Proceeding of the Second International Conference on Unsaturated Soils

Beijing, China, August 27 – 30, 1998

Volume 1, pp. 338 - 343

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Abstract

With the advent and growing acceptance of unsaturated soil mechanics comes a need for reliable and accurate matric suction measurements. There are several instruments available for measuring matric suction; however, available sensors do not sufficiently meet the need for accuracy and reliability when making in situ measurements.

A time domain reflectometry (TDR) matric suction sensor was developed through the Unsaturated Soils Group at the University of Saskatchewan. The TDR matric suction sensor was developed by combining a ceramic sensor with a short-wire TDR probe. This paper highlights the results of the development of a TDR matric suction sensor.

Discussion of the TDR probe research focuses on the effects of reducing the size of TDR probes with respect to the accuracy of resulting TDR data. Information gathered from the ceramic and TDR probe research was used to build several TDR matric suction sensors. The methods used for constructing the TDR matric suction sensors along with the sensor specifications are discussed. The TDR matric suction sensors were calibrated using a modified pressure plate apparatus. The resulting calibration curves are compared to a theoretical calibration curve. The theoretical calibration curve was calculated using the soil-water characteristic curve of the ceramic sensor material.

The TDR matric suction sensors have potential for providing adequate matric suction measurements for geotechnical engineering purposes. However, further refinements to the sensors are necessary and field testing is required to assess the reliability and longevity of the TDR matric suction sensor.

Introduction

The time domain reflectometry (TDR) matric suction sensor developed is an indirect measuring device which is conceptually similar to the thermal conductivity sensor. A ceramic with an acceptable pore size distribution can be used to directly measure matric suction in soil. The TDR probe inside the ceramic will be used to indirectly measure the water content of the ceramic. The soil matric suction can be inferred from the ceramic soil-water characteristic curve.

Research was conducted at the University of Saskatchewan on possible matric suction sensors which included thermal conductivity, ultrasonic, and dielectric sensors [1]. It was proposed that dielectric sensors could be developed to measure matric suction but suggested that TDR would not be an acceptable alternative. However, the conclusion was based on the size of commercially available TDR probes.

A TDR matric suction sensor was developed at the University of Saskatchewan by equipping a ceramic sensor with a TDR probe [2]. The following sections discuss the TDR matric suction sensor that was developed.

Ceramic Research

The ceramics that were to be used in the TDR matric suction sensors were developed for a measurement range from 0 kPa to approximately 300 kPa with a porosity of 60%. These specifications are comparable to commercially available thermal conductivity sensors.

Ceramic research focused on the use of mullite ceramic material. The constituents of mullite are alumina (Al_2O_3) and silica (SiO_2) and can be formed by firing pure kaolinite clay. Ammonium carbonate can be added to provide additional control of porosity and pore size distribution [3].

Ceramic soil-water characteristic curves were measured in a volumetric pressure plate extractor using a gravimetric method (i.e., gravimetric measurements were used to obtain water contents) which allowed simultaneous measurement of up to five ceramic soil-water characteristic curves. The apparatus used to determine the ceramic soil-water characteristic curves is shown in Fig. 1.

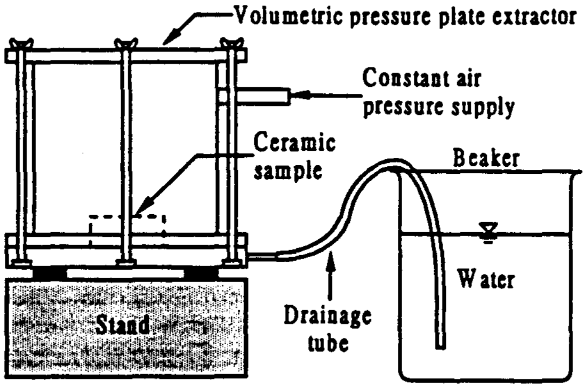

Fig. 1 Pressure plate apparatus for obtaining ceramic soil-water characteristic curves.

