Design of Access-Tube TDR Sensor for Soil Water Content: Testing

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***Abstract*—Soil water measurement is important in water management for irrigation and in hydrologic sciences. The purpose of this paper is to develop and test the design of a cylindrical access-tube mounted waveguide for use in time-domain reflectometry (TDR) for *in situ* soil water content sensing. Several prototypes with varying geometrical parameters were constructed. The sensors were compared by evaluating the characteristics of reflected waveforms from a (200-ps) step pulse in different media, including air, triethylene glycol, deionized water, and over a range of water contents in sand and a clay loam soil. Sensors with greater separation between electrodes, achieved by means different tube diameters or the separation angles, tend to have greater field penetration in both sand and clay. In addition, sensors with the shortest electrode separation show greater sensitivity to soil electrical conductivity. Together, these trends demonstrate that the propagating electromagnetic fields above 0 Hz do not take the transverse electromagnetic form commonly assumed in the analysis of TDR probes.**

***Index Terms*—Dielectric, electromagnetics, sensors, soil water.**

I. Introduction

KNOWLEDGE of soil water content in the root zone is vital for timely management of (irrigation) water available to crops. Recent efforts of scheduling irrigation to supply water to crops at near optimal or deficit conditions requires water content sensors with improved accuracies [1], [2]. Many methods have been explored for sensing soil water content, including remotely by passive microwave sensing [3] and in-situ by neutron thermalization, dielectric capacitance probes, or time-domain reflectometry probes [4]. Neutron probes are relatively impractical due to the regulatory burden and the fact that they cannot be left unattended for data logging. Capacitance probes suffer inaccuracies due to soil conductivity, temperature effects and variations in response due to variations in soil structure [2], [5], [6]. Time domain reflectometry (TDR) uses the travel time of a pulse sent down a waveguide surrounded by the medium to be measured [7]. The travel time is related to the soil dielectric permittivity, which in turn is related to the soil water content. Several TDR electrode designs have been explored including printed circuit board [8], trifilar rod probes [9], and cylindrical access-tube designs [10]. However, TDR sensing of soil water content presents three main problems. First, the dispersive nature of the soil medium distorts the transmitted waveform, usually a rectangular pulse. The transmitted pulse has spectral content over a broad bandwidth. Since the permittivity of many soils are strongly frequency-dependent, and soil conductivity attenuates high-frequency components, the reflected waveform is distorted and is difficult to interpret [11]–[13]. Second, probes that include some dielectric material in addition to the conductive elements measure a permittivity that is a combination of the soil permittivity and the permittivity of the probe body. The sampling area of the probe gives an indication of the fraction of the field penetrating into the soil and probe dielectric. This makes it difficult to translate the measured permittivity into a soil water content. Third, the soil medium is lossy, particularly at high frequencies, which can make waveform interpretation difficult. To overcome these difficulties, various approaches on the circuit side of the design could be considered, such as shorting diodes [14] or frequency-domain techniques [15]. Also, the sensor design could be optimized with respect to probe geometry.

A TDR sensor that can be installed easily, measure a deep soil profile, and disturb the soil minimally on installation would be of great value. Some different designs have been explored in the past for measuring the water distribution over a soil profile. [16]–[20] examined two-wired coil-type TDR, where the electrodes are coiled around the central shaft of a plastic substrate. These are good designs; however they are either limited in depth or unable to continuously monitor a complete soil profile. In addition, the coil type design disturbs the soil more on installation, potentially creating voids along the surface of the probe, affecting the TDR measurements. [21], [22] describe a combined TDR-penetrometer, where the electrodes are curved metal plates on a plastic substrate. This design has many benefits, however, the sensor as presented does not measure a complete profile, rather a 20 cm section. Additionally, the penetration of the probe may lead to excessive soil compaction and thus biases sensor readings.

This paper comprises the second of two investigating the performance of a particular sensor geometry. The first paper derived a quasi-analytical EM model to investigate the field distribution and waveforms, and concluded that increasing electrode separation distance increased field penetration. In this paper, we investigate a particular sensor design for use in

