Measurement of soil bulk electrical conductivity in saline soils and solutions using TDR probes partially coated with high-dielectric material

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ABSTRACT

Time Domain Reflectometry (TDR) is a valuable technique that allows simultaneous estimation of the apparent permittivity ($\varepsilon_a$) and the bulk electrical conductivity ($\sigma_a$). However, in highly conductive media the signal is completely attenuated which precludes permittivity measurements. This paper shows that $\sigma_a$ can be estimated in conductive media by applying the long-time TDR waveform analysis to a TDR probe partially insulated with a high-dielectric coating. Four 10-cm-long three-rod TDR probes with identical geometry but different percentages of rod-coating were tested: an uncoated sensor ($P_0$) and probes with 50% ($P_{50}$), 75% ($P_{75}$) and 95% ($P_{95}$) of the rod-length, respectively, coated with an insulator with a relative permittivity ($\varepsilon_r$) equal to 32.3. A good relationship ($r^2 = 0.99$) was found between the $\varepsilon_a$ estimated, if possible, with $P_0$ immersed in several conductive and nonconductive media and the corresponding values estimated with $P_{50}$, $P_{75}$ and $P_{95}$. The cell constant value (m$^{-1}$) for $P_0$ (5.10), $P_{50}$ (9.60), $P_{75}$ (16.92) and $P_{95}$ (51.31), which were experimentally determined in different NaCl-water solutions, were on average 10% greater than the corresponding values calculated using a numerical model. The results show that, for $\sigma_a$ values ranging between 0.4 and 0.75 S m$^{-1}$, simultaneous measurements of $\varepsilon_a$ and $\sigma_a$ were only possible using the partially coated probes. A good correlation was found between the $\sigma_a$ estimated with $P_0$ inserted in different soil columns wetted with highly saline solutions (i.e. $\sigma_a > 0.2$ S m$^{-1}$) and those values estimated with $P_{50}$, $P_{75}$ and $P_{95}$ ($R^2 = 0.96$, RMSE = 1.08 and SD = 0.38). For $\sigma_a$ values lower than 0.2 S m$^{-1}$ the accuracy of the partially coated TDR probes for estimations of $\sigma_a$ decreases.
as increases the percentage of the rod-coating, with errors up to 292% when $\sigma_a$ determined by $P_{95}$ was compared to that estimated by $P_0$.

Abbreviations: DC, direct current; TDR, time domain reflectometry.
Time domain reflectometry (TDR) is a non-destructive method that allows, in real time, simultaneous estimation of both the apparent permittivity ($\varepsilon_a$), which is a function of the volumetric soil water content ($\theta$), and the bulk soil electrical conductivity ($\sigma_a$) (Topp and Ferré, 2002). While $\varepsilon_a$ depends on the transit time of the electromagnetic pulse along a transmission line, $\sigma_a$ is estimated from the attenuation of the reflection coefficient $\rho$ (Topp and Ferré, 2002). Topp et al. (1988) found, using uncoated probes, that $\sigma_a$ could be estimated by analysing the amplitude of the long-time TDR signal according to the Giese and Tiemann (1975) model. In this case, the effects of the dielectric dissipation (resulting from polarization phenomena) vanish, and the value of the reflection coefficient after all multiple reflections have disappeared is linearly related to the direct current (DC) conductivity (Topp et al., 2000).

Castiglione and Shouse (2003) and Castiglione et al. (2006) improved this method and observed that dissipation due to cable losses and multiplexer-induced interference should be considered in the calibration of the Topp et al. (1988) method, since otherwise appreciable errors in the $\sigma_a$ determination at low values of electrical conductivity can be made. More recently, Lin et al. (2008) presented a rigorous full-waveform analysis for estimating bulk electrical conductivity by taking into account cable resistance.

