A TDR-pressure cell design for measuring the soil water retention curve

D. Moret-Fernández *, J.L. Arrúe, V. Pérez, M.V. López

Departamento de Suelo y Agua, Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas (CSIC), PO Box 202, 50080 Zaragoza, Spain

* Corresponding author.

Telf: +34 976 716124

Fax: +34 976 716145

E-mail address: david@eead.csic.es

Abstract

This paper presents a new type of pressure cell associated with a zigzag-shaped time domain reflectometry (TDR) probe for determining the soil water retention ($\theta(\psi)$) curve of disturbed thin soil samples. The pressure cell, designed for pressures ranging between 0 and 500 kPa, consisted of a zigzag copper rod (150-mm long, 2-mm in diameter) vertically installed in a clear plastic cylinder (60-mm high, 50-mm in internal diameter) with six vertical copper rods (60-mm long, 2-mm in diameter) arranged around the inner wall of the plastic cylinder. The cylinder was closed at the base with a nylon cloth and placed on a porous ceramic disc. The inner rod and the six-rod grille of the cell were connected respectively to the inner and outer conductors of a coaxial cable. The results showed that the correlation between the apparent dielectric constant measured with a standard three-rod TDR probe and the zigzag-shaped TDR probe, both immersed in five different non-conductive fluids, was excellent (R^2 = 0.99). On the other hand, the volumetric water content measured with the TDR probe of the pressure cell filled up with sand, 2-mm sieved loam and clay-loam soils was highly correlated to the corresponding values calculated from the gravimetric water content and the soil bulk density (R^2 = 0.97; RMSE = 2.32 10^{-2}). The parameters of the $\theta(\psi)$ curves measured for these three different soils with the TDR-pressure cell were within the range of values found in the literature. The cell was also used to study the $\theta(\psi)$ changes of a 2-4-mm sample of loam soil aggregates after a slow and a fast wetting process. While negligible changes in both the soil structure and $\theta(\psi)$ were observed following slow wetting, fast wetting resulted in disintegration of aggregates and drastic changes in the shape of the $\theta(\psi)$ curve.

Keywords: Time Domain Reflectometry; Soil Water Retention; Pressure Cell

1. Introduction

Time domain reflectometry (TDR) is an electromagnetic technique that is used worldwide for measuring the volumetric soil water content (θ). This technique is a non-destructive and accurate method that requires minimal calibration and can be easily automated and multiplexed (Jones et al., 2002). Typically, a standard TDR probe consists of two or three straight and parallel conductive rods of equal length connected to a coaxial cable (Topp et al., 1984; Zegelin et al., 1989). Although the minimum rod length required to obtain suitable accuracy in measuring θ is about 0.1 m (Dalton and van Genuchten, 1986), the relatively recent development of downsized TDR probes has also started to be applied in soil studies. For instance, unlike the standard TDR probe designs, Selker et al. (1993) developed a small non-invasive TDR probe consisting of a pair of serpentine wave guides to determine θ at the soil surface, and Nissen et al. (1998) designed a small two–rod coated TDR coil probe (15-mm long) for measuring variations in θ on a small spatial scale. Similarly, Bittelli et al. (2004) designed an alternative TDR waveguide in which the waveguides were arranged in a spiral configuration and allowed miniaturization of the TDR probe. In other studies, Vaz et al. (2002) developed a combined tensiometer-coiled TDR probe to determine soil water retention curves in both field and laboratory conditions, and Persson et al. (2006) developed a 30-mm-long TDR matric potential sensor consisting of two coils made of lacquer-coated copper wires embedded in gypsum.

The determination of the soil water retention curve, which describes the relationship between θ and the pressure head (ψ), is of paramount importance in both basic and applied soil-water studies. The standard laboratory device used for measuring soil water retention characteristics is the pressure extractor, which, depending on its design, can work at h values ranging between 0 and -1500 kPa (Dane and Hopmans, 2002). In this method, the volumetric water content of the sample at a given pressure head is calculated from the gravimetric water content and the dry bulk density. However, caution is due when using this tedious and time-consuming technique, since grave errors can also be incurred if the bulk density of the disturbed soil is not accurately determined. This problem was partially solved by Wraith and Or (2001), who measured the water retention curve of different soils using a combination of a 15-bar pressure plate and a TDR probe. More recently, Jones et al. (2005a) developed a TDR cell which provides measurements of water content at adjustable pressure heads without repacking or disturbing the soil sample. Using concentric stainless steel tubes as electrical conductors, the authors created a 19.6-cm-long coaxial cell in which the water content was measured by TDR and the complete or partial saturation of the porous medium was checked via matric potential control.

This article presents a new small-scale TDR pressure cell for the determination of the soil water retention curve (up to -500 kPa) in thin (4-cm high) disturbed soil samples. The new TDR pressure cell uses a zigzag-shaped TDR probe which was validated with a standard three-rod TDR probe. The TDR cell was contrasted with the standard gravimetric method for measuring water content and was used (i) to determine the water-holding characteristics of three different disturbed soils and; (ii) to study the changes in the water retention characteristics of a 2-4 mm sieved loam soil after a slow and fast wetting process.