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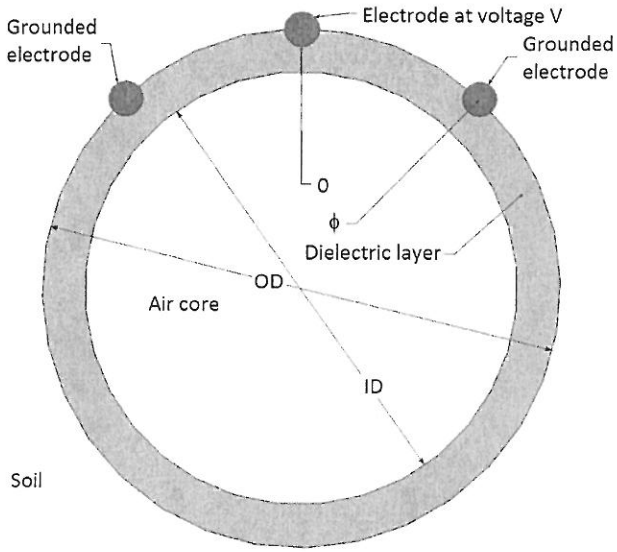

Fig. 1. Probe cross section and parameterization.

TDR, that of a cylindrical access tube with surface-mounted electrodes. This cylindrical geometry facilitates sensor installation at multiple depths in the soil profile. The cylindrical access tube provides structural support and allows soil to be augured out as the tube is pushed into the soil, which minimizes soil disturbance around the electrodes. Variations in the tube and electrode geometries are tested in different media, including air, triethylene glycol, deionized water, sand, and clay loam. First, the sensor geometry is detailed; then, the construction procedure is described; finally, the results of sensor waveforms and dielectric measurements are compared across sensors and across media to assess sensor performance.

II. Access Tube Design and Geometrical Parameterization

Figure 1 shows a cross-section of the probe design with design parameters. The waveguide-on-access-tube TDR design consists of a cylindrical plastic tube, with three electrodes on its surface that may or may not be connected to voltage ground or a source voltage. Specifically, we examine a three-wire design because it eliminates the need for an impedance matching balun used with a two-wire design [23]. The probe can be fully described by the following variables: probe length, dielectric tube inside diameter (ID), outside diameter (OD), dielectric value ϵ, electrode width and electrode spacing (or position ϕ).

III. Sensor Construction

The sensor prototypes were constructed from schedule 40 rigid polyvinyl chloride (PVC) tubing of various diameters, although it is stipulated that PVC is a relatively poor material in terms of dielectric losses for this purpose. The electrodes were 4.76-mm diameter stainless steel rods. To attach the electrodes to the tube body, grooves were milled. Then, the electrodes were electrically connected to a 2-m length of 50-ohm coaxial cable (LMR 240, Times Microwave Systems, Wallingford, CT).[1] Electrical properties of the cable are given in Table I. The electrodes were affixed using room temperature vulcanizing silicone sealant and the electrical connection between the coax and the electrodes was sealed in silicone. The specific sensor prototypes that were constructed are listed in Table II.

TABLE I
LMR-240 Properties

Cutoff frequency	31 GHz
Velocity of Propagation	84%
Impedance	50 Ω
Attentuation at 2 GHz	37.7 dB/100 m

The practical aspects of this design (installation, construction, field data acquisition) were considered in [24]. Briefly, the complete sensor is a length of PVC with TDR electrodes on the exterior at 20 cm intervals, which connect electrically to the interior of the PVC through machine screws. A cutting edge is affixed to the bottom edge of the PVC, and the tube is pushed into the soil with a hydraulic ram while soil is augured from the tube interior. Then, the electrodes are connected to the coaxial cable by mechanical connectors lowered down the access tube that snap onto the machine screws.

IV. Sensor Tests

Seven sensors were tested in different media by waveform acquisition using a Tektronix 1502B cable tester and a microcomputer running the TACQ software [12]. Waveforms were acquired using two time windows, one using a lower resolution of 251 points in 35 ns (7.17 points/ns) and another using a higher resolution of 251 points in 6 ns (35.86 points/ns). The tests were conducted in four main groups. First, four waveforms of 251 points were acquired and averaged in standard media: air, triethylene glycol (at various degrees of dilution with deionized water), and deionized water; then, in sand or clay loam, mixed to achieve homogeneous moisture distribution, up to 0.20 m^3/m^3 volumetric water content, in increments of roughly 0.05 m^3/m^3. The permittivity of the standard media was taken as the reading supplied by a standard trifilar probe. Soil properties are given in Table III, where surface areas were obtained by equilibrating moistened soils at 54.4% relative humidity [25] and bulk densities were the averages of packed values. Soil was contained in a 0.203-m diameter, 0.216-m high PVC cylinder (Fig. 2). Third, sensors were evaluated in sand or clay loam at or near saturation, achieved through introducing deionized water at the bottom of the packed column at a small positive pressure head while connected to a load cell (Fig. 3). Finally, sensor probe constants for bulk electrical conductivity calculations were determined by acquiring waveforms in KCl solutions of measured conductivity, using the relationship between reflection coefficient and conductivity described in [26].