TDR Probe Research

The size of the TDR probes used for a matric suction sensor must be small relative to commercially available TDR probes. Commercially available TDR probes are generally greater than 150 mm in length with wire to wire spacing greater than 50 mm. The ceramic required to fully contain the electrical field generated by these TDR probes in order to make a matric suction sensor would be much too large to be practical or economical. The limiting factors associated with the size of the probe have been addressed by many researchers; however, the limitations are based on field experiments where the volume of soil sampled by the TDR probes must be maximized.

Small TDR probe configurations were studied for use in the laboratory and it was found that the volume of soil contributing to the measurement is highly dependent on wire to wire spacing and somewhat dependent on wire diameter [4]. Errors encountered when using short probes will be larger than errors associated with longer probes; therefore, probes should be designed to be as long as possible.

Three and four wire TDR probes were designed and built for this research project. A three wire TDR probe is illustrated in Fig. 2. The probe head was machined from brass and the probe wires were made from stainless steel. A standard male quick connect type coaxial connector was threaded into the probe head. This would allow a coaxial cable to be connected and disconnected quickly and easily during testing. The outer probe wires were secured in the probe head using "set" screws and the center wire was soldered to the coaxial connector

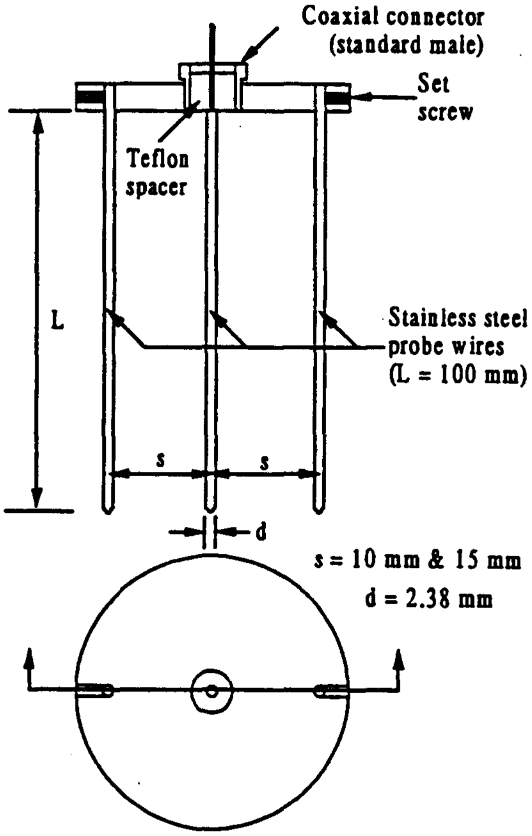

Fig. 2 Short-wire TDR probe specifications.

Two different wire spacings were used for the probes (i.e., 10 mm and 15 mm). Therefore, four different TDR probes were built for this research project. The four wire TDR probes were essentially identical to the three wire probes except that they had three outer shield wires distributed evenly around the outside of the probe head.

When fully inserted in a soil (or ceramic), the TDR probes can be used to measure volumetric water content. A voltage pulse is applied to the TDR probe, the voltage pulse travels to the end of the probe wires and is reflected back. The time required for the voltage pulse to travel to the end of TDR probe and back must be measured, t. The apparent dielectric constant, K_a, can be calculated if the probe length, L, is known (c = velocity of light = $3\text{x}10^8$ m/s):

$$K_a = \left(\frac{ct}{2L}\right)^2 \tag{1}$$

This equation has been fundamental to the application of TDR for measuring the volumetric water content of soils. The apparent dielectric constant of water is reported to be 80.36 at 20 °C [5]. The dielectric constant of air is 1 and the dielectric constant of most geologic minerals is 2 to 3. Therefore, the dielectric constant will change significantly with water content but not with different soils. Exceptions to this rule exist with organic soils and some clay soils.

A coaxial soil container was used to measure the dielectric constant of many different porous materials and calibrate the measured dielectric constant with volumetric water content. An empirical equation was developed to relate the volumetric water content to the apparent dielectric constant [6]. This equation has gained recognition as the universal equation for relating volumetric water content and apparent dielectric constant measured using TDR.

