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A Small-Scale Matric Potential Sensor Based on Time Domain Reflectometry

Magnus Persson,* Jon M. Wraith, and Torleif Dahlin

ABSTRACT

Measurements of soil matric potential (ψ) are needed in many soil science applications. In the present study, a small matric potential sensor having a length of 30 mm and a diameter of 9.6 mm was developed. The sensor consists of two coils made of lacquer-coated copper wires embedded in gypsum. The dielectric constant of the gypsum (K_{gypsum}) was measured with time domain reflectometry (TDR). The gypsum probes were tested in a sandy loam soil using a pressure extractor to obtain the relationship between K_{gypsum} and ψ, allowing inference of the soil ψ in equilibrium with the sensor. It was shown that the gypsum probe could give ψ estimates with a root mean square error (RMSE) of around 50 kPa in the range of -20 to -1500 kPa. Most of the sensitivity of the sensor was in the -50- to -1000-kPa range.

S OIL MATRIC POTENTIAL is a key parameter in soil science. Measurements of ψ can be used to address questions including where and how fast water will flow in the unsaturated zone and how much of that water is available to plants. Soil matric potential is traditionally measured using tensiometers, which consist of a porous cup that is connected to a vacuum gauge through a water-filled tube. The vacuum gauge can be read manually or electronically using pressure transducers. Small-scale tensiometers with pressure transducers are commonly used in laboratory experiments as their readouts can easily be automated. However, they are rather expensive and small air bubbles can lead to measurement errors or require frequent maintenance. More importantly, tensiometers are typically limited to measurement in the range of ψ greater than -100 (Cassel and Klute, 1986). Gypsum blocks are also commonly used for ψ measurements. In these, the electrical conductivity is measured using two electrodes embedded in gypsum. The electrical conductivity of the gypsum is then related to ψ. Other matric sensors are also available, but a consistent issue is the limited wetness range over which these are operable.

Time domain reflectometry (TDR) is an electromagnetic method used for soil water content (θ) measurements. Typical TDR probes consist of two or three parallel metal rods. A minimum probe length of about 0.1 m is required to obtain suitable accuracy in θ measurements through travel time analysis. Or and Wraith (1999) and Noborio et al. (1999) presented TDR-based ψ sensors. These sensors utilized TDR to measure θ in a rigid porous

material and related it to ψ through calibration. The ψ of the porous probe material equilibrates with ψ of the surrounding soil, enabling inference of the latter attribute. However, these sensors (Or and Wraith, 1999; Noborio et al., 1999) were between 0.1 and 0.175 m long and around 0.03 m wide. In some applications, like in laboratory soil columns, there is a need for smaller sensors.

There are examples where small TDR probes have been used. Nissen et al. (1998) presented a TDR coil probe to reduce the physical probe length without affecting the effective length of the transmission line, and hence the accuracy. Persson and Wraith (2002) employed the same idea and developed a shaft-mounted probe only 0.03 m long. By combining the principles of the ψ sensors of Or and Wraith (1999) and Noborio et al. (1999) with a small-scale TDR probe design, it should be possible to construct small-scale TDR-based ψ sensors.

The objective of this study was to design and evaluate a small matric potential sensor based on time domain reflectometry. The following requirements were considered important: (i) it should be small enough to be suitable for small-scale laboratory and field studies, and to promote rapid equilibration with the soil; (ii) the start and end reflections of the TDR waveform should be easily recognized by standard waveform analysis algorithms; and (iii) it should be inexpensive and easy to manufacture.

MATERIALS AND METHODS

Design of the TDR Matric Potential Sensor

Several different coil probe designs using different sizes of copper wire were evaluated. Standard lacquer-coated copper wires were used for two reasons: i) to avoid short circuiting of the ground and conductor wires in the coil; and ii) to avoid problems with attenuation of the TDR signal due to the high electrical conductivity of the solution within the gypsum body. Several designs similar to the coil probes suggested by Nissen et al. (1998), where only the conductor wire is coiled and one or several ground wires are routed on the outside of the coil, were tested. Ground wires were included on both the outside and inside of the coil; however, as noted by Nissen et al. (1998), the end reflection of the TDR signal was difficult to determine unless three or more ground wires were used. Finally, we decided to coil both the ground and conductor wires. This led to a fairly rigid construction, where both the start and end reflections for travel time analysis were easily detectable. The distance between the turns in the coils was an important factor. If greater space was left between the turns, the probe was more sensitive to changes in the dielectric constant of the surrounding media. On the other hand, the total length of the probe increased.

