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Installation, Calibration and Application of Dielectric Sensors in Laboratory Studies of Compacted Unsaturated Granular Materials

ABSTRACT: The use of small-scale, instrumented laboratory columns for the study of moisture content and electrical conductivity response of soils has historically been restricted primarily to fine-grained materials due to the size of available instrumentation and probe installation difficulties. This study explores the suitability of capacitance-type dielectric sensors for studies of coarse-grained granular materials by assessing installation and calibration requirements. A number of different methods for installing a Hydra Probe dielectric sensor in a gravelly granular material were assessed and their repeatability compared with sensor installation in a fine-grained material. Typical installation methods were found to result in highly inconsistent installation in the compacted granular material, with poor repeatability. An alternative installation method is presented for gravelly granular materials which resulted in an acceptable level of repeatability for both components of sensor measurement, consistent with that achieved by direct sensor insertion in fine-grained materials. It was also found necessary to develop a material-specific volumetric moisture content calibration relationship for the granular material as the manufacturer-supplied relationships were found to have very low accuracy. This material-specific calibration was found to improve the accuracy of the dielectric sensor to $\pm 0.03 \text{ m}^3/\text{m}^3$.

To demonstrate the potential of dielectric sensors for use in the study of compacted granular materials, two laboratory experiments are described; one monitoring changes in moisture content

with time and the other changes in electrical conductivity. General recommendations for use of dielectric sensors with granular materials are also presented.

KEYWORDS: granular materials, dielectric sensor, capacitance probe, unsaturated soil column

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1. Introduction

The moisture content and/or electrical conductivity of granular materials under various applied or natural conditions are important parameters for studying a diverse range of problems, from performance of road pavements under traffic loads to contaminant transport in coarse-grained fills. Soil columns have been used widely over the last 100 years to evaluate water and solute transport models, monitor the fate and mobility of contaminants in soils and for infiltration and evaporation studies, particularly in the fields of hydrogeology, agriculture and soil science (Moore 1939; Klein et al. 1997; Butler et al. 1999; Sahoo et al. 2009). Unfortunately the use of soil columns for gravelly granular materials, such as those used in unbound granular road and airfield pavement construction, has been restricted by the availability of suitable instrumentation and its ability to be installed correctly and function reliably.

Opportunities for the non-destructive measurement of moisture content and electrical conductivity in soils are available through a variety of techniques that measure dielectric properties of soils. Most of these (capacitance, Time Domain Reflectometry (TDR), etc) employ embedded waveguides which comprise a “head” with an array of attached “prongs” or tines. The size and physical arrangement of such devices varies widely. TDR is generally regarded as the most accurate available non-destructive technique for the measurement of volumetric water content (Seyfried et al. 2005). However, TDR probes are generally expensive and often too large (15-30 cm) for small-scale laboratory studies. Size in particular is a significant impediment for horizontal probe installation in typical soil columns (Seyfried and Murdock 2004). An alternative to TDR probes are capacitance-type dielectric sensors. These include the Hydra Probe (Stevens Water Monitoring Systems, Portland, OR, USA), the ThetaProbe ML2x (Delta-T Devices, Cambridge, UK) and the 5TM / 5TE (Decagon Devices, Pullman, WA, USA). These sensors are generally small enough (5-10 cm) that they can be relatively easily installed horizontally in small diameter soil columns and, for the range of water content typically encountered under natural conditions, they are reported to have an acceptable level of accuracy.

Some of these sensors, such as the Hydra Probe and 5TE can also estimate electrical conductivity, which is particularly appealing for studies involving contaminant transport.

When installing any moisture content sensor it is critically important that disturbance of the soil surrounding the tines is minimised, that there is intimate contact between the soil and the tines, and that the probe head is flush with the soil surface as any voids or disturbance within the probe sensing area may affect the measurements (Stevens 2007; Fityus and Rajkai 2011). For installation in very dense or highly compacted media, an installation jig is sometimes used prior to instrument insertion. In this case, the tines of the installation jig are slightly smaller in diameter than the tines of the sensor thereby creating pilot holes for subsequent installation of the probe, and minimising stress and disturbance of the tine-soil interface. However, consistent installation with intimate contact is particularly difficult to achieve in gravelly soils such as pavement materials, where the tines are likely to intersect gravel-size particles. In fact, the manufacturers of many sensors recommend relocating the probe to an adjacent area if 'rocks' or gravel particles are encountered during installation (Stevens 2007). This, of course, is not practical if the intention is to take measurements in gravelly materials. The installation of sensors in engineered granular materials is made even more difficult under high levels of compaction (e.g. the density of a compacted granular road or airfield pavement material may exceed 2400 kg.m^{-3}). Achieving homogeneous installation of instrumentation in such materials, whilst important, is therefore very difficult.