2. Theory

In Time Domain Reflectometry, TDR, a fast-rise step voltage electromagnetic pulse is propagated in the medium of interest along a transmission line. The cable tester records a TDR waveform type expressed by the reflection coefficient (ρ) as a function of time (t). The transit time, t_L (s), of the TDR pulse propagating one return trip in a transmission line (e.g. TDR probe) of length L (m) can be approached, for most soils and the TDR frequency range, by (Topp et al., 1980)

$$t_L = \frac{2L\sqrt{\varepsilon_a}}{c} \tag{1}$$

where c is the velocity of light in free space (3 x 10^8 m s^{-1}) and ε_a the apparent dielectric constant of the medium. Since the dielectric constant is highly dependent on the moisture content, travel time measurements can be directly related to the bulk soil volumetric water content (θ). Topp et al. (1980) found that for most soils θ could be calculated using the following empirical equation

$$\theta = -5.3x10^{-2} + 2.92x10^{-2}\varepsilon_a - 5.5x10^{-4}\varepsilon_a^2 + 4.3x10^{-6}\varepsilon_a^3 \tag{2}$$

The retention characteristics of the soils was modeled using the multimodal approach proposed by Durner (1994), DU, which, constructed by linear superposition of subcurves of the van Genuchten (1980), VG, type, is expressed as

$$\theta = \theta_r + (\theta_s - \theta_r)\sum_{i=1}^{k} w_i \left[\frac{1}{1+(\alpha_i \psi)^{ni}}\right]^{m_i} \tag{3}$$

$$0 < w_i < 1$$

$$\alpha_i > 0,\ m_i > 0,\ n_i > 1$$

where n_i is the pore size distribution parameter, m_i = 1-(1/n_i), α_i is the scale factor, θ_s and θ_r are the saturated and residual volumetric water contents, respectively, k is the total number of i "subsystems" that forms the total pore-size distribution, and w_i is a weighting factor for the subcurves. For the specific case of a soil constructed with two different type of pore-size distribution (i.e. soil aggregate samples), Eq. 3 simplifies to the bimodal function

$$\theta = \theta_r + (\theta_s - \theta_r)\left[w_1\left(\frac{1}{1+(\alpha_1\psi)^{n_1}}\right)^{m_1} + \left(1 - w_1\left(\frac{1}{1+(\alpha_2\psi)^{n_2}}\right)^{m_2}\right)\right] \quad (4)$$

If an homogeneous pore-size distribution is considered, then $w_i = 0$ and Eq. 3 reduces to the VG unimodal function

$$\theta = \theta_r + (\theta_s - \theta_r)\left(\frac{1}{1+(\alpha_2\psi)^{n_2}}\right)^{m_2} \quad (5)$$

3. Materials and methods

3.1. TDR-pressure cell design

The TDR cell consisted of a clear plastic cylinder (60-mm long and 50-mm in internal diameter, 5-mm thick) closed at the base with a nylon cloth of 20-μm mesh. The cylinder was joined through the base to a commercially available porous ceramic disc (7-mm thick and 50-mm in diameter) (Soil Moisture Inc. UK) and hermetically closed at the ends with two single-hole perforated caps (Fig. 1a). A 150-mm-long and 2-mm-diameter copper rod, with the bottom 120 mm bent into a zigzag-shape of 35 mm width, was vertically installed inside at the centre of the cylinder, and six vertical copper rods (60-mm long, 2-mm in diameter) were equidistantly arranged around the inner wall of the plastic cylinder (Fig. 1b). Although the use of copper rods is suitable for soil dielectric constant measurements in the short term, long-term use of copper can develop a coating on the rods as corrosion takes place, which can affect the dielectric measurements. For these reason, the use of stainless steel rods rather than copper rods would be more appropriate. The zigzag copper rod and the six-rod grille of the cell were connected, though a female BNC connector, to the inner and outer conductors of a coaxial cable, respectively. This TDR probe design formed a kind of coaxial cell providing a well-defined sample packing volume in which the radial distribution of the electromagnetic field averages the transmission line measurements over the sample. As observed by Bittelli et al. (2004), the miniaturization of the inner conductor allowed the measurement of water content for thin soil samples (4 cm height), since it had sufficiently long conductors for accurate time resolution. The TDR pressure cell was connected to a TDR cable tester (Tektronix model 1502C) through a 1.2-m long and 50 Ω coaxial cable. The TDR signal was transferred to a computer that recorded and analysed the TDR waveforms using the software WinTDR'98 (Or et al., 1998). The pressure resistance of the TDR pressure cell, tested in the laboratory using water, was higher than 50 bars.

3.2. Testing of the TDR-pressure cell

The apparent length of the inner zigzag-shaped conductor of the TDR-pressure cell was determined, using Eq. (1), by immersing the probe in distilled water ($\varepsilon_{a\text{-}water}$ = 80.63, Table 1). On the other hand, as suggested by Jones et al. (2005b), who characterized different electromagnetic sensors using homogeneous fluids of known permittivity, the zigzag-shaped TDR probe was validated by comparing the apparent dielectric constant, ε_a, measured with the pressure cell TDR probe immersed in five different non-conductive fluids (Table 1) with the corresponding values measured with a standard three-rod TDR probe (100-mm long, 2.2-mm rod diameter, 22-mm spacing of the outer conductor).

Three materials of different texture, sand (250-500 μm in diameter) and 2-mm sieved loam and clay-loam soils, were used to test the TDR pressure cell. The cell was filled in from the top to a height of 40 mm with the three materials, ensuring that the bottom 120 mm of the inner zigzag-rod was fully covered and keeping the central rod steady while packing the cell. The initial dry bulk density, measured as the relationship between the weight and volume of the soil sample, was 1.56, 1.23 and 1.29 g cm^{-3} for the sand, the 2-mm sieved loam and the clay-loam soil, respectively. The soil samples were slowly saturated with distilled water through a 0.5 bar ceramic disc placed at the base of the pressure cell (Fig. 1). Once the soils were saturated, pressure steps were sequentially applied at -0.2, -0.5, -1, -2, -5, -10, -25 -50, -100, and -500 kPa. While the hanging water column method (Dane and Hopmans, 2002) was applied for pressure heads up to -2 kPa, a gas pressure supply system was used for higher soil tensions. Four different ceramic plates (Soil Moisture Inc. UK), with bubbling pressures of -0.5, -1, and -5 bar, were used for the corresponding ranges of pressure heads. The volumetric water content measured by TDR, θ_{TDR}, using the Topp et al. (1980) model (Eq. 2) and the WinTDR'98 software (Or et al., 1998), was recorded 24 h after starting each pressure head step. For the 0-50 kPa range of pressure head the θ_{TDR} values were compared to the corresponding volumetric water content (θ_W) calculated from the measured gravimetric water content (W) and soil bulk density (ρ_b).