Based on a number of tests, the following design was ultimately selected. Three 0.45-mm diam. of lacquer-coated copper wires were coiled tightly around a metal rod 3 mm in diameter. After wrapping, one of the copper wires was carefully removed,

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Abbreviations: RMSE, root mean squared error; TDR, time domain reflectometry.
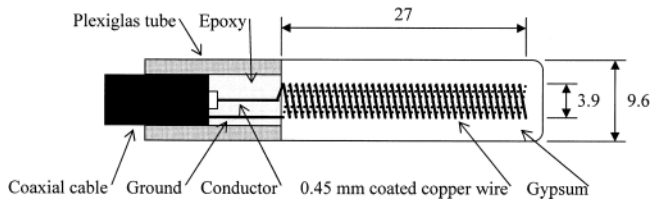
Fig. 1. Schematic design of the gypsum time domain reflectometry matric potential sensor; all measurements are in millimeters.

leaving about 0.225 mm of space between each turn of the remaining two wires. The two remaining coiled copper 'springs' were removed from the metal rod and a drop of general purpose glue was applied near the top and bottom of the springs to secure them together. The total length of the springs was 0.027 m, each consisting of a 0.20-m length copper wire. The ends of the copper springs were soldered to the conductor and ground of RG58 coaxial cable. A small piece of Plexiglas tubing with an inner diameter slightly larger than the coaxial cable was positioned so that it covered the cable end and the solder connections, and extended to the proximal end of the springs. The tube was then filled with epoxy to provide a rigid and watertight connection between the cable and springs.

The paired copper springs were then embedded in gypsum (plaster of Paris). The gypsum was prepared by mixing 100 g of gypsum powder and 50 g of water. A cast was made from the severed finger of a vinyl laboratory glove. To avoid air bubbles and achieve uniform contact between the copper wires and the gypsum, the gypsum was slowly injected into the center of the copper springs using a syringe. Finally, the surface of the cured gypsum was smoothed using sand paper. The final design is shown in Fig. 1. Four prototypes of the gypsum TDR probe were constructed, referred to here as GP1 through GP4.

Calibration

Before embedding the copper springs in gypsum, a series of measurements were made to relate the measured effective dielectric constant (K_{eff}) and the dielectric constant of the surrounding medium (i.e., gypsum, K_{gypsum}). This was achieved by taking 15 measurements in five different fluids (ethyl acetate, ethanol, 75% ethanol mixed with 25% water [v/v], 50% ethanol in water, and water) and in air with the lacquered copper spring probes. Reference measurements of surrounding media (K_{surr}) were made using two standard 0.2 m long three-rod TDR probes. All measurements were completed using a Tektronix 1502C cable tester with RS232 interface (Tektronix, Beaverton, OR) connected to a laptop computer. K_{eff} estimates were calculated from the TDR trace using WinTDR software (Or et al., 2003), using an effective probe (wire) length of 0.20 m.

The K_{eff} measured by the spring probe depends not only on the media surrounding the probe (K_{surr}), but also on the lacquer wire coating (K_L). To relate K_{eff} to K_{surr} a two-phase dielectric model was used (see Ferré et al., 1996):

$$K_{eff}^a = wK_L^a + (1-w)K_{surr}^a \qquad [1]$$

where w is a weighting factor describing the fractional contribution of the lacquer dielectric constant, and the exponent a summarizes the geometry of the medium with relation to the applied electrical field. The value of K_L was set to 2.8 based on Nissen et al. (1998). When the springs are embedded in gypsum, K_{surr} is replaced with the dielectric constant of gypsum (K_{gypsum}).