Dielectric sensors are widely used in soil science and agricultural applications and have even been used to monitor subgrade moisture changes beneath road pavements (MacDonald and Baltzer 1997; Janoo et al. 2003). However, to the authors' knowledge, these sensors have not been used in gravelly granular materials due to installation difficulties, and no published information exists on whether this is even possible, and if so, the best way to install the sensors under such conditions and their calibration requirements.

This paper seeks to inform the geotechnical community of the potential research applications of dielectric sensors for laboratory studies of engineered granular materials by assessing installation and calibration requirements. A number of different methods for installing a particular dielectric sensor in a gravelly granular material are assessed and compared with sensor installation in a fine-grained material. A volumetric moisture content calibration relationship has also been developed for the granular material and compared with published relationships for fine-grained materials. Finally, the design and results of two relatively simple laboratory experiments are described to demonstrate how these sensors may be used for geotechnical research purposes.

2. Instrumentation: Dielectric Sensors

Capacitance-type dielectric sensors, similar to time domain reflectometer (TDR) and frequency domain reflectometer (FDR) probes, actually measure dielectric permittivity (dielectric constant) which is the electrical response of a reflected standing electromagnetic wave (Stevens 2007). However, capacitance-type dielectric sensors operate at a much lower frequency (typically 20 to 100 MHz) compared to common TDR probes which typically operate at 600 to 1,000 MHz (Seyfried and Murdock 2004; Robinson et al. 2005). They rely on an understanding of the relationship between this measurement and volumetric soil moisture content (i.e. they require a calibration). The dielectric permittivity of water (approximately 80 at 25°C) is significantly greater than that of soil particles (2-5), minerals (5-10) and air (1) (Robinson et al. 2003). Therefore, the dielectric permittivity of a soil is primarily a function of water content (Topp et al. 1980; Seyfried and Murdock 2004).

Topp et al. (1980) first proposed a relationship between the dielectric permittivity of soil and soil moisture content which was reported to fit most soils. However, subsequent studies have concluded that this relationship is not unique, but may be influenced by a number of factors including clay content, mineralogy, organic matter, porosity, soil density and soluble salt content (Bouksila et al. 2008). Thus, a number of calibration curves, often based on soil texture, are generally supplied by

the manufacturers of the various dielectric sensors. Despite this, a number of studies have shown that manufacturer-supplied calibration relationships may not effectively describe measured data, particularly at high moisture contents and for materials outside the standard parameter ranges covered by the manufacturers' calibration. For example, in a study of the moisture response of four different fine-grained soil road subgrades, Janoo et al. (2003) found errors in excess of 50% between predicted and measured values of volumetric moisture content and therefore concluded that it was necessary to develop material-specific calibration relationships to accurately measure the volumetric water content of the materials. Janoo et al. (2003) reported that the material-specific calibration curves developed significantly increased the accuracy of the volumetric water content determined using the Hydra Probe dielectric sensor when compared with the measured water content. For research applications, material-specific calibration curves are therefore generally recommended to accurately relate measured dielectric parameters to the volumetric water content (Bosch 2004; Seyfried and Murdock 2004; Merlin et al. 2007). However, calibration is only necessary for each material not each individual sensor as previous studies have reported that inter-sensor variability is extremely low. So, for example, if different materials were used for the base, subbase and subgrade layers (as is fairly common) then three calibration relationships would be required which could then be used for multiple sensors.

This study focuses on use of the Hydra Probe dielectric sensor (Stevens 2007) as it is widely used and has been subject to significant peer review study in relation to soil applications (Bosch 2004; Seyfried and Murdock 2004; Seyfried et al. 2005). However, this is not to suggest that this sensor is necessarily superior to others commercially available; any other dielectric sensor could have been chosen as the subject of this study. The Hydra Probe is an electrical capacitance probe which can be used to monitor soil moisture, salinity (electrical conductivity) and temperature. The sensor consists of a 42 mm diameter probe head, 25 mm diameter base plate and four tines (wave guides) 45 mm in length and 3 mm wide, one centred, surrounded by the other three, as shown in [Figure 1](#). The probe head contains the circuit boards, microprocessors, and other electrical components (Stevens 2007).