In discussion of TDR waveforms here we will use the waveform nomenclature of [12], [27] and [28], which relates to

[1]The mention of trade names of commercial products in this paper is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

TABLE II
SENSOR PROTOTYPE DIMENSIONS

Probe number	ID (mm)	OD (mm)	ϕ (°)	Arc distance (center to ground, mm)	L (m)
1	50.8	60.3	60	31.6	0.195
2	50.8	60.3	75	39.5	0.195
3	31.8	42.1	45	16.5	0.195
4	50.8	60.3	45	23.7	0.195
5	50.8	60.3	45	23.7	0.100
6	76.2	88.9	45	34.9	0.195
7	50.8	60.3	90	47.4	0.195

TABLE III
SOIL PROPERTIES

Soil type	Bulk density	Specific surface area	Clay content
Fine Sand	1.49 Mg/m^3	not measured	not measured
Pullman Ap Clay Loam	1.21 Mg/m^3	249 m^2/g	39.4%

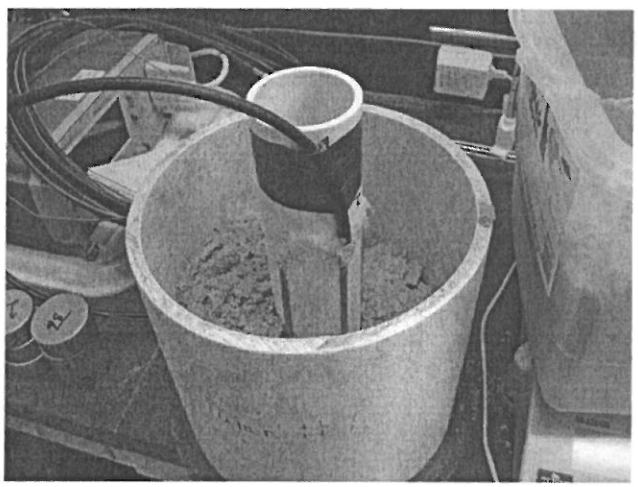

Fig. 2. Surrounding the probe with soil.

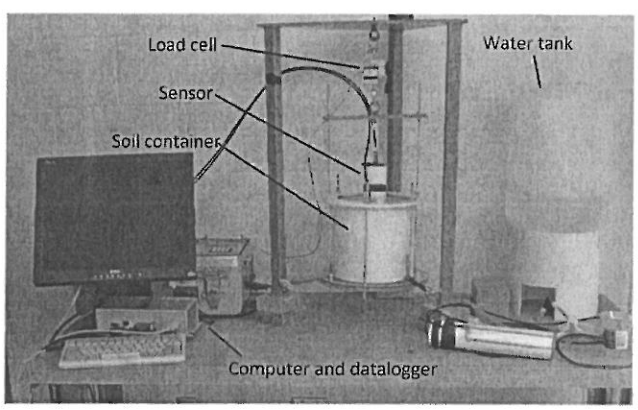

Fig. 3. Load cell used for saturated soil tests.

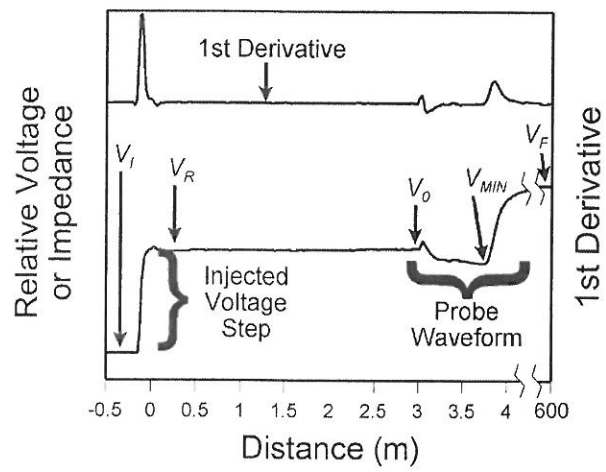

Fig. 4. Plot of waveforms and first derivatives as seen on a scope. V_i is the injected voltage, V_r is the reflected voltage, V_0 is the voltage before the wave exits the coax, $V_{\min}$ is the minimum voltage after the pulse exits the coax, and V_f is the final voltage level.

measurements of pulse travel time, final reflection coefficient (relative impedance) and slope of the waveform reflection at the electrode ends defined there and in [12], [27]. A labeled waveform and its derivative are shown in Fig. 4.

