluation of the Impact of Initial Water Content**

341 The purpose of this series of tests was to assess the impact of the amount of water in the soil
342 during compaction and the associated changes in soil structure on the temperature effects on the
343 capacitance sensor response. The time series of changes in temperature for each of the tests are
344 shown in Figure 5(a). In all cases, the temperature rise curves were relatively consistent except in
345 a special test where the sensor was placed into the oven to measure its response in air. When the
346 sensor was heated in air, the temperature response was significantly faster than when it was in
347 soil. The dielectric permittivity of the soil versus time is shown in Figure 5(b). The absolute
348 values of dielectric permittivity are shown in this figure to highlight the impact of the initial
349 volumetric water content on the sensor response. Although the greatest degree of saturation
350 evaluated in this study was only 0.63, it captures the range of degrees of saturation most
351 important for thermally active geotechnical systems (Coccia and McCartney 2013). For the
352 sensor in air and in dry soil, there were relatively negligible effects of temperature on the sensor,
353 consistent with the observations of Seyfried and Grant (2007). For the unsaturated soils, the
354 initial volumetric water content was observed to have an impact on the slope of the temperature
355 rise curves. This is better evaluated through the temperature versus dielectric permittivity plot
356 shown in Figure 5(c). Although there is some variability associated with the repeated tests, the
357 changes in the slope show that the changes in permittivity are more sensitive to temperature for
358 soils with higher water content.

359 It is interesting to note that when the capacitance sensor was in air, there was a negligible
360 effect of temperature on the readings. These results corroborate Decagon’s statement that the

sensor itself is “perfectly insensitive” to temperature effects (Cobos and Campbell 2007). This observation also confirms the observations by Rosenbaum et al. (2007), who found that the temperature effect depends on the dielectric properties of the media in which the sensor is located. The sensor was also tested in water, but the maximum reading of the sensor was obtained throughout the test. The lack of temperature effect when the sensor is in water may have been due to its programming, which is meant to provide a maximum value of dielectric permittivity when the sensor is in water.

Testing Series C: Evaluation of the Impact of Initial Dry Density

The purpose of this series of tests was to assess the impact of initial dry density on the temperature effects on the capacitance sensor response. Specimens were prepared at dry densities of 1300, 1400, and 1600 kg/m³, at the same gravimetric water content of 15.7%. Because the gravimetric water content was the same, the initial volumetric water content of the soil layers calculated using Equation (1) increased with initial dry density. Nonetheless, the results from the tests evaluating the impact of the initial volumetric water content in Figure 5 can be used to isolate the impact of dry density on the temperature effect when analyzing the results. The time series of changes in temperature for each of the tests are shown in Figure 6(a). Again, these curves indicate that the similar boundary conditions were applied to each soil specimen. The corresponding time series of dielectric permittivity are shown in Figure 6(b). Although there is some variability in the initial dielectric permittivity for each test, there are three distinct groupings that are associated with the initial dry density and volumetric water content values for each group of specimens. The slopes of the temperature versus dielectric conductivity curves in Figure 6(c) indicates that the increase in dielectric permittivity readings were more sensitive to increases in temperature for soils with higher dry density.

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ANALYSIS

The data from the different test series were first analyzed to define a calibration curve for the capacitance sensors in Bonny silt at ambient temperature conditions (23 °C), and also to investigate the role of initial dry density on the calibration. A soil-specific calibration was developed by plotting the volumetric water content values calculated from the measured values of gravimetric water content and dry density against the initial readings of the capacitance sensor before heating, as shown in Figure 7. The data in this figure is separated by the initial dry density values of 1300, 1400, and 1600 kg/m³. Although there is some scatter in the data, a clear linear trend is observed. No distinguishable trend with density was observed, which contradicts the findings of Pozzato et al. (2008) who studied the impact of temperature on TDR calibrations in silt. For reference, the calibration curve of Topp et al. (1980) is shown in this figure. It is clear that the calibration curve overestimates the volumetric water content for specimens dryer than a volumetric water content of 0.25 m³/m³ (degree of saturation of 0.55 for a dry density of 1400 kg/m³). Although there is only one data point at 0.3 m³/m³, the nonlinear trend in the calibration of Topp et al. (1980) may underestimate the volumetric water content at higher water contents. Accordingly, a linear calibration curve for Bonny silt was proposed, as follows:

$$\theta = A\varepsilon + B \tag{5}$$

where A = 0.026 and B = 0.094. Further testing at additional dry densities and for additional water contents at the same density may reveal an effect of dry density on the data. However, the range of 1300-1600 kg/m³ encompasses the range of dry densities expected for Bonny silt in most geotechnical applications.

As the data shown in Figures 5(c) and 6(c) indicates that the change in dielectric permittivity measured by the capacitance sensors is relatively linear with temperature, a linear temperature

correction equation having a similar form to those of Pepin et al. (1995) and Cobos and Campbell (2007) was employed in this study. To account for the effects of the initial volumetric water content and initial dry density, the following temperature correction equation is proposed:

$$\epsilon_{\text{actual}} = \epsilon_{\text{measured}} - \Delta T \times (m_{\text{VWC}} + m_d) \quad (6)$$

where ϵ_{actual} is the actual dielectric permittivity of the soil without the temperature effect on the sensor, $\epsilon_{\text{measured}}$ is the dielectric permittivity measured using the capacitance sensor, ΔT is the change in temperature, and m_{VWC} and m_d are temperature correction slopes for initial volumetric water content and initial dry density. It is expected that both of these temperature correction slopes may not be constant values, but may change with either initial volumetric water content or initial dry density, respectively.