A 50 MHz signal is generated in the probe head which is transmitted via planar waveguides to the tines, forming a coaxial transmission line (Seyfried et al. 2005). The electromagnetic radio waves are transmitted and received by the centre tine (Stevens 2007). The measured electrical response is related to the capacitance of the circuit which in turn is directly related to the complex dielectric permittivity of the circuit (Seyfried and Murdock 2004). Temperature is determined from a calibrated thermistor incorporated within the probe head (Stevens 2007). Other dielectric sensors available commercially generally have different tine size and/or array of tines but work in much the same way.

Figure 1: Hydra Probe dielectric sensor (Stevens Water Monitoring Systems).

The Hydra Probe measures the complex dielectric permittivity (ϵ^*) of a medium and simultaneously outputs both the real (ϵ_r) and imaginary (ϵ_i) components of the electrical response. The capacitive (real) part is associated with energy storage and used to infer volumetric soil moisture (θ). The conductive (imaginary) component is associated with energy loss and relates to electrical conductivity (EC) (Robinson et al. 2003; Seyfried et al. 2005; Bouksila et al. 2008). Both components of the electrical response are dimensionless. Standard relationships to relate the two components of dielectric permittivity to θ and EC are typically supplied by manufacturers of dielectric sensors or built into the sensors themselves.

3. Materials

The gravelly granular material investigated in this study was a “20mm” crushed basalt roadbase meeting typical road authority specification requirements for unbound pavement materials used for rural highway construction in Australia. An alluvial sandy clay was also studied as a reference material to assess repeatability. This fine-grained material meets the typical requirements specified in Australia for general fill and for earthworks upper zone materials (Austroads 2009; RTA 2011). A summary of characteristics of the materials are shown in [Table 1](#), and the particle size distribution is shown in [Figure 2](#).

Table 1: Summary characteristics of granular and sandy clay materials.

Parameter	Granular Material	Sandy Clay Material
California Bearing Ratio (CBR) (4 day soak) (%)	> 50	11
Liquid limit (%)	24	20
Plastic limit (%)	19	13
Plasticity index (%)	5	7
Maximum dry density (kg.m^{-3})	2,100 ¹	1,750 ¹
Optimum moisture content (%)	10.4 ¹	13 ¹
Quantitative clay mineralogy of the <2 μm fraction (by mass)	43% Smectite 20% Kaolin 20% Chlorite 17% Mica	100% Kaolin

(1) Using standard compactive effort

Figure 2: Grading of granular and sandy clay materials.

4. Methods

4.1 Overview

This study was split into two components; (1) assessment of probe installation methods and calibration, and (2) application of the sensors in two typical granular material research experiments. These are detailed below.

To determine an accurate and reliable method of installing dielectric sensors in gravelly granular materials four installation methods were trialled using the Hydra Probe dielectric sensor. Installation repeatability in a compacted granular material was compared with installation in a fine-grained sandy clay material and the manufacturer's reported repeatability. Using the most repeatable method for probe installation, a large number of specimens were prepared over a range of moisture contents in order to generate relationships between the real component of dielectric permittivity, as recorded by the sensor, with volumetric moisture content for both the sandy clay and granular materials. Probe calibration for electrical conductivity was not explored in this study as the process is the same as was used for volumetric moisture content calibration. However, in the case of electrical

conductivity the material-specific calibration generated would be related to the specific combination of soil and contaminant(s) present.

To demonstrate the application of dielectric sensors to studies of engineered granular materials, two instrumented evaporative soil column experiments were also conducted. A typical road pavement structure was reproduced for experiment 1 in order to monitor volumetric moisture content changes under simulated, typical in situ conditions. However, as the rate of salt accumulation under these conditions was very low (as evidenced by the measured changes in electrical conductivity), a 2nd experiment incorporating a shorter soil column was conducted where the focus was on monitoring significant changes in electrical conductivity with time.

4.2 *Assessment of Probe Installation Methods and Calibration*

4.2.1 *Sample Preparation*

Installation and calibration of the sensor in the sandy clay and granular materials was assessed by compacting specimens in a PVC mould, 105 mm internal diameter and 154 mm deep. Four (4) layers of material were placed and compacted using 25 blows of the standard proctor compaction hammer resulting in compactive effort and energy equivalent to standard proctor compaction. A single sensor was installed horizontally through a 44 mm diameter hole the in PVC shell, located at mid-depth, within layers 2 and 3 ([Figure 3](#)). For each set of tests, specimens were prepared and compacted to the same specified target moisture content and density.