To evaluate sensor performance in soil, several metrics were employed. Waveforms were compared across sensors and media. Differences in probe response with respect to water content in sand and clay loam media were assessed using general linear models in SAS with a quadratic model and probe design as a classification variable (excluding the short, 10 cm, probe, whose travel times are necessarily shorter than the other, longer probes). The quadratic model was ultimately chosen because the quadratic term was significant. In the air, triethylene glycol, and deionized water tests, the TDR-estimated apparent permittivity was compared to the apparent permittivity as measured by a standard trifilar probe to give an indication of the probe's field penetration into the surrounding media. In the soils, the data were analyzed by comparing waveform slope at the second reflection. This gives a measure of waveform quality; higher slope indicates a less degraded waveform as the high frequency components of the input pulse are not attenuated as strongly.

Acquired waveforms in sand and clay loam media varied among sensor designs principally at or near saturation as a result of greater signal degradation at higher water

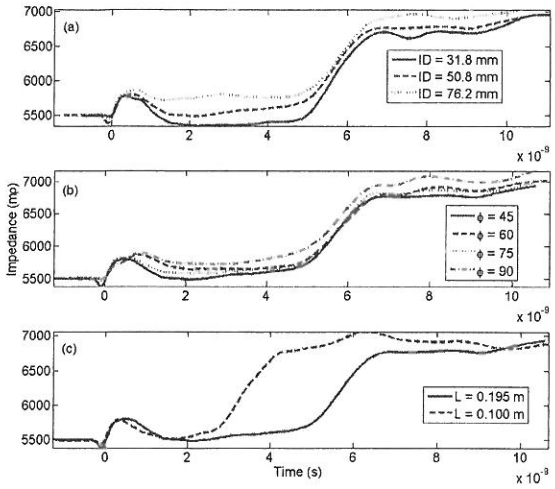

Fig. 5. Waveforms at saturation for all sensors in sand. (a) Effect of changing ID, while L is fixed at 0.195 m and ϕ at 45. (b) Effect of changing ϕ, while L is fixed at 0.195 m and ID at 50.8 mm. (c) Effect of changing L, while ϕ is fixed at 45 and ID at 50.8 mm.

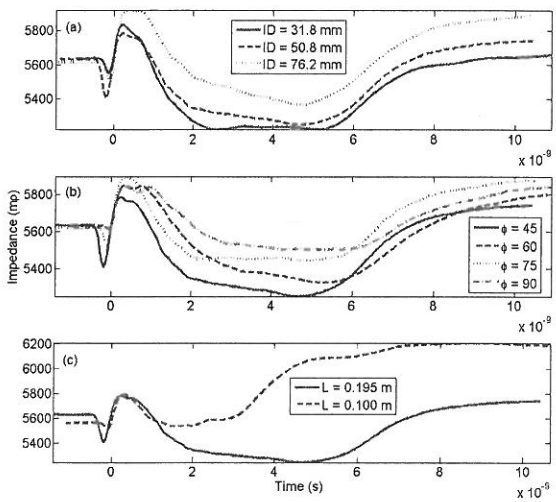

Fig. 6. Waveforms at saturation for all sensors in clay. (a) Effect of changing ID, while L is fixed at 0.195 m and ϕ at 45. (b) Effect of changing ϕ, while L is fixed at 0.195 m and ID at 50.8 mm. (c) Effect of changing L, while ϕ is fixed at 45 and ID at 50.8 mm.

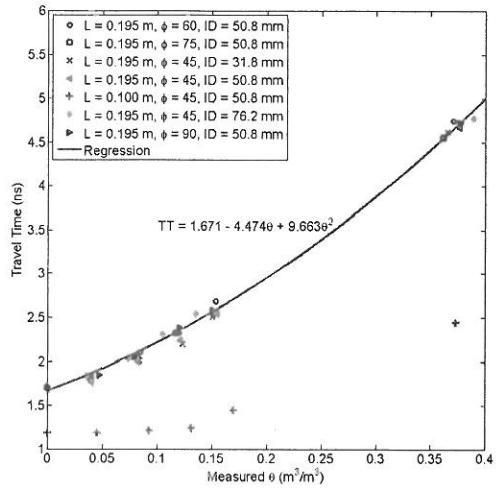

Fig. 7. Effects of the actual VSW on travel time, with quadratic regression for 0.195-m sensors, in sand.