Measurements of water content with uncoated TDR probes are restricted to low values of $\sigma_a$ (e.g. 0 to 0.5 S m$^{-1}$; Nichol et al., 2002), since in highly conductive conditions the attenuation of the TDR signal makes the end of the reflection disappear, and $\varepsilon_a$ is then not measurable (Topp and Ferré, 2002). This effect can be lessened if the rods of the TDR probe are coated with an insulating material (Ferré et al., 1996). Fujiyasu et al. (2004) found that high relative-permittivity (high-$\varepsilon_r$) coatings ($\varepsilon_{r-coat} \approx 35$) allowed measurements of $\varepsilon_a$ in highly conductive media without reducing the sensitivity of the TDR probe. In this case, a single $\varepsilon_a$ vs. $\theta$ calibration curve is required. However, the coating material of the TDR probes, which blocks
the DC current flow through the sensed material, prevents estimations of $\sigma_a$ using the Topp et al. (1988) method. This restriction was partially solved by Moret-Fernández et al. (2009), who demonstrated that $\sigma_a$ could be estimated by applying the Dalton et al. (1984) procedure, which analyses the one return trip of the TDR pulse along the transmission line, to a TDR probe insulated with a high-$\varepsilon_r$ coating. Although this method allows satisfactory measurements of both $\varepsilon_a$ and $\sigma_a$ in highly conductive media, this analysis presented several limitations since: (i) it does not take into account the impact of multiplexers (Castiglione et al., 2006) and cable length (Robinson, et al., 2003) on $\rho$, (ii) it does not ignore the effect of the dielectric losses on the $\sigma_a$ estimations when highly lossy soils (e.g. clay) are used (Logsdon, 2005), and (iii) it requires a coating calibration which becomes less sensitive to changes in $\sigma_a$ with increasing $\sigma_a$.

The objective of this research is to demonstrate that $\sigma_a$ can be estimated in highly conductive media by applying the Castiglione and Shouse (2003) TDR waveform analysis to a 10-cm-long three-rod TDR probe partially insulated with a high-$\varepsilon_r$ coating. The $\sigma_a$ estimated with three TDR probes with identical geometry but different percentages of rod-length coating (50, 75 and 95%), immersed in different water-saline solutions and in a sand column and in loam, gypsum-silt loam and silty clay loam soil columns with different values of $\theta$ and $\sigma_a$, was compared to the corresponding values estimated with an uncoated TDR probe of identical geometry.

**MATERIALS AND METHODS**

**Theory**
The TDR waveform is expressed by the voltage \( (V) \) or reflection coefficient \( (\rho) \) as a function of time \( (t) \) (Fig.1). The transit time of the TDR pulse propagating one return trip in a transmission line of length \( L \) (m), \( t_L \), is expressed by

\[
t_L = \frac{2L}{c} \sqrt{\frac{\epsilon_a}{\epsilon_0}}
\]  

[1]

where \( c \) is the velocity of light in free space \( (3 \times 10^8 \text{ m s}^{-1}) \) and \( \epsilon_a \) is the apparent permittivity of the medium (Topp and Ferré, 2002). Commonly, \( t_L \) is obtained from the TDR waveform (Fig. 1) and \( \epsilon_a \) is related to the volumetric water content, \( \theta \), through the empirical Topp et al. (1980) formula, which remains widely used.

The reflection coefficient, \( \rho \), as a function of time, \( t \), is typically defined as

\[
\rho(t) = \frac{V(t) - V_0}{V_0 - V_i}
\]

\(-1 \leq \rho \leq +1\)  

[2]

where \( V(t) \) is the measured voltage at time \( t \), \( V_0 \) is the voltage in the cable just prior to the insertion of the probe (standard impedance value of 50 \( \Omega \)), and \( V_i \) is the incident voltage of the cable tester prior to the pulse rise.

As an electromagnetic signal propagating in conductive media, the TDR waveform undergoes attenuation. On the basis of the Giese and Tiemann (1975) thin-layer method, Topp et al. (1988) found that, for ideal systems where dissipation only occur in the sample medium, the sample electrical conductivity, \( \sigma_a \) (S m\(^{-1}\)), recorded with an uncoated twin-rod TDR probe, can be related to the long-time attenuation of the TDR signal, where the effects of the dielectric dissipation caused by polarization phenomena vanish. Castiglione and Shouse (2003) showed that, due to the dissipation produced by the coaxial cable, probe handle or other devices (such as multiplexers and transient suppressors), the \( \sigma_a \) estimated with an uncoated probe is more accurately estimated according to
\[
\sigma_a = \frac{K_p}{Z_r} \left( \frac{\rho_{\text{air}} - \rho_f}{\rho_f - \rho_{\text{sc}}} \right)
\]

where \(\rho_f\), \(\rho_{\text{air}}\) and \(\rho_{\text{sc}}\) are the long-time reflection coefficient measured in the studied medium, in the air and in the short-circuited probe, respectively (Fig. 1). The \(Z_r\) is the output impedance of the TDR cable tester (50 \(\Omega\)), and \(K_p\) (m\(^{-1}\)) is the probe-geometry-dependent cell constant value, which can be determined by immersing the probe in different electrolyte solutions of known conductivity (Wraith, 2002).