Figure 3: (a) Probe installation jig, (b) Sample preparation mould and (c) Sample preparation following probe installation.

4.2.2 Assessment of Installation Methods

Accurate dielectric sensor measurements require a repeatable installation method which does not compromise either the integrity of the soil structure or the sensor itself. The ease and repeatability of the following installation methods were investigated:

1. Direct insertion of the probe after compaction of the entire specimen (as recommended by the manufacturer for most media).
2. Insertion of the installation jig followed by insertion of the probe, after compaction of the entire specimen (as recommended by the manufacturer for highly compacted media).
3. Insertion of the installation jig, then probe, after compaction of the 3rd layer but prior to compaction of the final (4th) layer of material. Thus, the probe had approximately 10-20 mm of compacted material above the upper tine prior to placement of the final layer of material, and an opportunity for any disruption of the compacted material to be corrected during the compaction of the final layer.
4. A modified version of method 3 to eliminate the probe tines intersecting gravel particles greater in size than the spacing between the probe tines. This was achieved by replacing material within the probe installation zone with modified material (sub 9.5 mm) scalped from the host material. To do this 80% (by mass) of layer 2 placed, material was cleared from the probe area, then the < 9.5 mm material was placed in this area. Layer 2 was then compacted. For layer 3, some additional < 9.5 mm material was placed in the probe installation area, then the remaining 80% of layer 3 placed and the entire layer compacted. The probe was then installed prior to placement and compaction of the final layer. A maximum particle size of 9.5 mm was selected as the distance between the Hydra Probe's tines was approximately 10 mm.

The repeatability of readings obtained by the four different methods of probe installation was assessed for both the sandy clay and granular materials. To minimise variation between individual installations a single operator was employed for all testing and the duration between sample preparation and testing was minimised and kept consistent. For all tests the real (ϵ_r) and imaginary (ϵ_i) components of dielectric permittivity were recorded and an assessment of repeatability was made on the basis of both these measurements.

Testing for the sandy clay material was conducted on specimens compacted to an average dry density of $1,700 \text{ kg.m}^{-3}$ and 12.5% moisture content (by dry weight determined post-testing using the gravimetric method). Sixty (60) individual installations and subsequent measurements were undertaken comprising 20 installations using method 1, 20 using method 2 and 20 using method 3.

Granular specimens were prepared at an average dry density of $2,100 \text{ kg.m}^{-3}$ (100% relative density) and 10.4% moisture content by dry weight (100% of OMC), broadly equivalent to road authority compaction requirements for unbound granular road pavements in Australia. Eighty (80) individual installations and subsequent measurements were undertaken comprising 20 installations each using method 1, method 2, method 3 and method 4. The compaction process used for the granular material was found to produce uniform specimens with dry density values varying by less than $\pm 15 \text{ kg.m}^{-3}$ (standard deviation of 8 kg.m^{-3} or 0.3%) and volumetric water content values varying by less than $\pm 0.015 \text{ m}^3.\text{m}^{-3}$ (standard deviation of 0.007 kg.m^{-3} or 3.3%).

4.2.3 Volumetric Moisture Content Calibration

As discussed earlier, a number of authors have identified the need to determine soil-specific calibration relationships for dielectric sensors in order to achieve high levels of accuracy. There are a number of different calibration methods available, the two most common (Quinones et al. 2003; Seyfried et al. 2005) being:

1. A discontinuous process, whereby a number of specimens are prepared in a standard mould, each containing different amounts of water. The resultant soil moisture measurements

produce a number of points which describe the relationship between water content and dielectric response.

2. A continuous process, whereby a specimen is prepared at a known moisture content then continuous or step-wise measurements are taken while water is either added or removed from the surface or bottom.

The continuous method has the advantage that a large number of points can be obtained in a short time from a single specimen. It also eliminates the risk of density variations which may occur during specimen preparation. However, with the continuous method, it is difficult to ensure that the water content is spatially uniform at the time of measurement. Whilst time consuming, Cataldo et al. (2010) found the discontinuous method produced the lowest measurement uncertainty and therefore this method was adopted for the present study.