The TDR pressure cell was also used to study the changes in the soil water retention characteristics of a sample of 2-4 mm loam soil aggregates after a slow and fast wetting cycle. The initial dry bulk density of the soil aggregate sample was 1.15 g cm^{-3}. The pressure cell was filled in to a height of 40 mm with loam soil aggregates of 2-4 mm in diameter and then slowly saturated with distilled water through the 0.5 bar ceramic disc placed at the bottom of the pressure cell. Following the same step-wise procedure described above, pressure was sequentially applied at -0.2, -0.5, -1, -2, -5, -10, -25 -50, -100, and -500 kPa. Next, the soil was air-dried for a period of 72 h, and subsequently fast-saturated with distilled water through the top and the bottom of the cylinder. The saturated soil was again drained for the same pressure heads described above. For each pressure step and wetting and drying cycle, the volume of the soil sample within the pressure cell was measured from the cylinder radius and the height of the soil column after equilibrium was reached.

The VG (Eq. 5) and DU (Eq. 4) models were used when the measured $\theta(\psi)$ curves presented an unimodal or bimodal behaviour, respectively. In all cases, the parameters for the $\theta(\psi)$ curves (n_i, α_i, w_1, and θ_r) were automatically fitted using the SWRC Fit Version 1.2. software (Seki, 2007) (http://seki.webmasters.gr.jp/swrc/).

4. Results and discussion

The apparent length of the 12-cm-long zigzag-shaped inner conductor of the TDR probe calibrated in water was 9 cm. Although caution is required when using alcohol for TDR probe calibration, due to the fact that alcohol relaxes at much lower frequencies than water (Jones et al., 2005b), an excellent correlation was observed between the apparent dielectric constant measured with the standard three-rod TDR probe ($\varepsilon_{a\text{-}3\text{-}rod}$) immersed in the five different non-conductive fluids (Table 1) and the corresponding values estimated with the zigzag-shaped TDR probe ($\varepsilon_{a\text{-}zigzag}$) ($\varepsilon_{a\text{-}zigzag}$ = 0.986 $\varepsilon_{a\text{-}3\text{-}rod}$ + 0.754, R^2 = 0.999). Fig. 2 shows the TDR waveforms obtained with the zigzag-shaped TDR probe immersed in water, an aqueous ethanol solution (15:85, *v/v*), a solution of ethanol plus acetic acid (50:50, *v/v*) and in sand and loam soil with a volumetric water content of 0.03 and 0.14 m^3 m^{-3}, respectively. The well-defined shape of the TDR waveforms shown in Fig. 2, together with the good correlation found between $\varepsilon_{a\text{-}3\text{-}rod}$ and $\varepsilon_{a\text{-}zigzag}$, indicates that the proposed zigzag-shaped probe is robust and accurate enough for measuring the soil water content in thin soil samples.

Fig. 3 shows, for the sand and the 2-mm sieved loam and clay-loam soil, the comparison between the volumetric water content calculated from the gravimetric water content and the soil bulk density, $\theta_{W,}$ (Eq. 6) and the corresponding values measured by the zigzag-shaped TDR probe, θ_{TDR}, for the soil pressure heads ranging between 0 and -50 kPa. The good correlation (θ_{TDR} = 0.933 θ_W + 0.026; R^2 = 0.974; RMSE = 2.32 10^{-2}) found for the three different soils indicates that the TDR method applied to the pressure cell is accurate enough for determining soil water retention curves. Compared to the gravimetric method, the proposed TDR method is much quicker and easier to use than the standard procedure, in which additional errors can be incurred due to variations in the weights of the ceramic discs in the course of the soil drainage process.

The soil water retention curves measured with the pressure cell for sand and the 2-mm sieved loam and clay-loam soils are shown in Fig. 4. The shape (n_2) and scale (α_2) parameters of the water retention curves estimated with the unimodal VG function (Eqs. 5) are summarized in Table 2, as well as the root mean square error (RMSE) and the determination coefficient (R^2) for the comparison between the measured and modelled water retention curves for the three soils. The values of n_2 and α_2 for the three soils are within the range of values found in the literature (Haverkamp et al., 1998). In comparison to the clay-loam soil, the loam soil presents a similar volume of large pores but a significantly smaller volume of pores for pressure heads higher than -25 kPa. These differences at high pressure heads should be attributed to the different textural characteristics between the two soils. The value of n_2 found for the 2-mm sieved loam soil is close to that measured in the field by Moret et al. (2007) for the same undisturbed soil under agricultural management. In all the cases, the RMSE between the experimental and the simulated soil water retention curves found for the three soils was very low and the correlation between the two curves excellent, with the R^2 value higher than 0.99 (Table 2). These results indicate that the proposed TDR pressure cell is able to estimate the water retention curve for soils with different structural and textural characteristics.