The values of m_{VWC} were first defined by plotting the slope of the temperature versus dielectric permittivity curves in Figure 5(c) versus the initial volumetric water content, as shown in Figure 8(a). The data follows a nonlinearly increasing trend, from the volumetric water content of 0.00 which corresponds to oven-dry soil to a value of 0.30 which corresponds to a degree of saturation of 0.63. A hyperbolic equation was fitted to the data, with the equation and parameters presented in Figure 8(a). It is possible that greater changes in the slope of the curve could be expected for larger degrees of saturation, so the nonlinear trend in this figure is only applicable for the range of water contents tested. Nonetheless, the extents of the calibration equation are still relevant to the evaluation of capacitance sensors in thermally-active geotechnical systems, where operation of geothermal heat exchangers will cause thermal drying of the soil leading to degrees of saturation less than 0.6 (Coccia and McCartney 2013)..

Next, the value of m_d was defined by first estimating the volumetric water content temperature correction for the different tests in Figure 6, as the specimens not only have different

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initial dry densities but also different initial volumetric water contents. Then the slopes of the temperature versus dielectric permittivity curves in Figure 6(c) were determined. The difference between the actual slope and the slope expected from the initial volumetric water content temperature correction was calculated, which is equal to m_d . The values of m_d are plotted as a function of dry density in Figure 8(b). A clear linear trend was observed in the data. The parameters for the linear relationship for m_d are shown in Figure 8(b).

The temperature correction equation in Equation 6 along with the functional forms for the temperature correction slopes shown in Figures 8(a) and 8(b) was evaluated by applying it to different data sets at different initial dry density and volumetric water content values. The temperature versus dielectric permittivity curves measured using the capacitance sensor are shown in Figure 9, along with those corrected using Equation 6. The trend in permittivity corrected for temperature for different densities is nearly vertical, which indicates that the temperature effect has been sufficiently removed. A vertical trend in corrected dielectric permittivity is expected in these experiments because the soil layers in the compaction mold did not experience a change in water content during the heating process. Comparison of the corrected and uncorrected curves indicates that if the temperature correction is not considered, the capacitance sensors will provide a dielectric permittivity that is 24% greater than in reality for a change in temperature of 26 °C (i.e., a 0.9% increase in dielectric permittivity per 1 °C increase in temperature). This indicates that Equation 6 provides an adequate temperature correction for the capacitance sensors in Bonny silt. The temperature correction in Equation 6 has been applied to physical modeling data collected from physical modeling tests on thermally active geotechnical systems presented by Coccia et al. (2013) and Başer et al. (2014) that do experience changes in volumetric water content due to thermally-driven water flow, and the

correction equation appears to provide logical trends in the data. The VWC values in these studies were originally interpreted using a simple temperature correction equation similar to that of Pepin et al. (1995). It should be mentioned that it is possible that the form of Equation 6 and those for the parameters m_{VWC} and m_d may be different for other soil types.

CONCLUSIONS

This study involved an investigation into temperature effects on the response of capacitance sensors used to infer the volumetric water content of unsaturated soils. A testing method was developed to prevent thermally induced water flow within a compacted silt specimen so that the temperature effects on the sensor could be isolated and the role of initial compaction conditions could be characterized. Gravimetric water content measurements obtained before and after a series of heating tests having different durations confirm that negligible water redistribution occurred during heating. A soil-specific calibration equation between volumetric water content and dielectric permittivity at room temperature indicates that Topp's equation may overestimate the water content of this compacted soil, although this may not be general for other soils. The dry density of the soil in the range of 1300 to 1600 kg/m³ (porosities of 0.39 to 0.51) was not observed to have an effect on the calibration equation. Heating experiments on compacted specimens of Bonny silt indicate capacitance sensor temperature effects are impacted by initial water content and dry density. An empirical temperature correction equation was defined using the experimental data that accounted for the separate roles of initial volumetric water content and dry density, and was found to adequately correct the dielectric permittivity from sensors in soils with different compaction conditions. These observations indicate that the volumetric amount of water and the soil structure associated with compaction at different water contents can have complex effects on the measured dielectric permittivity of soils using capacitance sensors.

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474 However, the temperature correction equation indicates that these effects can be accounted for so
475 that capacitance sensors can be used with reliability in the evaluation of thermally-active
476 geotechnical systems.

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LIST OF TABLE AND FIGURE CAPTIONS

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FIG. 8: Temperature correction factors for: (a) Initial volumetric water content mVWC; (b) Initial dry density m_d

FIG. 9: Example of the application of the temperature correction equation to Bonny silt specimens compacted at different initial conditions

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603 TABLE 1: Relevant geotechnical properties of Bonny silt
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Parameter	Value
D ₁₀	< 0.0013 mm
D ₃₀	0.022 mm
D ₅₀	0.039 mm
% Fines (passing the No. 200 sieve)	83.9%
% Clay size	14.0%
% Silt Size	69.9%
% Sand Size	16.1%
Liquid Limit, LL	25
Plastic Limit, PL	21
Plasticity Index, PI	4
Activity	0.29
Thermal Conductivity	1.0-1.2 W/mK

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128x185mm (300 x 300 DPI)

120x85mm (300 x 300 DPI)

195x428mm (300 x 300 DPI)

194x425mm (300 x 300 DPI)

64x46mm (300 x 300 DPI)

129x189mm (300 x 300 DPI)

63x45mm (600 x 600 DPI)