For volumetric moisture content calibration of the sandy clay material a total of 37 discrete specimens were prepared over a gravimetric moisture content range of 3.9% to 24.2% (determined after testing) using a discontinuous process. Specimens were prepared in accordance with installation method 3, described in the preceding section (placement and compaction in four equal layers, with the installation jig then the sensor being inserted after compaction of layer 3). The resultant dry density ranged from 845 kg.m^{-3} to 1695 kg.m^{-3} and the volumetric water content was calculated to range from 0.035 to $0.368 \text{ m}^3/\text{m}^3$.

For the granular material a total of 46 discrete specimens were prepared over a gravimetric moisture content range of 5.8% to 13.8% using a discontinuous process. Compaction was achieved using the standard proctor compaction hammer with 25 blows per layer. Specimens were prepared in accordance with installation method four (4), described in the preceding section (placement and compaction in four equal layers, with the installation jig then the sensor being inserted after compaction of layer 3 and only material passing the 9.5 mm sieve was used in the vicinity of the

probe). The resultant dry density was found to vary from $1,712 \text{ kg.m}^{-3}$ to $2,106 \text{ kg.m}^{-3}$ and the volumetric water content ranged from 0.10 to $0.29 \text{ m}^3/\text{m}^3$.

4.3 Applications

4.3.1 Monitoring Changes in Moisture Content

An instrumented laboratory soil column was manufactured simulating a typical bitumen-sealed unbound granular pavement. The soil column, 105 mm internal diameter and 650 mm high, was produced in two PVC segments as shown in Figure 2. The lower segment (Segment 2), representing a road subgrade, was 350 mm thick and the upper segment (Segment 1), representing a road pavement, 300 mm thick. The two segment system was used for ease of placing and compacting the sandy clay (subgrade) material in the lower segment. However, once the sandy clay material was placed and compacted in Segment 2, the two PVC segments were glued together prior to placing and compacting the granular (pavement) material, thus creating a single soil column. To withstand the high lateral forces during compaction the outer shell was constructed of Class 8 PVC pipe with nominal wall thickness of 4.6 mm. The column was open at the top to allow evaporation. The column base was also open and immersed 50 mm into a water bath to allow free flow into the column.

To simulate mean summer maximum temperature at the soil surface (nominally 40°C) a heating array, consisting of one 12 Volt 50 Watt down-light, was installed 120 mm above the column and monitored by a thermocouple. One layer of filter paper (with particle retention in liquid of $11 \mu\text{m}$) was included at the base of the column to prevent loss of fine material into the water bath. The column was then placed on top of stainless steel mesh (2 mm grid) on 40 mm high PVC spacers.

The moisture content and dry density were measured as 12.3% and $1,770 \text{ kg.m}^{-3}$ (respectively) for the sandy clay and 9.6% and $2,074 \text{ kg.m}^{-3}$ for the granular material, which are consistent with values typically specified in construction. The column was instrumented with four (4) Stevens Hydra Probe

II dielectric sensors at 75 mm, 225 mm, 375 mm and 525 mm from the surface (as shown in [Figure](#)

4). The real component of dielectric permittivity measured by the sensors was recorded every 15 minutes over a period of 52 weeks and converted to volumetric water content using the equations determined from the calibration procedure.

Figure 4: (a) Instrumented laboratory soil column design, (b) Photo of soil column and (c) Photo of sealed surface.

4.3.2 Monitoring Changes in Electrical Conductivity

To demonstrate the application of dielectric sensors in the study of electrical conductivity (salinity) changes in granular materials, an instrumented laboratory soil column, 108 mm internal diameter and 325 mm high, was manufactured. Nine (9) layers of granular material were placed and compacted using 25 blows of the standard proctor compaction hammer. The sensor was installed in a 44 mm diameter hole through the PVC shell located 75 mm from the top of the column. The column was open at the top to allow evaporation while the column base was open and immersed 40 mm into a saline water bath to allow free flow into the column. The concentration of saline bath was 10 g Sodium Chloride (NaCl) per Litre. The column was placed on top of stainless steel mesh (1.6 mm grid) on PVC spacers 20 mm high. The column surface temperature during testing was initially 20°C ($\pm 2^\circ\text{C}$). The volumetric water content and salinity (electrical conductivity) determined by the dielectric sensor were measured every 20 minutes over a period of more than 3 months. For clarity,

a manufacturer-supplied conversion from ϵ_i to grams of NaCl was used to represent the salinity of the pore water, noting that as discussed earlier, for a different contaminant a user determined relationship would be necessary. To assess the effect of surface temperature on the rate of salt accumulation a heat lamp was placed above the column surface after 4 weeks, elevating the surface temperature to 40° C for a period of 2 weeks then switched off.