Fig. 5a shows the soil moisture retention curves measured for the 2-4 mm loam soil aggregates after a slow and a fast wetting process. In this case, the $\theta(\psi)$ curves were fitted using the bimodal function proposed by Durner (1994) (Eq. 4). Table 2 shows the parameters of the bimodal $\theta(\psi)$ curves and the statistical parameters (RMSE and R^2) for the comparison between the measured and modelled water retention curves after the soil wetting processes. The w_1 value indicates that the soil sample presented two clear different types of pore-size distribution. The large pores observed between the 2-4 mm aggregates after a slow wetting is reflected by the large α_1 value found in the $\theta(\psi)$ curve. However, the disintegration of the aggregates following fast wetting, which collapsed large soil pores, promoted a significant decrease of α_1 and α_2. On the other hand, the high α_1 value observed for the $\theta(\psi)$ curve after a slow wetting indicates high water stability in the aggregates, as is also deduced from the nearly constant values of the soil volume within the pressure cell (Fig. 5b). The transparent wall of the cylinder allowed us to confirm that no appreciable changes occurred in the aggregate structure during the slow wetting process. This high structural stability can be explained by the oven-dry initial condition of the soil aggregates (105 ºC for 24 h), as a way of equalizing the initial moisture of the samples before measurements. As discussed by Munkholm and Kay (2002), an increase in aggregate strength with decreasing water content can be ascribed to the higher cohesive forces of capillary-bound water because of reduced pore water pressure and to the increased effectiveness of cementing materials. On the other hand, large differences were observed between the water retention curves measured in the 0-2 mm (Fig. 4) and the 2-4 mm (Fig. 5a) sieved loam soil after the slow soil wetting. The drop in water content between the matric potentials of 0 and -1 kPa for the 2-4 mm sieved loam soil (Fig. 5a) indicates, as visually observed, the presence of large macropores between the aggregates, which promotes fast drainage in conditions very near to saturation. The water retention curve of the 2-4 mm sieved loam soil after a slow soil wetting changed significantly in comparison to the water retention function obtained after the fast soil wetting (Fig. 5a). The rapid saturation produced the disintegration of aggregates by slaking, which resulted in pores of smaller size and thus an increase in water content at low pressure head values (up to 0.5 kPa), the blockage of the pore space with soil particles and small aggregates, and therefore a decrease in soil water infiltration (Collis-George and Greene, 1979). The effect of the slaking process was also assessed visually through the extensive structural degradation of the aggregates and the marked and irreversible decrease in the soil volume that were observed through the clear plastic cylinder (Fig. 5b). This phenomenon suggests that the shape of the water retention function of the 2-4 mm sieved loam soil after a fast wetting process tends to match that observed in the 2 mm sieved loam soil (Fig. 4).

The suitability of the TDR pressure cell for describing changes in soil moisture retention characteristics associated with alterations in soil structure is of great interest in soil structure studies. Most of the studies carried out to date have evaluated soil properties in samples of undisturbed soil but not in individual aggregates. However, soil behaviour at a macro-scale level depends on the aggregate properties, and these can differ from those of undisturbed soil due to the dynamics of aggregate formation (Blanco-Canqui et al., 2005). A better knowledge of aggregate characteristics, including their water retention properties, will help to explain, for example, the response of soil to tillage, compaction and crop growth, and hence to plan adequate soil management practices.

5. Conclusions

The proposed TDR-pressure cell for measuring the soil water retention curves is precise, simple and relatively easy to implement. Unlike the Jones et al. (2005a) coaxial cell, the proposed zigzag-shaped TDR probe allows the use of a thinner soil sample, which makes it possible to bring the soil sample to equilibrium at shorter time intervals. On the other hand, the transparent TDR-pressure cell design allows direct observation of soil structural changes and simultaneous measurements of soil volume and volumetric water content. However, caution is due when using the Topp et al. (1980) equation for water content determination (Eq. 2) since errors can result if, for instance, highly organic soils are used. Finally, further efforts should be made to (a) improve the pressure cell to determine soil water content for pressure heads up to 1500 kPa (permanent wilting point) and (b) test alternative dielectric methods for measuring the water content in thin undisturbed soil samples.

Acknowledgements

This research was supported by the Comisión Interministerial de Ciencia y Tecnología of Spain (grants AGL2004-07763-C02-02 and AGL2007-66320-CO2-02/AGR) and the European Union (FEDER funds). The authors are grateful to R. Gracia for his help in various aspects of this study.

References

Blanco-Canqui, H., Lal, R., Owens, L.B., Post, W.M., Izaurralde, R.C. 2005. Mechanical properties and organic carbon of soil aggregates in the Northern Appalachians. Soil Sci. Soc. Am. J. 69, 1472-1481.

Bittelli M., Flury, M., Campbell, G.S., Schulz, V. 2004. Characterization of a spiral-shaped time domain reflectometry probe. Water Resour. Res. 40, W09205, doi: 10.1029/2004WR003027.

Collis-George, N., Greene, R.S.B. 1979. The effect of aggregate size on the infiltration behaviour of a slaking soil and its relevance to ponded irrigation. Aust. J. Soil Res., 17, 65-73.

Dalton, F.N, van Genuchten, M.T.. 1986. The time-domain reflectometry method for measuring soil water content and salinity. Geoderma 38, 237-250.

Dane, J.H., Hopmans, J.W. 2002. Water retention and storage. In: J.H. Dane and G.C. Topp (Eds.). Methods of soil analysis. Part 4- Physical methods, SSSA Book Series No. 5, Madison, WI, USA, pp. 680-683.

Durner, W. 1994. Hydraulic conductivity estimation for soils with heterogeneous pore structure. Water Resour. Res., 30, 211-223.

Haverkamp, R., Zammit, C., Bouraoui, F., Rajkai, K., Arrúe, J. L., Heckmann, N. 1998. GRIZZLY, Grenoble Catalogue of Soils: Survey of soil field data and description of particle-size, soil water retention and hydraulic conductivity functions. Laboratoire d'Etude des Transferts en Hydrologie et Environnement (LTHE), Grenoble Cedex 9, France.

Jones, S.B., Wraith, J.M., Or, D. 2002. Time domain reflectometry principles and applications. Hydrol. Process. 16, 141-153.

Jones, S.B., Mace, R.W., Or, D. 2005a. A time domain reflectometry coaxial cell for manipulation and monitoring of water content and electrical conductivity in variable saturated porous media. Vadose Zone J. 4, 977-982.