Time domain reflectometry probe research was done to establish how sensitive each probe was to changes in water content and to determine which probe would perform most satisfactorily. Apparent dielectric constant measurements of distilled water were taken with each of the four TDR probes. The percent error between the measured apparent dielectric constants and the accepted value of 80.36 varied from 2.7 % to 4.2 %. The three-wire probe with a 10 mm wire spacing (i.e., W3S10) varied the most while the four-wire probe with a 15 mm wire spacing (i.e., W4S15) varied the least; however, all had less than 5 % error.

Standard Proctor density samples were prepared with processed silt and Indian Head till. Each soil specimen was prepared according to ASTM standard D698. The apparent dielectric constant of each soil specimen was measured twice with each of the four small TDR probes. TDR response curves were obtained with the TRASE System I TDR sampler from Soilmoisture Corporation and then downloaded into a microcomputer for analysis. Measured apparent dielectric constants were plotted versus volumetric water content and compared to the Topp et al (1980) equation. Data from the four wire probe with 10 mm wire spacing (i.e., W4S10) is presented in Fig. (3). Apparent dielectric constants measured with W4S10 were lower than expected; however, the measurements were consistent since the experimental data had minimal scatter.

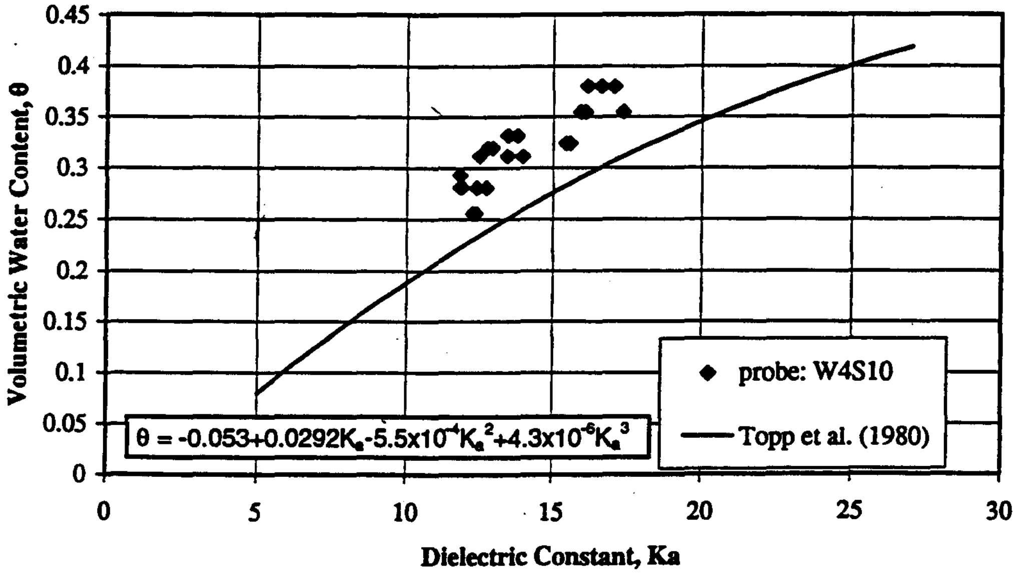

Fig. 3 Volumetric water content versus apparent dielectric constant measurements from small four wire TDR probe (W4S10).

Probe W4S10 was chosen for use in the TDR matric suction sensors since there was less scatter in apparent dielectric constant measurements. Probe W4S10 shows evidence of "skin effects"; however, and this may affect the sensitivity of the TDR matric suction sensor. The probe was chosen over the others since the resulting matric suction sensor would be smaller than one created from the probes with a 15 mm wire spacing and the four wire probe would provide more consistent measurements than the three-wire probe.