5. Results and Discussion

5.1 *Probe Installation and Calibration*

5.1.1 *Assessment of Installation Methods*

For the 60 sandy clay material specimens, installation was readily achieved using all three different methods, and the measured values of ϵ_r and ϵ_i varied by less than ± 2.0 from the mean value as shown in [Figure 5](#). No significant difference in repeatability (assessed in terms of measurement variability) was observed for the three installation methods investigated (i.e. there was no observed benefit or improvement of one method over another). Additionally, the average standard deviation of the individual and combined components of dielectric permittivity were observed to be comparable to the probe accuracy and inter-sensor variability claimed by the manufacturer (Stevens 2007).

Figure 5: Variation in dielectric permittivity (from the mean value of each set) with installation method – sandy clay material.

For the granular material specimens, direct probe insertion (installation method 1), as recommended by the manufacturer, was found to be extremely difficult (effectively impossible) to achieve due to the density of the specimens and presence of gravel-size particles. Significant force was required to penetrate the sensor even partially into the specimen. Severe spalling occurred and no successful, full-depth, installations were achieved in more than 20 attempts. Use of the installation jig (installation methods 2 and 3) was found to offer improvement in ease of installation but unsatisfactory measurement accuracy / repeatability (refer [Figure 6](#)). The standard deviation in real and imaginary dielectric permittivity values for each of these methods, determined from the difference between the measured value and the mean value, were 2.06 and 1.93 for method 2, and 1.87 and 1.70 for method 3. The installation jig tines were observed to occasionally intersect large (> 9.5 mm) gravel particles, causing significant tine/soil interface disturbance, poor contact between the sensor and the material, and significantly distort the measured dielectric response.

However, installation method 4, where the material in the vicinity of the probe was sieved to eliminate the risk of tines intersecting with gravel-size particles greater than the spacing between the probe tines, was found to both improve the ease of probe installation significantly and result in an acceptable level of accuracy. The standard deviation in real and imaginary dielectric permittivity values for this method, were 0.85 and 0.75 (cf. 2.06 and 1.93 for method 2, 1.87 and 1.70 for method 3). Repeatability, assessed as variation in dielectric permittivity (as shown in [Figure 7](#)) was observed to be equivalent to that achieved in the sandy clay material and stated by the manufacturer.

Figure 6: Variation in dielectric permittivity (from the mean value) with installation method – granular material.

It is acknowledged that removing the gravel-size particles will change the porosity, and have an effect on the dielectric permittivity of a granular material. For a given volume of sample, and with all other things being equal, removing gravel-size particles would result in higher permittivity as moist, porous, fine-grained material (higher permittivity) replaces solid gravel particles (lower permittivity). The magnitude of the difference in permittivity was not able to be quantified for the granular

material studied, as direct measurements could not be made since the gravel particles would not physically fit within the space between the tines. However, localised removal of a small portion of gravel particles (for the granular material studied the fraction retained by a 9.5 mm sieve represents 20% of the total material by mass) is considered to have a limited influence on the overall moisture content. Additionally, this issue was accounted for by calibrating the Hydra Probe readings in the modified material against the volumetric moisture content of the surrounding un-modified granular material. This method may not be appropriate for materials with significantly higher proportions of material passing the 9.5 mm sieve. It is also worth noting that the appropriate maximum particle size for material within the sensing area may differ for other dielectric sensors, being primarily a function of the spacing between the various tines.

5.1.2 Volumetric Moisture Content Calibration

The relationship between the real component of dielectric permittivity measured by the sensor and the volumetric water content (determined from the measured mass, density and gravimetric moisture content) for both the sandy clay material and granular material are shown in [Figure 7](#).

Figure 7: Relationship between the real component of dielectric permittivity (ϵ_r) and volumetric water content (θ).