**Experimental design**

The TDR measurements were performed using a Tektronix model 1502C cable tester. A 1.2-m 50-\(\Omega\) coaxial cable connected the TDR probes to the TDR pulser, and the TDR waveforms were transferred to a computer for display and analysis using the software WinTDR’98 (Or et al., 1998), which automatically calculates the reflection coefficient for an incipient voltage, \(V_i\), (Eq.[2]) equal to zero. Four three-rod TDR probes of identical geometry (rod length: 100 mm; rod diameter: 4 mm; spacing of the outer conductors: 40 mm) but with different percentages of rod-length coating were compared: an uncoated sensor (\(P_0\)) and a probe with 50% (\(P_{50}\)), 75% (\(P_{75}\)) and 95% (\(P_{95}\)) of the rod-length insulated with a high-\(\varepsilon_r\) material (Fig. 2).

The coating consisted of a 0.2-mm-thick high-\(\varepsilon_r\) material made with a mixture of epoxy resin (10% vol.), graphite powder (25% vol.) and BaTiO\(_3\) (65% vol.). The stainless steel rods of the partially coated TDR probe were insulated by rotating the rods, with the uncoated section cover with an adhesive tape, on a 12-cm-long and 2-cm-wide film of the wet mixture placed on a flat surface. The measured relative permittivity of the mixture, \(\varepsilon_{r-coat}\), was 32.3 at 100 kHz, and the DC electrical conductivity of the coating was less than 3 \(\times\) 10\(^{-7}\) S m\(^{-1}\). More
details of the resin + BaTiO$_3$ + graphite powder commercial materials used in the experiment together with its sensitivity for $\varepsilon_a$ estimations are described in Moret-Fernández et al. (2009).

A first experiment was performed to estimate the cell constant value (Eq. [3]) of the different TDR probes ($K_{pm}$). The four probes, directly connected to the TDR cable tester without using a multiplexer, were immersed in a cylindrical clear plastic container (30 cm in internal diameter and 30 cm in height) filled up with deionized water and eight different NaCl-water solutions with an electrical conductivity ($\sigma$) equal to 0.01, 0.05, 0.1, 0.2, 0.5, 0.75, 1.0 and 1.5 S m$^{-1}$ at 25 °C. The $K_{pm}$ values were then calculated by applying to Eq. [3] the $\rho_f$ values recorded for the different probes immersed in the above-mentioned NaCl-water solutions and the corresponding $\sigma$ values measured with an electrical conductivity cell (Crison Instruments, model conductimeter 522).

The cell constant ($K_{pc}$) of each probe was also calculated numerically by solving, in DC conditions, the corresponding current conduction problem by the finite elements method. A short probe 3D model, which was developed with a commercial finite element software package (Multiphysics with AC/DC module V3.4) that takes into account fringe fields, was set up with an idealized geometry based on the real measuring system. The model consisted of a cylindrical domain (30 cm in diameter and 15 cm in height) with 1 S m$^{-1}$ conductivity, from which the volume of the probes, modelled as 98-mm-long, 4-mm-diameter cylinders with half spherical tips, was subtracted. The resulting volume was meshed to obtain a grid of over 1,250,000 nodes, finer close to the probe rods and coarser towards the container walls. The boundary conditions on all surfaces were first set to electrical insulation (current density flowing parallel to the surfaces). Then, in each case, the boundary conditions on the exposed metallic surface of the rods were modified to ground (zero) potential and to floating potential with a total injected current of 1 A for the side and centre rods respectively. The resulting linear finite element problem was solved by the conjugate gradient method to obtain the value
of the centre electrode floating potential, which is directly $K_{pc}$ for the selected conditions (1 S/m domain conductivity and 1 A applied current). The experimental $K_{pm}$ was subsequently compared to the numerically calculated cell constant $K_{pc}$.