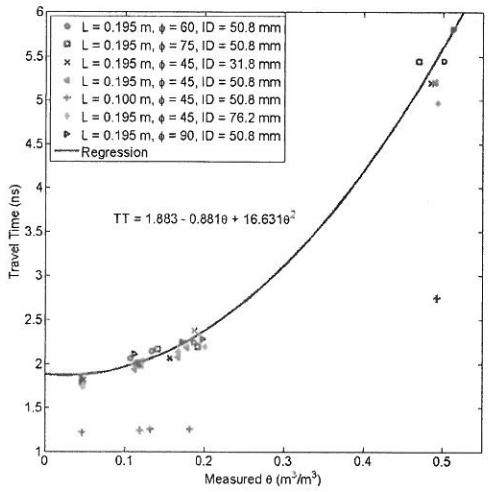

Fig. 8. Effects of the actual VSW on travel time, with quadratic regression for 0.195-m sensors, in clay.

contents. Comparison of waveforms from different diameter sensors in near-saturated sand (0.38 m^3/m^3) shows that the waveform depression after the initial peak and before the final reflection (end of electrodes) increases as diameter decreases (Fig. 5a). This result is corroborated by the fact that for a constant diameter, decreasing angular separation also caused the waveform depression to mostly increase between initial peak and final reflection (Fig. 5b). There is increasing physical electrode separation as diameter increases for the constant angular electrode separation, and increasing electrode separation as angle increases for constant diameter. Deeper waveform depression indicates a lower characteristic impedance. A lower characteristic impedance is caused by a lower effective permittivity, consistent with less field penetration into the high permittivity soil and more in the low permittivity PVC and air core. Therefore, the waveforms show greater field penetration into the soil with greater electrode separation. The effect of electrode length on travel time is as expected (Fig. 5c). Waveforms in near-saturated clay loam show more obvious inter-sensor differences (Fig. 6), as the water content is higher (0.48 m^3/m^3) and clay loam has more high-frequency losses.

In sand, the waveform differences among sensors are fairly indistinct (aside from the effect of electrode length shown by the 0.10 m probe: when scaled appropriately, the travel times for the 0.10 m probe are consistent with the other probes, except for low θ values, where they are higher due to fringing

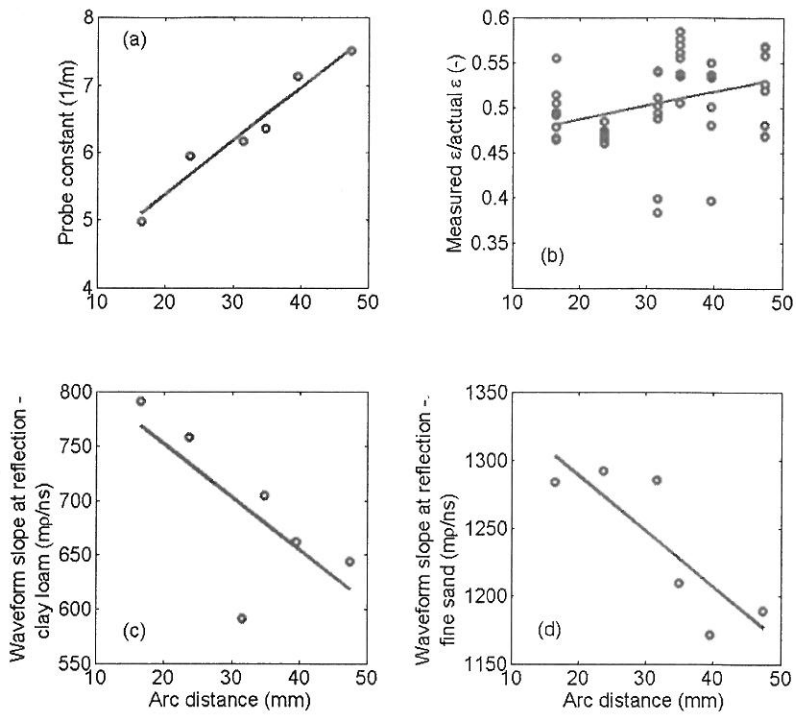

Fig. 9. Performance metrics versus electrode separation arc distance, with linear regressions. (a) Probe constant. (b) Measured ϵ/actual ϵ. (c) Waveform slope at reflection in clay loam. (d) Waveform slope at reflection in fine sand.

field effects), and consistent with a nonsignificant (P = 0.38) probe design effect on the quadratic response of travel time with respect to volumetric water content (Fig. 7). Although a linear response between travel time and water content is theoretically predicted for sand [11], the differences between modeled linear and quadratic responses were highly significant (P<0.001). This result is evidently a result of the contributions of the PVC fraction to the permittivity and its dependency on water content. Modeled response of travel time to water content in the clay loam soil (Fig. 8) also had a significant quadratic response (P<0.001), however the linear term was nonsignificant (P = 0.511).