Jones, S.B., Blonquist, J.M., Robinson, D.A., Rasmussen, V.P., Or, D. 2005b. Standardizing Characterization of Electromagnetic Water Content Sensors: Part 1. Methodology. Vadose Zone J. 4, 1048-1058.

Moret, D., Braud, I., Arrúe, J.L. 2007. Water balance simulation of a dryland soil during fallow under conventional and conservation tillage in semiarid Aragon, Northeast Spain. Soil Till. Res. 92, 251-263.

Munkholm, L.J., Kay, B.D. 2002. Effect of water regime on aggregate-tensile strength, rupture energy, and friability. Soil Sci. Soc. Am. J. 66, 702-709.

Nissen, H.H., Moldrup, P., Henriksen, K. 1998. High-resolution time domain reflectometry coil probe for measuring soil water content. Soil Sci. Soc. Am. J. 62, 1203-1211.

Or, D., Fisher, B., Hubscher, R.A., Wraith, J. 1998. WinTDR 98 V.4.0 –Users Guide-. Department of Plants, Soil & Biometeorology, Utah State University, Logan, UT.

Persson, M., Wraith, J.M., Dahlin, T. 2006. A small-scale matric potential sensor based on time domain reflectometry. Soil Sci. Soc. Am J. 70, 533-536.

Selker, J.S., Graff, L., Steenhuis, T. 1993. Noninvasive time domain reflectometry moisture measurement probe. Soil Sci. Soc. Am. J. 57, 934-936.

Seki, K. 2007. SWRC fit – a nonlinear fitting program with a water retention curve for soils having unimodal and bimodal pore structure. Hydrol. Earth System Sci. Discus, 4, 407-437.

Topp, G.C., Davis, J.L., Annan, A.P. 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resour. Res. 16, 574-582.

Topp, G.C., Davis, J.L., Bailey, W.G., Zebchuk, W.D. 1984. The measurement of soil water content using a portable TDR hand probe. Can. J. Soil Sci. 64, 313-321.

van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic properties of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892-898.

Vaz, C.M.P,. Hopmans, J.W., Macedo, A.,. Bassoi, L.H., Wildenschild, D. 2002. Soil water retention measurements using a combined tensiometer-coiled time domain reflectometry probe. Soil Sci. Soc. Am. J. 66, 1752-1759.

Wraith J.M., Or, D. 2001. Soil water characteristic determination from concurrent water content measurements in reference porous media. Soil Sci. Soc. Am. J. 65, 1659-1666.

Zegelin, S.J., White, I., Jenkins, D.R. 1989. Improved field probes for soil water content and electrical conductivity measurement using time domain reflectometry. Water Resour. Res. 25, 2367-2376.

Table 1. Values of the apparent dielectric constant for five non-conducting fluids measured with a standard 10-cm-long 3-rod probe ($\varepsilon_{a\text{-}3\text{-}rod}$) and the corresponding values measured with the zigzag-shaped TDR probe ($\varepsilon_{a\text{-}zigzag}$) used in the TDR pressure cell.

Fluid	$\varepsilon_{a\text{-}3\text{-}rod}$	$\varepsilon_{a\text{-}zigzag}$
Sunflower oil	2.40	2.32
Ethanol plus acetic acid solution (50 : 50, *v/v*)	15.47	16.76
Aqueous ethanol solution (15 : 85, *v/v*)	26.07	27.42
Aqueous ethanol solution (50 : 50, *v/v*)	48.85	49.31
Distilled water	80.86	80.78

Table 2. Values of the measured saturated (θ_s) and residual (θ_r) volumetric water content, the weighting factor for the subcurves (w_1), the shape (n_1 and n_2) and scale (α_1 and α_2) parameters for the water retention curves corresponding to the Durner (1994) and van Genuchten (1980) models, and the root mean square error (RMSE) and the correlation coefficient (R^2) for the comparison between the measured and modelled water retention curves for sand, the 2-mm sieved loam and clay-loam soils and the 2-4 mm sieved loam soil after a slow and fast soil wetting.

		0-2 mm aggregates soil		2-4 mm aggregates loam soil	
	Sand	Loam soil	Clay-loam Soil	After slow soil wetting	After fast soil wetting
θ_s (m^3 m^{-3})	0.43	0.51	0.51	0.58	0.47
θ_r (m^3 m^{-3})	0.09	0.16	0.24	0.08	0.22
w_1	-	-	-	0.61	0.63
α_1 (m)	-	-	-	16.10	5.60
n_1	-	-	-	1.76	1.28
α_2 (m)	0.27	0.44	1.24	0.53	0.04
n_2	3.49	1.64	1.72	1.63	2.07
RMSE	1.13 10^{-2}	1.18 10^{-2}	6.14 10^{-3}	4.71 10^{-3}	2.79 10^{-3}
R^2	0.99	0.99	0.99	0.99	0.99

Figure captions

Fig. 1. Scaled schematic diagram (a) and photo (b) of the TDR-pressure cell.

Fig. 2. Example of TDR waveforms measured with the zigzag-shaped coaxial TDR probe immersed in water, an aqueous ethanol solution (15:85, *v/v*), a solution of ethanol plus acetic acid (50:50, *v/v*) (see Table 1) and in dry sand and loam soil with a volumetric water content (θ) of 0.03 and 0.14 m^3 m^{-3}, respectively.

Fig. 3. Relationship between the soil volumetric water content calculated from the gravimetric water content and the soil bulk density (θ_W) and the corresponding values estimated by the TDR pressure cell (θ_{TDR}) measured in the sand and the 2-mm sieved loam and clay-loam soils for the pressure heads ranging between 0 and -50 kPa.

Fig. 4. Soil water retention curves measured with the TDR pressure cell on sand and a 2-mm sieved loam and clay-loam soils for pressure heads ranging between 0 and -500 kPa. Continuous lines are the corresponding water-holding characteristics functions calculated with the van Genuchten (1980) model (Eq. 5) for the water retention curve parameters shown in Table 2.