Third order polynomial equations are generally considered to be the most accurate way of relating dielectric permittivity and volumetric water content (i.e. $\theta = A + B \epsilon_r + C \epsilon_r^2 + D \epsilon_r^3$), and are therefore most commonly used in empirical calibration curves (Bouksila et al. 2008; Cataldo et al. 2010). Using this general equation, the relationship between the real component of dielectric permittivity (ϵ_r) and volumetric water content (θ) for the two materials studied were determined to be:

Sandy Clay Material:

$$\theta = -0.04201 + 0.03024 \epsilon_r - 0.001258 \epsilon_r^2 + 0.000025252 \epsilon_r^3, n = 37, R^2 = 0.98, \sigma = 0.014 \text{ m}^3 \cdot \text{m}^{-3} \quad (1)$$

Granular Material:

$$\theta = -0.01677 + 0.02275 \epsilon_r - 0.0006297 \epsilon_r^2 + 0.0000062457 \epsilon_r^3, n = 46, R^2 = 0.95, \sigma = 0.012 \text{ m}^3 \cdot \text{m}^{-3} \quad (2)$$

The relationship determined for the sandy clay material (Equation 1) has a broadly similar shape to other published relationships for similar fine-grained materials, including that recommended by the manufacturer for sand, but it is very different to the manufacturer's recommended relationship for clay as shown in [Figure 8](#) (Bosch 2004; Seyfried 2008). However, Equation 1 was found to describe the measured volumetric moisture content significantly better than the standard relationships. The difference between Equation 1 and the manufacturer's standard relationships is likely due to the material being a sandy-clay and therefore not falling within the basic textural classifications used by the manufacturer (i.e. sand, clay or silt) and because the material studied was compacted in the laboratory to reflect a typical road subgrade and therefore had a significantly higher density than would be encountered under 'natural' conditions as used by the manufacturer in developing the standard calibration equations. The goodness of fit of Equation 1 (R^2 of 0.98), determined for the

sandy clay material, was consistent with the typical range of R^2 reported by the manufacturer of 0.97 to 0.99 (Stevens 2007).

Figure 8: Comparison of material-specific and standard volumetric moisture content relationships.

Unlike the sandy clay material, the calibration determined for the granular material is observed to be significantly different to any of the published relationships and the manufacturer supplied relationships, as shown in [Figure 8](#). The granular calibration was found to have a much flatter curve than relationships for fine-grained materials. For real component of dielectric permittivity values exceeding 20, the error in volumetric moisture content, determined using Equation 3, exceeded 100% for the granular material as shown in [Figure 9](#).

$$\theta \text{ (error)\%} = \frac{\theta \text{ (Manufacturer Relationship)} - \theta \text{ (Material-Specific Equation 1 or 2)}}{\theta \text{ (Material-Specific Equation 1 or 2)}} \times 100 \quad (3)$$

This reaffirms the need to undertake material-specific calibration when using dielectric sensors with materials which are outside the standard classifications, such as gravelly granular materials. It is also worth noting that no dry density effect was observed in the measured real component of dielectric permittivity for equivalent volumetric moisture content. The accuracy of Equation 2 for the granular

material (R^2 of 0.95) translates to $\pm 0.03 \text{ m}^3/\text{m}^3$ (99% confidence limit) and, while lower than typical for fine-grained materials, is considered acceptable due to the difficulty of installation and the highly compacted nature of the granular material. The lower R^2 of granular material compared with that of the sandy clay material is likely due to minor disturbance during installation of the probes, though it may also be a function of greater variation in particle size, and therefore pore space, of the granular material within the probe sensing area.

Figure 9: Error in predicted volumetric moisture content of sandy clay and granular materials using relationships provided by the manufacturer compared with material-specific relationships.

5.2 Applications

5.2.1 Monitoring Changes in Moisture Content

The volumetric moisture content, as recorded by the two sensors located within the sandy clay subgrade at 375 mm and 525 mm below the column surface, was observed to reach equilibrium moisture content for the applied boundary conditions within 3 months, as shown in [Figure 10](#). The volumetric moisture content recorded by the two upper probes, located within the granular material

at 75 mm and 225 mm below the column surface, was observed to decrease at a diminishing rate from the initial value to an equilibrium value over a significantly longer period of time. It is also clear from [Figure 10](#), that capillary rise within the subgrade was less than the distance between the sensing area of the lowest sensor and the water bath (approximately 55 mm), evidenced by a lack of increase in volumetric moisture content to saturation ($0.30 \text{ m}^3\text{m}^{-3}$) at this depth.

Figure 10: Volumetric moisture content of bitumen sealed column using Hydra Probes.

The volumetric moisture content measurements determined from the Hydra Probe were also compared with the initial moisture content (at the time of fabrication) and the moisture content of a destructively-tested replicate column after 52 weeks. It is calculated from [Figure 10](#), that moisture contents determined using the Hydra Probes generally reflect the destructively-measured moisture contents to within approximately $0.005 \text{ m}^3/\text{m}^3$.