Comparing the TDR-estimated apparent permittivity (ϵ) to the known permittivity of fluids gives a measure of the field penetration into the media. Since the surrounding permittivity is different than the permittivity of the PVC (about 3) and air core (about 1), a greater penetration of the electromagnetic field into the surrounding media would be manifested by a measured permittivity closer to the known value. Consequently, the ratio of measured permittivity to known permittivity would approach unity as the field penetration increases. In practice, a calibrated power law mixing model could be used to translate between the measured permittivity and the actual permittivity of the soil, such as that employed by [18], [29]. The relationship between this ratio and electrode separation was examined by a linear regression (shown in Fig. 9b), using the data from the triethylene glycol and deionized water tests. The slope of this regression was statistically significant (P = 0.0195) and positive, showing that field penetration increases with increasing electrode separation. However, the RMSE of regression was +/−0.045, the same order of magnitude as the change in measured ϵ/actual ϵ over the range of arc distances, indicating that a strong relationship is not clear.

The mean slope of the waveform at the open termination reflection (Fig. 4; V_{min}) in sand and in clay loam were compared across sensors and with respect to arc distance between electrodes. For a given bulk EC, a lower slope is indicative of a narrower bandwidth resulting from signal attenuation at higher frequencies [30]. In sand, the slopes were greater than in the clay loam, as sandy soils have less high-frequency dielectric losses [31]. In both sand and clay loam, the slope of the reflection decreased with increasing arc separation distance (Figs. 9c and 9d) despite the fact that greater separation distances are associated with a larger probe constant and less attenuation of long-time reflection coefficients. Such a result is indicative of greater signal attenuation at high frequencies caused by dielectric relaxation mechanisms and associated with a greater field penetration into the soil for probes with greater electrode separation distance.

Calibrated probe constants ranged from 5 to 10 m^{-1} and are considerably greater constants than those of standard TDR probes of similar lengths [31]. A lower probe constant indicates the probe has a greater sensitivity to DC soil conductivity. The most sensitive probe was the 31.8-mm diameter probe, followed by the 50.8-mm diameter sensors, in order from 45-degree separation to 90-degree separation. Sensitivity

to conductivity increased with decreasing electrode separation (Fig. 9a), and correlated closely ($r = 0.988$) with an analytical derivation three-rod probe constants by Paolo Castiglione (personal communication, 2008).

The probe constant is related to the field distribution at 0 Hz, where the fields are TEM. The probe constants decrease with increasing electrode separation, which conforms to the predictions of a TEM field model, but only at DC. Increasing field penetration (as measured by slope at reflection and the permittivity ratio discussed earlier) with increasing electrode separation conflicts with the predictions of a TEM model, indicating that fields above DC must be non-TEM. In theory, TEM modes are not supported above DC when a substrate is used, due to boundary conditions, and increasing field penetration with increasing electrode separation matches the prediction of the hybrid mode propagation derived in [32].

V. Conclusion

In this paper, we investigated a particular sensor design, that of a cylindrical access tube with surface-mounted electrodes. Variations in the tube geometry were tested in different media, including air, triethylene glycol, deionized water, sand, and clay loam. First, the sensor geometry was detailed; then, the construction procedure was described; finally, the results of sensor waveforms and dielectric measurements were compared across sensors and across media to assess sensor performance.

The sensors exhibit a quadratic relationship between pulse travel time and soil water content, with no significant difference between sensors. Based on the sensor tests in triethylene glycol and deionized water, increasing electrode separation increased field penetration as shown by the measured permittivity. Waveform slopes at reflection in sand and clay loam decreased with increasing electrode separation, an indication of greater high-frequency dielectric losses which implicates greater field penetration, matching the theoretical results presented in [32]. Sensitivity to DC electrical conductivity was greatest for prototypes having the smallest electrode separations, demonstrated by lower probe constants, conforming with a TEM model at DC. These trends indicate that the propagating modes above DC on the TDR are non-TEM. This makes physical sense, as a probe which includes some substrate is incapable of supporting TEM modes above 0 Hz.

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