TDR Matric Suction Sensor

Once an acceptable ceramic sensor material was developed, large ceramic sensors were made and the TDR probes were inserted to form TDR matric suction sensors. Holes were drilled into the ceramic using a drill press and the TDR probes were inserted. Different methods were used to bind the TDR probes into the ceramic.

A Portland cement binder was used in one TDR matric suction sensor. The ceramic was initially saturated prior to inserting the TDR probe. A slurried mixture of Portland cement was used to fill the holes in the ceramic then the TDR probe was inserted and the cement was allowed to cure.

Epoxy binder was used in two TDR matric suction sensors. These two sensors were constructed differently in that the ceramic for one sensor was left dry when the TDR probes were inserted and the other ceramic was initially saturated. The holes in the ceramic were filled with epoxy prior to inserting the TDR probes for both sensors.

Castone was used as a binder in nine TDR matric suction sensors. Two batches of TDR matric suction sensors were constructed with Castone binder. Both batches were constructed by placing slurried castone into the holes of a saturated ceramic sensor, the TDR probes were then inserted and the castone was allowed to cure. Great care was taken with the second batch to eliminate air bubbles form being trapped between the probe wires and the ceramic.

The TDR matric suction sensors were then calibrated. Several TDR matric suction sensors were calibrated in a thermal conductivity calibration chamber. The saturated TDR matric suction sensors were placed, upright, inside the pressure plate apparatus and covered with a mixture of slurried silty sand. The ceramic part of the sensors was completely covered with the slurry and the TDR probe heads were left uncovered.

Air pressure (i.e., matric suction) was applied to the calibration chamber and left for several hours. The TDR response from each sensor was obtained by removing the lid of the pressure vessel and connecting a coaxial cable to each sensor. TDR measurements were taken throughout the calibration process using the Trace System. The TDR response curves from each of the TDR matric suction sensors were downloaded to a microcomputer for analysis. The air pressure in the calibration vessel was increased after the water content in the ceramics reached equilibrium. The apparent dielectric constants were calculated using Eq. (1).

A modified Tempe Cell was used for calibrating one of the TDR matric suction sensors. The height of the Tempe Cell was increased to allow a TDR matric suction sensor to be placed inside. The saturated TDR matric suction sensor was placed in the modified Tempe Cell and a kaolinite paste was used to establish good contact between the sensor and high air entry disk. The TDR response of the sensor was monitored in the same manner as the large calibration vessel.

A typical set of TDR response curves obtained during the calibration process are plotted in Fig. (4) for suctions ranging from 0 kPa to 150 kPa. This matric suction sensor was constructed using castone binder.

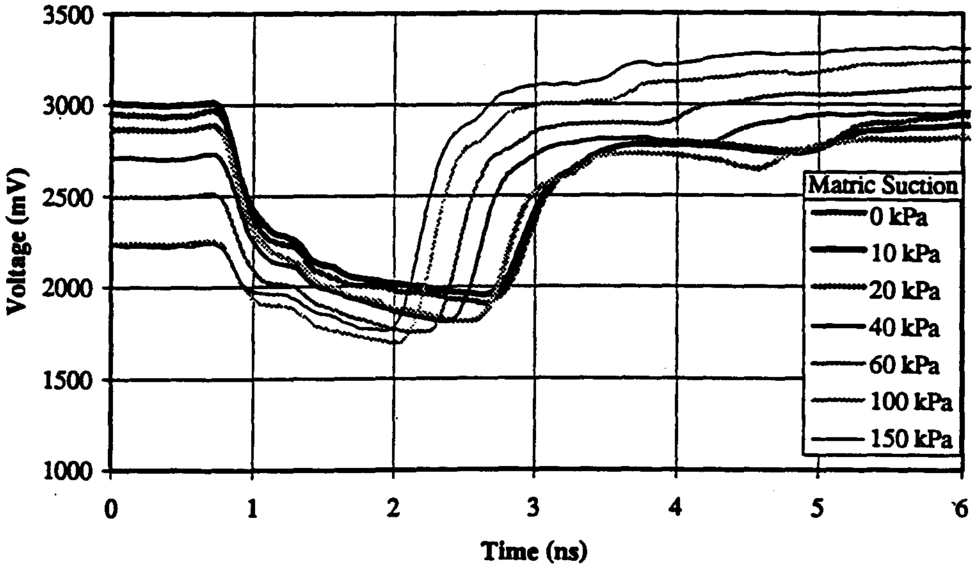

Fig. 4 TDR response curves from the calibration of a TDR matric suction sensor.