5.2.2 Monitoring Changes in Electrical Conductivity

Over the 3 month monitoring period very little variation was observed in the measured volumetric moisture content except in response to the increased evaporative rate when the temperature at the

surface of the column was increased from 20°C to 40°C (refer [Figure 11](#)). At this point in time the increase in evaporative flux was observed to result in a temporary reduction in volumetric moisture content until an equilibrium condition was re-established.

The variation in pore-water salinity, calculated as a function of the measured electrical conductivity divided by the measured volumetric moisture content, is shown in [Figure 11](#). It was observed to increase at a relatively constant rate related to the applied surface temperature. The rate of pore water salinity increase was calculated to be five (5) times greater at 40°C compared with 20°C. Interestingly, the influence of minor changes in ambient conditions (temperature and air flow) as a result of operation the thermostatically-controlled air conditioning system are clearly visible, particularly within the first 21 days, before a 'wind' shield was placed between the main air conditioner vent and the column. Salt crystallisation was evident on the column surface after 4.5 weeks ([Figure 12](#)).

Figure 11: Volumetric moisture content and pore water salinity with time.

Figure 12: Salt crystallization visible on surface of column.

[Figure 11](#) demonstrates how a dielectric sensor, such as the Hydra Probe, may effectively describe both net changes in soil salinity and also changes in the rate of soil salinisation. However, as discussed earlier, for other materials and/or contaminants it is likely that a material- and contaminant-specific calibration relationship would be necessary in order for results to be expressed in meaningful units.

The results of these two experiments confirm the applicability of the Hydra Probe specifically, and dielectric sensors more generally, to studies of engineered granular materials to monitor changes in moisture content and/or electrical conductivity.

6. Conclusions

This study explored the suitability of capacitance-type dielectric sensors for small-scale laboratory studies of engineered gravelly granular materials by assessing methods of installation and calibration requirements. The design and results of two experiments were also presented to demonstrate how dielectric sensors may be utilised in laboratory studies to monitor changes in moisture content and/or electrical conductivity of granular materials.

Direct insertion of the sensor (as recommended by the manufacturer) was found to achieve acceptable reliability for installation in a fine-grained sandy clay material, even when heavily compacted. Use of an installation jig or modifications to the compaction process were found to make no difference to the variability of readings for this material.

For the gravelly granular material, there would seem to be no satisfactory method of installation of the probe due to the presence of gravel particles greater than the spacing of the tines, even when an installation jig was employed to form the holes and the compaction process was staged. However, when the larger gravel particles were removed in the area of the sensor tines, by passing the material to be used in this zone through a 9.5 mm sieve prior to compaction, installation of the probe utilising the jig was observed to result in an acceptable level of repeatability. It is therefore concluded that the Hydra Probe is generally unsuitable for installation in compacted granular materials where a significant portion of particles are retained on a 9.5 mm sieve. However, the probe may be suitable for granular materials where the proportion of particles retained on a 9.5 mm sieve is low, provided these particles are removed from the tine sensing area prior to compaction of the specimen.

The volumetric moisture content relationship determined for the sandy clay material was broadly similar in shape to published relationships for similar fine-grained materials and the manufacturer-supplied relationship for sand. Nevertheless, use of the soil-specific calibration was found to significantly improve the accuracy of the predicted values. However, the soil volumetric moisture content relationship determined for the granular material was found to be significantly different to the standard relationships supplied by the supplier and others published in the literature, with errors in predicted values using these relationships exceeding 100%. Use of a material-specific calibration curve for the granular material improved the accuracy of predicted volumetric moisture content values significantly to $\pm 0.03 \text{ m}^3/\text{m}^3$. As such, it is concluded that material-specific calibration is essential for use of dielectric sensors with coarse-grained granular materials and recommended for use with fine-grained materials.

The two experiments presented demonstrate how dielectric sensors may be used for laboratory studies of granular materials to monitor changes in moisture content and/or electrical conductivity over time and/or in response to applied boundary conditions. Dielectric sensors represent an alternative to other commercially available sensors for laboratory studies of infiltration, evaporation and contaminant transport, particularly those incorporating small-scale laboratory columns. Given the size of these sensors it is also possible to include corresponding tensiometers within soil columns so that temperature, moisture content, electrical conductivity and suction are all measured. Thus a more accurate picture of the unsaturated behaviour of granular materials may be developed and aid in applying unsaturated soil mechanics to an area which historically has been predominantly the domain of empirical research.

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8. References

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