A second experiment, using a sand column wetted with different NaCl-water solutions, was performed to compare the $\sigma_a$ values estimated with $P_0\left(\sigma_{aP_0}\right)$ and the corresponding values obtained with the $P_{50}\left(\sigma_{aP_{50}}\right)$, $P_{75}\left(\sigma_{aP_{75}}\right)$ and $P_{95}\left(\sigma_{aP_{95}}\right)$. The column consisted of a clear plastic tube (30 cm in internal diameter and 30 cm high) with the base covered with a 20-μm mesh nylon cloth. The tube was packed with air-dry sand (80-100 μm grain size) by hand, up to a height of 15 cm, pouring and gently tapping the sand in small incremental steps to achieve a uniform bulk density. The 10-cm-long sensors were vertically inserted into the sand column, the probe heads rested at the top of the container, and the rods were separated at least 5 cm from the wall of the container to avoid distortions during the measurements. Next, the sand column was wetted with deionised water from the top using a drip irrigation system until the water started to drain through the base of the column. Once the sand was wetted, the top of the column was hermetically closed and connected to an air pressure system. The sand water was drained by injecting air into the container at fixed pressures and time intervals. Four different $\theta$ values ($\theta \approx 0.40, 0.35, 0.25, 0.20$ m$^3$ m$^{-3}$) were obtained and the TDR signal of the different TDR probes was recorded for the different values of volumetric water content.

The same experiment was repeated using three different NaCl-water solutions with an electrical conductivity of 0.5, 1.0 and 2.0 S m$^{-1}$ at 25ºC. A salt-free and air-dry sand column was prepared for each water solution. The bulk electrical conductivity of the sand column was considered uniform when the electrical conductivity of the drained water equalled that used for wetting the sand. A similar experiment was repeated in a 2 mm sieved loam, gypsum-silt loam and silty clay loam (Table 1) soil at saturated conditions. The gypsum-silt loam soil was
saturated with deionized water and the loam and silty clay loam soils were wetted with three different NaCl-water solutions of 0, 0.5 and 1.0 S m$^{-1}$ at 25ºC. An additional NaCl-water solution of 1.5 S m$^{-1}$ was also applied to the silty clay loam soil. Finally, the $\sigma_a$ for the different TDR probes was calculated by applying to Eq. [3] the $K_{pm}$ factor obtained in the NaCl-water solution experiment and the $\rho_f$ measured by the four TDR probes inserted in the different soil columns.

In order to determine the sensitivity of the high-$\varepsilon_r$ coating of the different probes for estimating the apparent permittivity, the $\varepsilon_a$ (Eq. [1]) measured by the $P_0$ immersed in media with different values of $\varepsilon_a$ and $\sigma_a$ (air, dry sand, distilled water and the sand and soils above described) was compared to the corresponding $\varepsilon_a$ values estimated with $P_{50}$, $P_{75}$, and $P_{95}$. To this end, the WinTDR 6.1 (Or et al., 2004) software, which allows recalculating the $\varepsilon_a$ values from the recorded TDR waveform, was also used.

**RESULTS AND DISCUSSION**

The apparent permittivity, $\varepsilon_a$, estimated, if possible, with the 10-cm-long $P_0$ immersed in air, dry sand, distilled water and in the sand column and the loam, gypsum-silt loam and silty clay loam columns with different values of $\theta$ (from 0 to 0.45 m$^3$ m$^{-3}$) and $\sigma_a$ (between 0 and 0.5 S m$^{-1}$) was highly correlated with the corresponding values measured with $P_{50}$, $P_{75}$, and $P_{95}$ (Fig. 3). As observed by Fujiyasu et al. (2004) in similar research, the result indicates that, for a typical apparent permittivity range of soils ($5 < \varepsilon_a < 35$), the estimation of $\varepsilon_a$ with a partially coated TDR probe is not strongly influenced by the high-$\varepsilon_r$ coating.