Fig. 5. Soil water retention curves (a) and soil volume (b) measured (points) with the TDR-pressure cell on a 2-4 mm sieved loam soil for pressure heads ranging between 0 and -500 kPa after a slow-wetting and a fast-wetting process. In the upper graphic,

the lines correspond to the water retention curve calculated with the bimodal function proposed by Durner (1994) (Eq. 4) for the soil parameters shown in Table 2.

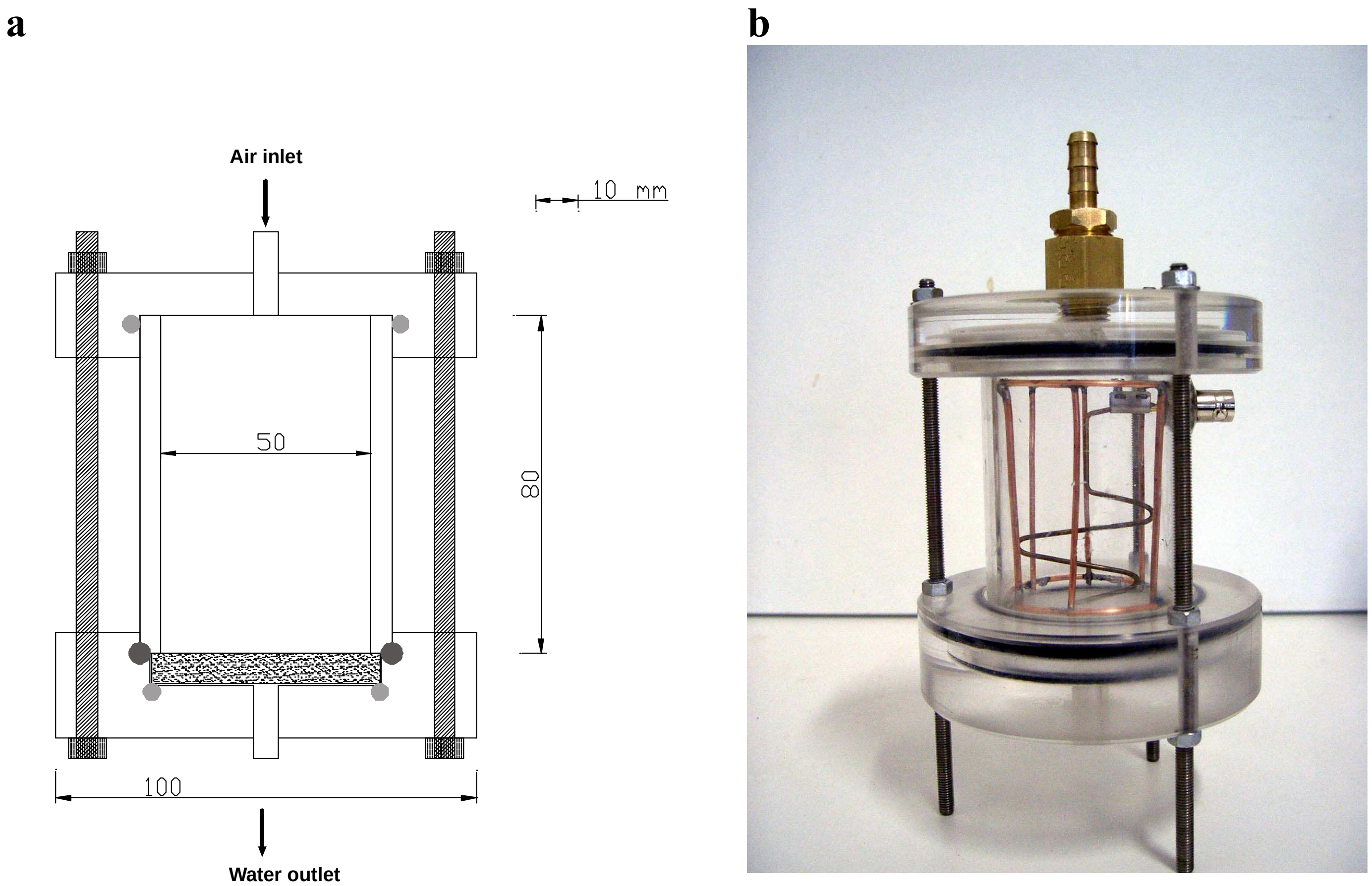


Fig. 1

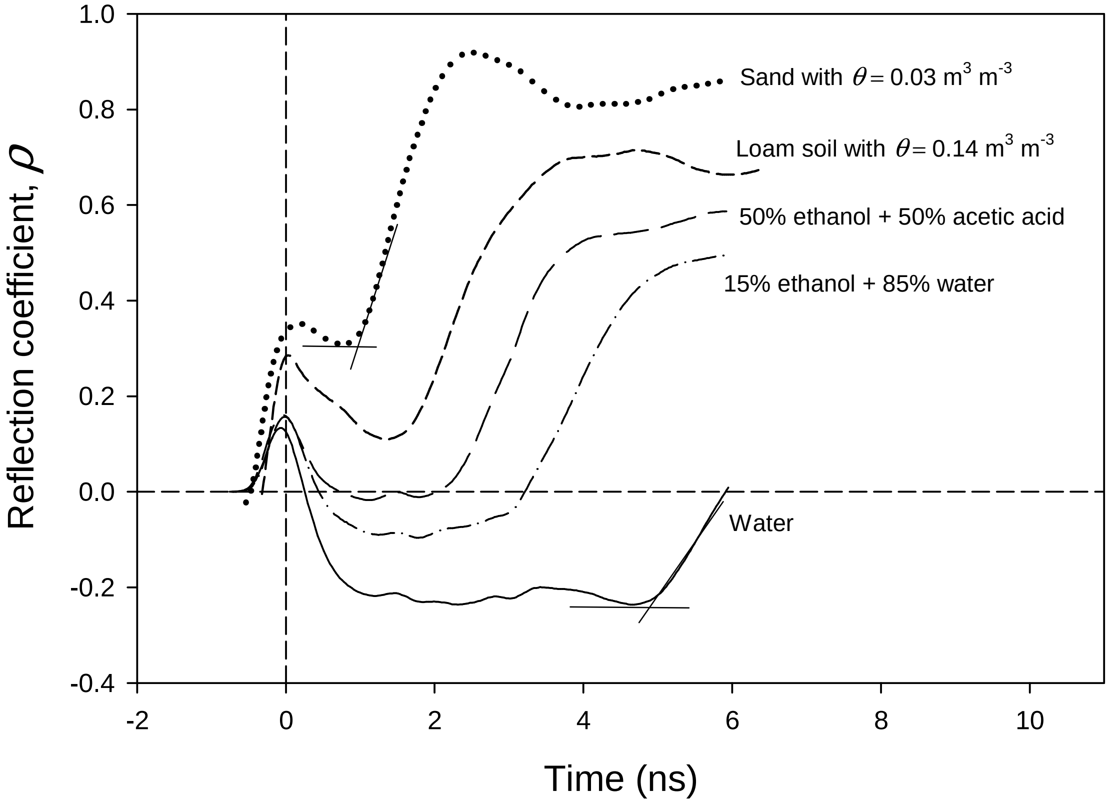
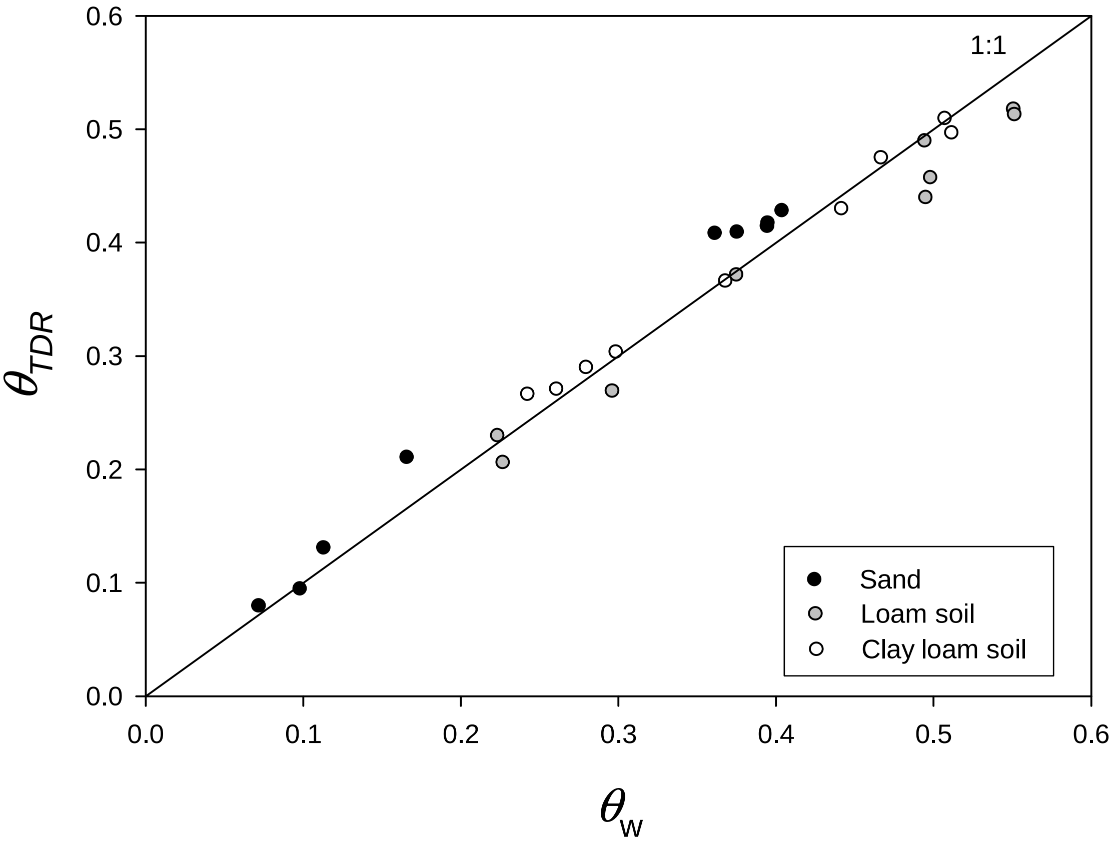

Reflection coefficient, ρ
Time (ns)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-2
0
2
4
6
8
10
Sand with θ = 0.03 m3 m-3
Loam soil with θ = 0.14 m3 m-3
50% ethanol + 50% acetic acid
15% ethanol + 85% water
Water

Fig. 2.



0.0
0.1
0.2
0.3
0.4
0.5
0.6
θ_{TDR}
θ_w
1:1
Sand
Loam soil
Clay loam soil

Fig. 3.