To obtain a relationship between K_{gypsum} and ψ, a series of measurements were completed in a pressure extractor. Plexiglas frames were filled with a sandy loam soil (68% sand, 27% silt, 5% clay). The frames were 0.08 m long 0.05 m wide, and

0.036 m high and had two holes in the front wall allowing for insertion of two gypsum probes. The samples were placed in a 1500-kPa pressure plate extractor (Model 1500, Soilmoisture Equipment Corp., Santa Barbara, CA) for several days up to a week until equilibrium was reached. Then, the pressure extractor was opened and ten measurements were completed and averaged for each gypsum probe and applied pressure. A higher pressure was then applied and the procedure was repeated until the pressure reached the porous plate limit (bubbling pressure). Three plates were used, having bubbling pressures of −100, −300, and −1500 kPa. When the bubbling pressure was reached, the sample was removed from the extractor and discarded and a new soil sample was prepared. Two separate runs were made on each plate. In total 13 different pressures were applied in the range between 0 and −1500 kPa.

The relationship of Noborio et al. (1999), similar to the van Genuchten (1980) water retention model, was used to describe the relationship between K_{gypsum} and ψ:

$$K_{gypsum}(\Psi) = K_r + (K_s - K_r)\left[\frac{1}{(1 + |\alpha\Psi|)^n}\right]^m \qquad [2]$$

where K_s and K_r are the dielectric constants at saturation and residual water contents, and α, n, and m are empirical calibration coefficients. For K_s and K_r we used the measured K_{gypsum} when the probes were submerged in water and when air dry, respectively. Since the van Genuchten model originally was developed for water contents and since the relationship between the square root of K and water content is linear, one would expect that using the square root of K in Eq. [2] would result in a better fit. However we found that using Eq. [2] gave almost identical results as when the square root of K was used (data not shown). We chose to use the same equation as in Noborio et al. (1999) to facilitate the comparison between our studies.

RESULTS AND DISCUSSION

Calibration

The parameters w and a of Eq. [1] were obtained using nonlinear regression. The optimized a and w values for the four probes are presented in Table 1. As expected, the a value is rather close to −1.0, which is valid for the case where the electrical field is perpendicular to layers of dielectrics. Differences of a and w between the probes are probably due to small differences in length of the copper wires (0.20 m ± a few millimeters) and separation distance between each turn of the copper springs. In Fig. 2, the measured K_{eff} for bare (no gypsum) spring probes is plotted against K_{surr} measured by the reference probes.

The final paired copper springs design always provided a very distinct TDR trace (Fig. 3). The travel time analysis start and end points were easily detected by the WinTDR software at all encountered K_{gypsum}.

Table 1. Best-fit parameters of sensors GP1 to GP4 to Eq. [1], based on nonlinear regression.

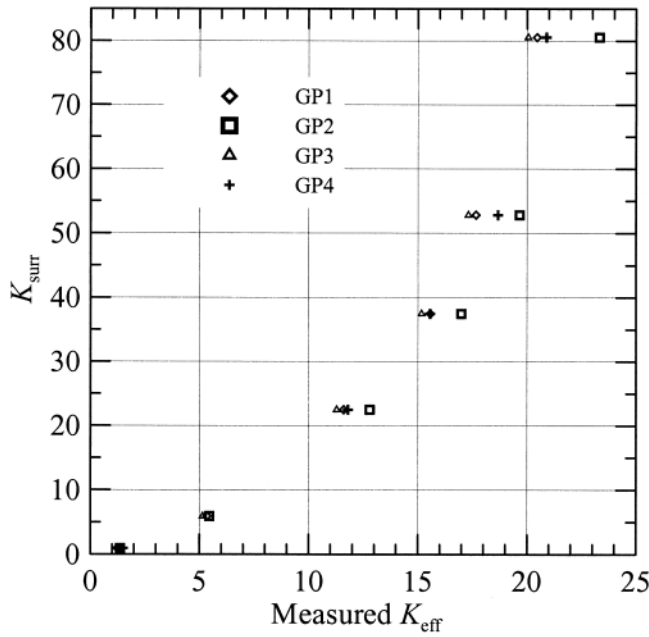| Probe	a	w	r^2
GP1	−0.723	0.162	0.9959
GP2	−0.702	0.145	0.9997
GP3	−0.680	0.179	0.9992
GP4	−0.825	0.136	0.9947

Fig. 2. Measured effective dielectric constant K_{eff} for the four coiled probes before adding gypsum, versus the reference dielectric constants of the surrounding media measured in five different fluids and air.