The negligible differences observed between the TDR waveforms recorded by the four TDR probes immersed in deionised water (Fig. 4) indicate that the high-$\varepsilon_r$ coating has a low influence on the $\varepsilon_a$ estimation. In conductive media, the attenuation of the second reflection
point, which increases with $\sigma_a$, decreases as the percentage of the rod-coating increases (Fig. 4). Thus, while complete attenuation of the TDR waveform is observed in $P_0$ at approximately 0.4 S m$^{-1}$ (e.g. loam or silty clay loam soils with $\sigma_a$ equal to 0.43 and 0.47 S m$^{-1}$, respectively), a weak but visible second inflection point is observed in the $P_{50}$, $P_{75}$ and $P_{95}$ TDR signals. A comparison between the TDR waveforms recorded by the $P_0$ and $P_{95}$ probes inserted in the sand column wetted with a NaCl-water solution of 0.5 and 2.0 S m$^{-1}$ shows that the $P_{95}$ is the only probe that presents, in highly conductive media (e.g. sand with a saline solution of 2.0 S m$^{-1}$), a positive slope after the second reflection point of the TDR waveform (Fig. 5). The comparison between the $\varepsilon_a$ estimated by the different probes from the TDR waveforms showed in Fig. 4 (Fig. 6) shows that, for low $\sigma_a$ values (i.e. distillate water and the sand and the gypsum soil with $\sigma_a$ equal to 0.29 and 0.09 S m$^{-1}$, respectively), the differences among the $\varepsilon_a$ estimated with the four probes was very small (SD ranged between 0.17 and 3.27). For higher $\sigma_a$ values (i.e. water and loam soil with $\sigma_a$ = 0.5 and 0.43 S m$^{-1}$, respectively) the $P_0$ tended to overestimate the $\varepsilon_a$, due to the time in the second reflection point increased with the attenuation of the TDR waveform (Fig. 4). Finally, for the highest values of $\sigma_a$ (i.e. water and silty clay loam soil with $\sigma_a$ equal to 0.75 and 0.47 S m$^{-1}$, respectively) the complete attenuation of the second reflection point for the $P_0$ prevented the determination of $t_L$ (Fig. 1) and consequently the estimations of $\varepsilon_a$. In these cases only the $P_{75}$ and $P_{95}$ allowed satisfactory estimations of the apparent permittivity (Fig. 6). These results would indicate that the partially coated TDR probe can measure $\varepsilon_a$ for $\sigma_a$ values for which uncoated probes are not operative.

The TDR waveforms at long time, recorded with $P_0$, $P_{50}$, $P_{75}$ and $P_{95}$ immersed in nine different NaCl-water solutions, with $\sigma$ values ranging between 0 and 1.5 S m$^{-1}$, show that the magnitude of the $\rho$ attenuation in conductive conditions decreases as the percentage of the rod coating increases (Fig. 7). The $K_{pm}$ value of the different TDR probes estimated from the
NaCl-water solution experiment by applying the corresponding measured $\sigma$ and $\rho_f$ values to Eq. [3] increases exponentially with the percentage of the rod-coating (Table 2). The excellent correlation observed between the electrical conductivity measured with the conductivity meter and the corresponding values estimated with $P_0$, $P_{50}$, $P_{75}$ and $P_{95}$ immersed the different NaCl-water solutions (Table 3) indicates that the $K_{pm}$ values estimated for the different partially coated TDR probes are consistent enough to determine the bulk electrical conductivity. However, the comparison between the $K_{pm}$ and the cell constant values calculated with a numerical model ($K_{pc}$) shows that on average the $K_{pm}$ was about 10% higher than the modelled values (Table 2). These differences might be explained by deviations of the real probes from the ideal conditions assumed by the model, due to losses in the transmission lines, non-ideal generator output impedance, variations from the ideal probe geometry - sharper tips and/or edges would lead to fringe fields larger than the estimated- and finite time data.