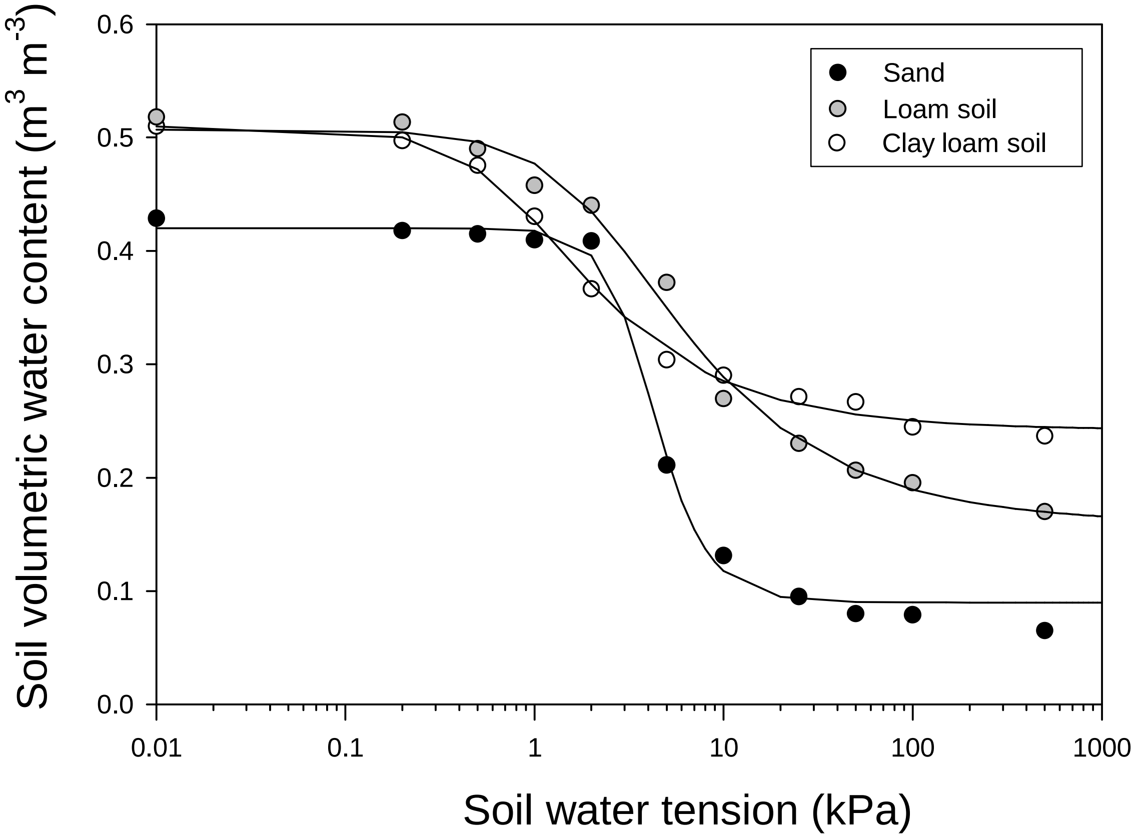

Sand
Loam soil
Clay loam soil
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.01
0.1
1
10
100
1000
Soil volumetric water content (m3 m-3)
Soil water tension (kPa)

Fig. 4.

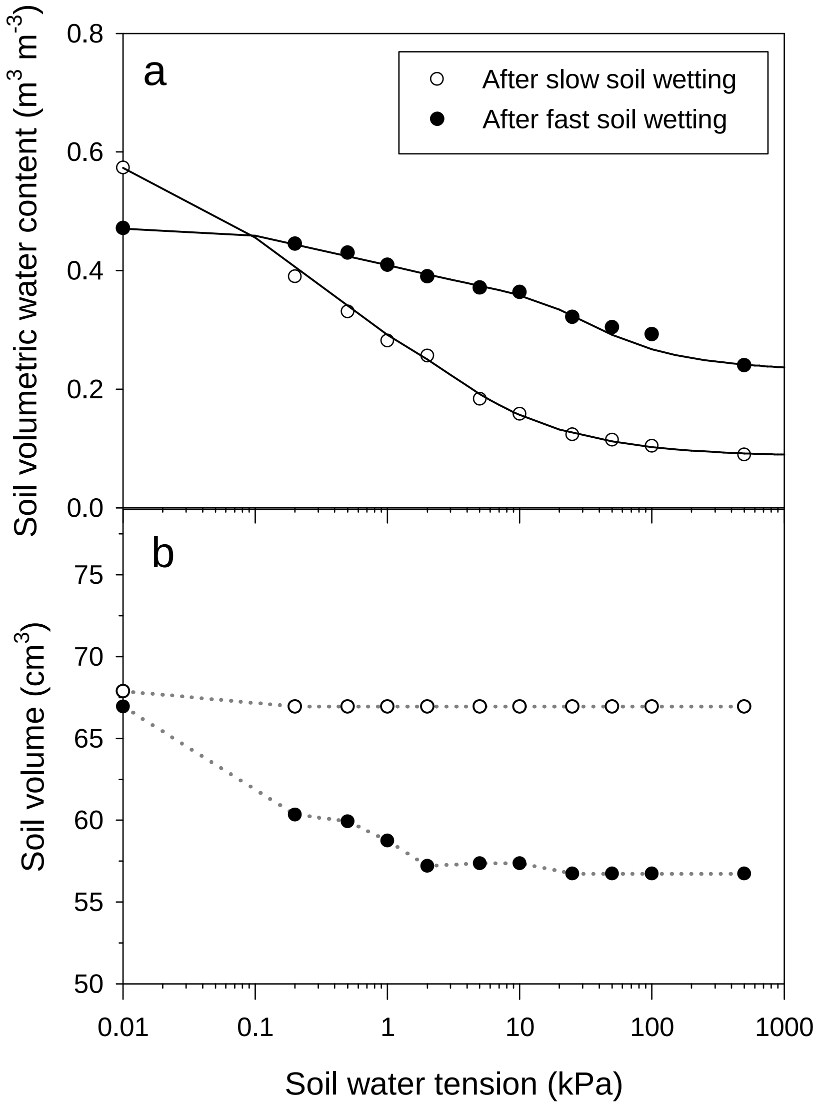

a
b
After slow soil wetting
After fast soil wetting
Soil volumetric water content (m3 m-3)
0.0
0.2
0.4
0.6
0.8
Soil volume (cm3)
50
55
60
65
70
75
0.01
0.1
1
10
100
1000
Soil water tension (kPa)

Fig. 5.