We also examined the variability of the K_{surr} measurements. This was done by using the measured K_{eff} and the best-fit parameters of w and n to calculate the K_{surr} for each of the 15 measurements in each fluid. Then, the standard deviation of the K_{surr} estimation could be calculated. The standard deviations of our spring probes were similar to those of standard 0.20 m long three-rod probes (around 0.002 for air and 0.03 for water).

Root mean square error across the calibrated wetness range (-1500 to -20 kPa) was about 50 kPa (Table 2). The measurements using GP4 were discarded since the first reflection of the probe gradually moved to the right in the TDR trace. Probably there was a small leak in the probe head, which allowed water to penetrate the solder-

Table 2. Best-fit parameters of sensors GP1 to GP3 to Eq. [2].

Probe	K_r	K_s	α	n	m	r^2	RMSE kPa
GP1	3.14	22.20	0.802	1.988	0.543	0.987	49.6
GP2	3.29	22.94	0.101	0.978	3.745	0.987	50.7
GP3	3.91	30.98	0.697	0.960	1.236	0.986	52.3

ing and the cable. Since we are dealing with such a large span in ψ, the RMSE is not a good indicator of the accuracy. If instead we looked at the relative error we found that it was around 10% in average and displayed a slight decreasing trend with decreasing pressure. Noborio et al. (1999) found a slightly higher accuracy for their probe. The accuracy of our probe design is also similar to the one for gypsum blocks. The main advantage of our design compared with gypsum blocks is that it is less sensitive to temperature changes since the K measurement is less temperature dependent compared with the electrical conductivity.

The measurements in the pressure extractor using GP1 through GP3 are presented in Fig. 4. The three probes showed a similar response to ψ with the exception of GP3 at ψ higher than about -50 kPa. A possible explanation might be that a small air bubble was trapped inside the copper coils when casting. At high ψ this void would fill with water causing an overestimation of K_{gypsum}. It is interesting (and reassuring) to note that the relationship between K_{gypsum} and ψ is similar to the one presented by Noborio et al. (1999), the only difference is that it is shifted slightly to the right. It is likely that some variation in the relationship shown in Fig. 4 is due to consecutive insertion of the probes in three different soil frames for the -100, -300, and -1500 kPa plates during the calibration procedure. Hysteresis (i.e., at a fixed soil water potential, the sensor can display different ψ when wetting than when drying) is a problem in all cases where water content is measured in a porous media. The effect of hysteresis was not studied for our probe, but it is likely that this will affect the accuracy.