Overall, a satisfactory relationship was found between the $\sigma_{a_{P_0}}$ estimated in the sand column and in the loam, gypsum-silt loam and silty clay loam soil columns wetted with different NaCl-water solutions and the corresponding $\sigma_a$ values estimated with $P_{50}$, $P_{75}$ and $P_{95}$ for the $K_{pm}$ values (Table 2) calculated in the NaCl-water solution experiment (Fig. 8). The poorer correlation observed in the soil columns experiments (Table 4) when compared to those obtained in the NaCl-water solution experiment (Table 3) may be explained by a less uniform distribution of $\sigma_a$ along the soil column, which would entail that the average $\sigma_{a_{P_0}}$ did not exactly correspond to the $\sigma_a$ values estimated by the $P_{50}$, $P_{75}$ and $P_{95}$ probes. On the other hand, for $\sigma_a$ values lower that 0.2 S m$^{-1}$, the error level of the different partially coated probes, calculated as the relative difference between $\sigma_{a_{P_0}}$ and the $\sigma_a$ estimated by the $P_{50}$, $P_{75}$ and $P_{95}$, increases with the percentage of rod-coating (55, 106 and 292% for $P_{50}$, $P_{75}$ and $P_{95}$, respectively). This behaviour should be related to the influence of the coating on the
attenuation of the long-term TDR waveform with $\sigma_a$. At low values of $\sigma_a$, the attenuation range of the TDR signal decreases as the percentage of rod-coating increases (Fig. 7), which prevents accurate estimations of $\rho_f$ (Fig. 1). These results indicate that, for low $\sigma_a$ values (i.e. $\sigma_a < 0.2 \text{ S m}^{-1}$), the TDR probes highly partially coated (i.e. P75 and P95) are not adequate for accurate estimations of $\sigma_a$.

The above results suggests that the Castiglione and Shouse (2003) method can be satisfactorily applied to partially coated TDR probes for estimations of $\sigma_a$ in highly conductive media since, unlike the Dalton et al. (1984) analysis applied to high-$\varepsilon_r$ coated probes (Moret-Fernández et al., 2009), (i) the partially coated probes allow estimations of $\sigma_a$ for $\sigma_a$ ranges similar to those obtained with the coated sensors, (ii) estimations of $\sigma_a$ are not affected by the $t_L$ vs. $\sigma_a$ dependence, as a result of which the $t_L$ value increases with the bulk electrical conductivity (Nichol et al., 2002; Evett et al., 2005), and (iii) the long-time TDR signal analysis, which runs at low frequency, minimizes the effect of the dielectric losses on the $\sigma_a$ estimation. However, some care should be taken when using the partially coated TDR probe since estimations of $\sigma_a$, which are restricted to a specific soil depth interval, may not always correspond with the average $\sigma_a$ estimated with $P_0$. This limitation could be minimized by designing alternative TDR probes where short uncoated rod-sections are uniformly distributed along the TDR wires. Finally, the partially high-$\varepsilon_r$ coated TDR probes can offer new applications for soil science since, unlike the uncoated probes, the partially coated sensors (e.g. P95) may be a plausible method for estimations of $\sigma_a$ at specific soil depth intervals.

**CONCLUSIONS**

This paper demonstrates that the $\sigma_a$ can be estimated in highly conductive media by applying the long-time TDR waveform analysing to a 10-cm-long three-rod TDR probe
partially insulated with a high-εᵣ coating. The results showed that the partially coated probe is a good solution for achieving simultaneous, accurate and consistent estimations of both εᵣ and σᵣ in highly conductive media. Afterwards, θ can be determined using a specific θ(εᵣ) model. For low values of bulk electrical conductivity (i.e. 0.2 S m⁻¹), however, the accuracy of the partially coated TDR probes for σᵣ estimations decreases as the percentage of the rod-coating increases. Since estimations of σᵣ with the partially coated probes are restricted to a specific soil depth interval, these estimations do not always correspond with the average σᵣ estimated with the uncoated probe. This problem may be minimized by designing an alternative TDR probe where uncoated rod-sections are uniformly distributed along the TDR rods.

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Table 1. Characteristics of the different soils used in the experiment.