Some of the TDR response curves had a "bump" in the valley portion of the curve. This suggests that air gaps may be present between the TDR probe and the ceramic in some of the sensors. The presence of air gaps significantly affected the resulting sensitivity of the TDR matric suction sensors.

The calibration curves of the TDR matric suction sensors constructed with an epoxy binder differed significantly from the theoretical calibration curve. The range of measurement was approximately 0 kPa to 40 kPa for the sensor constructed dry and 0 kPa to 150 kPa for the sensor constructed saturated.

The calibration curves for the second batch of TDR matric suction sensors constructed using a castone binder are plotted in Fig. (5). The theoretical calibration curve is also plotted in Fig. (5). The calibration curves vary only slightly with each other. The differences between these calibration curves are largest at 0 kPa and decrease with increasing matric suction. The calibration curves have the same shape as the theoretical estimate from ceramic 817d but there was a significant difference between the theoretical and actual values. The apparent dielectric constant of the sensors at saturation is much less than the theoretical value.

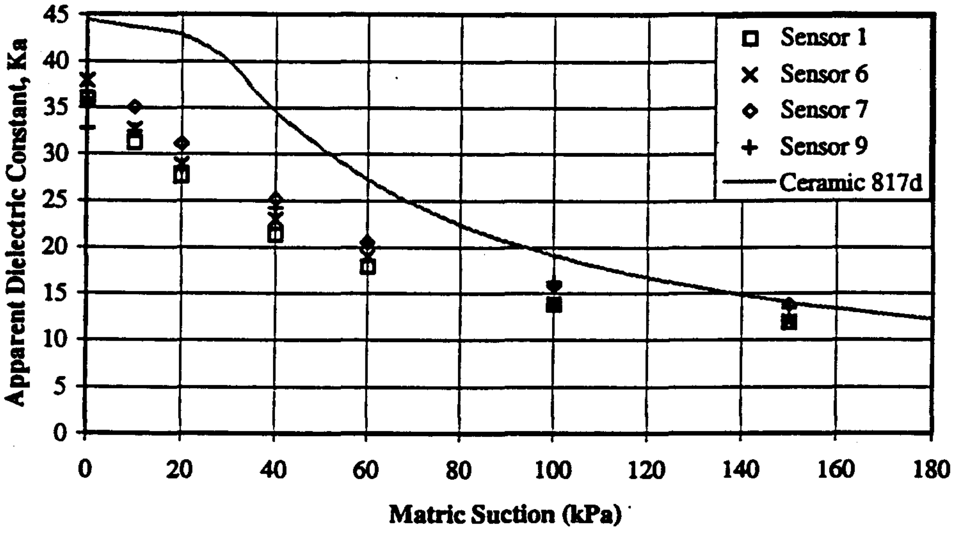

Fig. 5 Typical calibration curves from several TDR matric suction sensors plotted with the theoretical calibration curve.

These sensors compared the best overall with the theoretical calibration curve even though the apparent dielectric constants at saturation were less than the theoretical value. However, the lower measured apparent dielectric constant may be due to "skin effects" because the binder directly in contact with the probe wires had a lower water content and there were less gaps between the ceramic and the probe wires. There is further evidence that there are fewer air gaps in the castone binder sensors since the apparent dielectric constant decreases at a similar rate as the theoretical calibration curve.

Conclusions

Twelve time domain reflectometry matric suction sensors were developed at the University of Saskatchewan. The following conclusions are the result of the laboratory study undertaken as part of this research project. Recommendations are made for future research into TDR matric suctions sensors.