In the present study, we first calibrated the copper springs using Eq. [1] so that K_{gypsum} could be calculated. However, this step can be omitted by using the measured
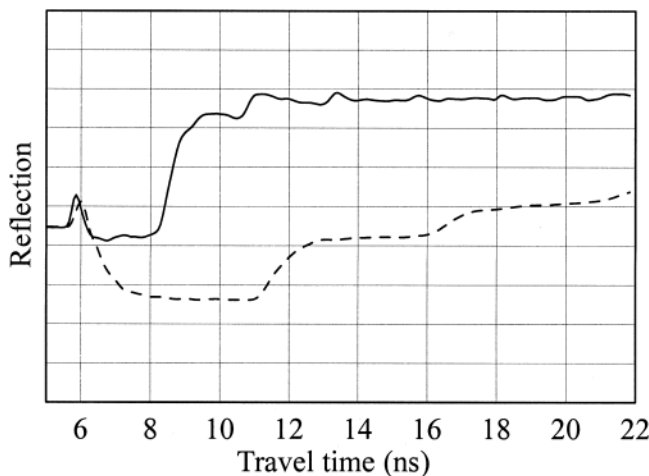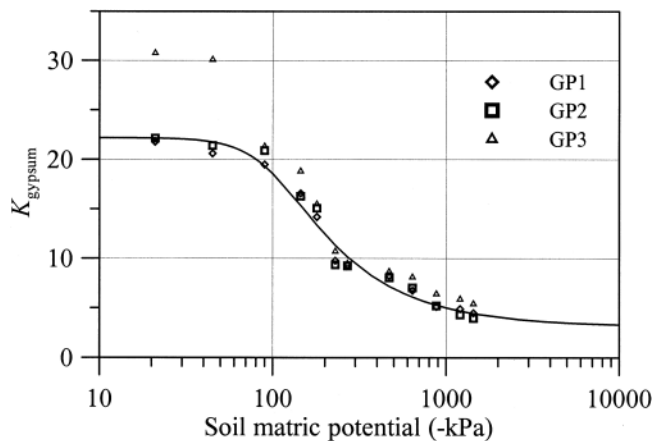

Fig. 3. Typical TDR traces of the gypsum TDR probes. The two traces are from measurements in air dry (solid line) and water saturated (dotted line) gypsum using probe GP1.

Fig. 4. Measured dielectric constant of three gypsum probes (GP1–GP3) plotted vs. soil matric potential ψ. The solid line is the modeled relationship using Eq. [2] with parameters calibrated using the GP1 measurements (Table 2).

K_{eff} instead of K_{gypsum} in Eq. [2]. Doing so, the real K_{gypsum} is never known, but the accuracy of the ψ estimations are almost identical (data not shown) to those calculated using the approach presented here.

The exact size and shape of the sampling volume of the new probes is not known. However, it is likely that it doesn't extend more than a few millimeters outside the coil and that the volume inside the coil has the highest influence of K_{eff}. An evaluation was conducted whereby the copper spring probe (before embedding it in gypsum) was put inside a small water-filled Plexiglas tube with an inner diameter of 6 mm. The measured K_{eff} was about 99% of K_{eff} when the probe was immersed in water. Thus, the gypsum surrounding the probe should contain virtually the entire effective measurement volume. It should be noted though that the sampling volume will vary with K. For higher K values the sampling volume will be more restricted (Ferré et al., 1998). Because the small volume of gypsum should equilibrate rapidly with soil wetness, the variable sample volume (i.e., sensitivity) should not affect the measurement accuracy.

Any porous materials that can be cast can be used as retention media for coating TDR matric probes. Gypsum was used since it is inexpensive and readily available and it has a wide range of pore sizes leading to a rather broad relationship between K_{gypsum} and ψ. The pore-size distribution of the gypsum can be somewhat modified when casting, with a higher water/gypsum ratio resulting in smaller average pore size. The main disadvantage with gypsum is that it degrades relatively rapidly in soils.

CONCLUSIONS

A new small and inexpensive TDR-based matric potential sensor that functions over almost the entire plant-available water range was developed. The sensor consists of paired coiled copper wires embedded in gypsum, and is easy to manufacture. The coiled copper wires design was selected to produce a compact physical size, and so that the TDR trace exhibits easily detectable start and end reflections, which facilitates TDR travel time analysis using available software. Pressure extractor measurements with a sandy loam soil provided a relationship between ψ and K_{gypsum}, with RMSE for ψ measurements of about 50 kPa over the calibrated range of -20 to -1500 kPa. Most of the sensitivity of the sensor was in the -50- to -1000-kPa range. The sensors can easily be automated, and multiple sensors can be arrayed using standard TDR signal multiplexers. They can be used alone or in concert with standard TDR probes to simultaneously measure water content and electrical conductivity. The small probe size should contribute to rapid equilibration with changing soil wetness, and is suitable for many applications that require a small sample volume. Examples of potential applications are in laboratory studies using small soil columns or two-dimensional flow cells.

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