<table>
<thead>
<tr>
<th></th>
<th>Sand</th>
<th>Loam soil</th>
<th>Gypsum – silt loam soil</th>
<th>Silty clay loam soil</th>
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<tr>
<td>Bulk density (g cm⁻³)</td>
<td>1.30</td>
<td>1.31</td>
<td>0.94</td>
<td>1.36</td>
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<td>Organic matter (g kg⁻¹)</td>
<td>ND †</td>
<td>1.59</td>
<td>1.39</td>
<td>1.48</td>
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<tr>
<td>CaCO₃ (g kg⁻¹)</td>
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<td>4.39</td>
<td>1.17</td>
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<td>Gypsum (g kg⁻¹)</td>
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<td>0.43</td>
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<td>Particle size distribution (%)</td>
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<td>Sand (2000-50 μm)</td>
<td>96.2</td>
<td>32.4</td>
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<td>Silt (50-2 μm)</td>
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<td>Clay (&lt;2 μm)</td>
<td>1.1</td>
<td>22.1</td>
<td>10.4</td>
<td>33.5</td>
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† Not determined
Table 2. Cell constant values estimated in a NaCl-water solutions experiment, $K_{pm}$, and numerically calculated, $K_{pc}$, and the relative differences between $K_{pm}$ and $K_{pc}$ for the uncoated ($P_0$) and the 50%, 75% ($P_{75}$) and 95% ($P_{95}$) high-$\varepsilon_r$ coated 10-cm-long TDR probes.

<table>
<thead>
<tr>
<th></th>
<th>$K_{pm}$</th>
<th>$K_{pc}$</th>
<th>$\frac{K_{pm}}{K_{pc}} - 1$</th>
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<tr>
<td>$P_0$</td>
<td>5.1</td>
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<td>$P_{75}$</td>
<td>16.9</td>
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<td>8.5</td>
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<td>$P_{95}$</td>
<td>51.3</td>
<td>45.5</td>
<td>12.7</td>
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Table 3. Coefficient of determination, $r^2$, slope and intercept of the regressions, root mean squared error (RMSE) and standard deviation of the regression (SD) for the comparison between the electrical conductivity measured in different water-NaCl solutions (from 0 to 1.5 S m$^{-1}$) with an electrical conductivity cell and the corresponding values obtained with the uncoated ($P_0$) and the 50% ($P_{50}$), 75% ($P_{75}$) and 95% ($P_{95}$) high-$\varepsilon_r$ coated 10-cm-long TDR probes.

<table>
<thead>
<tr>
<th></th>
<th>Regression</th>
<th>$r^2$</th>
<th>RMSE</th>
<th>SD</th>
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</thead>
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<tr>
<td>$P_0$</td>
<td>$y = 0.993x + 0.063$†</td>
<td>0.998</td>
<td>0.207</td>
<td>0.087</td>
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<tr>
<td>$P_{50}$</td>
<td>$y = 0.980x + 0.189$</td>
<td>0.999</td>
<td>0.212</td>
<td>0.069</td>
</tr>
<tr>
<td>$P_{75}$</td>
<td>$y = 0.967x + 0.309$</td>
<td>0.999</td>
<td>0.282</td>
<td>0.072</td>
</tr>
<tr>
<td>$P_{95}$</td>
<td>$y = 0.9674x + 0.3129$</td>
<td>0.999</td>
<td>0.248</td>
<td>0.029</td>
</tr>
</tbody>
</table>

† $x$ and $y$ are the electrical conductivity measured with the electrical conductivity cell and the corresponding values estimated with the different TDR probes, respectively.
Table 4. Coefficient of determination, $r^2$, slope and intercept of the regressions, root mean squared error (RMSE) and standard deviation of the regression (SD) for the relationship between the bulk electrical conductivity estimated with the uncoated TDR probe ($P_0$) inserted into a sand column and into loam, gypsum-silt loam and silty clay loam soil columns wetted with different solutions of water-NaCl (from 0 to 2.0 S m$^{-1}$) and the corresponding values obtained with the 50% ($P_{50}$), 75% ($P_{75}$) and 95% ($P_{95}$) high-$\varepsilon_r$ coated TDR sensors.

<table>
<thead>
<tr>
<th>Regression</th>
<th>$r^2$</th>
<th>RMSE</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{50}$</td>
<td>$y = 0.973x + 0.210$ †</td>
<td>0.958</td>
<td>0.332</td>
</tr>
<tr>
<td>$P_{75}$</td>
<td>$y = 0.855x + 0.428$</td>
<td>0.933</td>
<td>0.399</td>
</tr>
<tr>
<td>$P_{95}$</td>
<td>$y = 0.864x + 0.603$</td>
<td>0.960</td>
<td>0.466</td>
</tr>
</tbody>
</table>

† $x$ and $y$ are the bulk electrical conductivity estimated with $P_0$ and the corresponding values estimated with $P_{50}$, $P_{75}$ and $P_{95}$, respectively.
FIGURE CAPTIONS

Figure 1. TDR waveforms recorded with a 10-cm-long short-circuited TDR probe and with the same probe immersed in air and in water with an electrical conductivity of 0.03 S m$^{-1}$. The $\rho_l$ denotes the reflection coefficient of the TDR waveform recorded at long time.