Ceramic Research

An acceptable ceramic material was created by using a combination of kaolinite, alumina, silica flour and ammonium carbonate. Control of the physical properties of the ceramic, specifically the soil-water characteristic curve, was gained primarily by combining powders of different grain sizes. The use of ammonium carbonate provided additional control of the soil-water characteristic curves. The effects of temperature and consolidation were minimal for the materials studied.

TDR Probe Research

Four different short-wire TDR probe configurations were constructed and researched. The four wire probe with a wire spacing of 10 mm was selected to use in the TDR matric suction sensors. The short-wire TDR probes had less than 5% error when measuring the apparent dielectric constant of distilled water. The TDR measurements taken in silt and till contained errors due to experimental procedures. Scatter in the data was also magnified due to "skin effects".

There was evidence that "skin effects" were greatest in the TDR probes that had a wire spacing of 10 mm. Data from the TDR probes with a larger wire spacing had less scatter since there was a larger volume of soil being measured. Scatter in the data from the probes with a 10 mm wire spacing was amplified by "skin effects".

The four wire probe with a 10 mm wire spacing was chosen for use in the TDR matric suction sensors. Data from this probe had less scatter than the three wire probe. The size of the ceramic required to contain the electromagnetic influence of the TDR probes was significantly smaller than what would be required for a probe with a 15 mm spacing. By limiting the ceramic volume, the cost of the sensor and the influence of the probe on the soil are reduced significantly.

TDR Matric Suction Sensor Research

Twelve TDR matric suction sensors were constructed and calibrated. The materials and methods used to insert and bind the TDR probe into the ceramic were found to affect the sensitivity of the resulting TDR matric suction sensor.

The TDR matric suction sensor constructed using a Portland cement binder worked well; however, the Portland cement did not bind well with the ceramic material and could be easily chipped. This sensor was calibrated from 0 kPa to 200 kPa in a modified tempe cell and remained sensitive to changes in matric suction in this range.

Epoxy was used as a binder material for two TDR matric suction sensors. These two sensors were constructed differently in that one ceramic sensor was left dry when the TDR probe was inserted and the other was saturated. The epoxy significantly affected the TDR response from the sensors since epoxy was absorbed into the ceramic. The TDR matric suction sensor constructed with a dry ceramic was only sensitive to changes in matric suction from 0 kPa to 40 kPa. The TDR matric suction sensor constructed with a saturated ceramic responded to changes in matric suction from 0 kPa to 150 kPa; however, the sensitivity was fairly poor.

Castone was used as a binder for several TDR matric suction sensors. Some of the sensors showed evidence of air gaps between the probe wires and the ceramic which significantly affected their performance. The first batch of TDR matric suction sensors constructed using a castone binder produced sensors with inconsistent measurement ranges. The measurement ranges for this batch of TDR matric suction sensors varied between 0 kPa to 60 kPa and 0 kPa to 150 kPa.

The second batch of TDR matric suction sensors were made with a castone binder; however, more detail was paid to reducing air gaps between the probe wires and the ceramic. The calibration curves of these TDR matric suction sensors plotted close together (Fig. 5). The calibration curves also compare well with the soil-water characteristic curve from ceramic specimen 817d. The measurement range for this batch of sensors was consistently 0 kPa to greater than 150 kPa. However, the TDR matric suction sensors will still require individual calibration.

Recommendations

Further research into TDR matric suction sensors should focus on reducing "skin effects" and improving the method used for constructing the sensors. The "skin effects" evident in the TDR probe used could be reduced by increasing the probe wire diameter. The larger diameter used may also reduce the probability of significant air gaps being trapped between the probe wires and the ceramic.

The ceramic material used for the TDR matric suction sensor has a desirable soil-water characteristic curve; however, the material is relatively soft. Therefore, research into an appropriate ceramic material should continue.

Further research on the TDR matric suction sensors produced should focus on the long term performance of the sensors since this could not be adequately researched during this project. Research into the response of the TDR matric suction sensors in the presense of contaminants should also be considered.

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