Figure 2. Schematic diagram of the four three-rod 10-cm-long TDR probes used in the experiment: the uncoated sensor ($P_0$) and the probes with 50% ($P_{50}$), 75% ($P_{75}$) and 95% ($P_{95}$) of the rod-length insulated with a high-$\varepsilon_r$ material.

Figure 3. Comparison between the apparent permittivity estimated with the 10-cm-long uncoated TDR sensor ($P_0$) and the corresponding values estimated with the 50% ($P_{50}$) ($\bigcirc$), 75% ($P_{75}$) ($\blacklozenge$), and 95% ($P_{95}$) ($\bullet$) partially high-$\varepsilon_r$ coated TDR probes immersed in air, dry sand, distilled water and in a sand column and in a loam, gypsum-silt loam and silty clay loam soil column with different values of water content and bulk electrical conductivity.

Figure 4. TDR traces within the one return trip along the uncoated ($P_0$) and the 50% ($P_{50}$), 75% ($P_{75}$) and 95% ($P_{95}$) partially high-$\varepsilon_r$ coated 10-cm-long TDR probes immersed in NaCl-water solutions with an electrical conductivity ($\sigma$) of 0, 0.5, 0.75 and 1.0 S m$^{-1}$, and in a sand column and in a loam, gypsum-silt loam and silty clay loam soil columns with a bulk electrical conductivity ($\sigma_a$) value of 0.29, 0.43, 0.09 and 0.47 S m$^{-1}$, respectively.
Figure 5. TDR waveforms within the first peak and the second reflection point recorded at different water contents (0.4, 0.35, 0.25 and 0.2 m$^3$ m$^{-3}$) with the uncoated (thin lines) and the 95% partially high-$\varepsilon_r$ coated (thick lines) 10-cm-long TDR probes inserted in a sand column wetted with a NaCl-water solution of (a) 0.5 and (b) 2.0 S m$^{-1}$.

Figure 6. Values of apparent permittivity estimated from the TDR waveforms showed in Figure 4 for the uncoated (P$_0$) and the 50% (P$_{50}$), 75% (P$_{75}$) and 95% (P$_{95}$) partially high-$\varepsilon_r$ coated 10-cm-long TDR probes immersed in distillate water (W$_0$) and water with an electrical conductivity of 0.5 (W$_{0.5}$), 0.75 (W$_{0.75}$) and 1.0 (W$_{1.0}$) S m$^{-1}$, and in sand (Sand$_{0.29}$) and in a loam (LM$_{0.43}$), gypsum-silt loam (GySLS$_{0.09}$) and silty clay loam (SCILS$_{0.47}$) soil with a bulk electrical conductivity value of 0.29, 0.43, 0.09 and 0.47 S m$^{-1}$, respectively.

Figure 7. TDR waveforms at long time recorded with the uncoated (P$_0$) and the 50% (P$_{50}$), 75% (P$_{75}$) and 95% (P$_{95}$) partially high-$\varepsilon_r$ coated 10-cm-long TDR probes immersed in nine different NaCl-water solutions with an electrical conductivity ($\sigma$) value ranging between 0 and 1.5 S m$^{-1}$.

Figure 8. Relationship between the bulk electrical conductivity estimated with the uncoated TDR probe, $\sigma_{aP_0}$, inserted in a sand column and in a loam, gypsum-silt loam and silty clay loam soil column wetted with different NaCl-water solutions and the corresponding values obtained with the (a) 50% , $\sigma_{aP_{50}}$ , (b) 75% , $\sigma_{aP_{75}}$ , and (c) 95% , $\sigma_{aP_{95}}$ , partially high-$\varepsilon_r$ coated 10-cm-long TDR probes.
Figure 1.
Figure 2.
Figure 3.
Figure 4.
Figure 5.
Figure. 6.
Figure 7.
Figure. 8