



LUND UNIVERSITY

A profiling TDR probe for water content and electrical conductivity measurements of soils

Persson, Magnus; Dahlin, Torleif

Published in:
European Journal of Soil Science

DOI:
[10.1111/j.1365-2389.2010.01306.x](https://doi.org/10.1111/j.1365-2389.2010.01306.x)

2010

[Link to publication](#)

Citation for published version (APA):

Persson, M., & Dahlin, T. (2010). A profiling TDR probe for water content and electrical conductivity measurements of soils. *European Journal of Soil Science*, 61(6), 1106-1112. <https://doi.org/10.1111/j.1365-2389.2010.01306.x>

Total number of authors:
2

General rights

Unless other specific re-use rights are stated the following general rights apply:

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

Read more about Creative commons licenses: <https://creativecommons.org/licenses/>

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

A profiling TDR probe for water content and electrical conductivity measurements of soils

M. PERSSON^a & T. DAHLIN^b

^aDepartment of Water Resources Engineering, Lund University, Box 118, SE-221 00 Lund, Sweden, and ^bDepartment of Engineering Geology, Lund University, Box 118, SE-221 00 Lund, Sweden

Summary

Measurements of water content profiles are of great interest in hydrology and soil science. Time domain reflectometry (TDR) is a well-established method for water content measurements; however, most TDR probe designs are suitable for measurements in only a small soil volume. In this article, a 1-m long TDR profiling probe with five measurement sections is described. Unlike most other previous profiling probes, our probe allows for both dielectric permittivity (ϵ) and electrical conductivity (σ_a) measurements. The accuracy of the ϵ and σ_a measurements was excellent; the precision of the measurements was, however, significantly poorer than with a 0.20-m long standard three rod TDR probe. The new probe was installed in a field and successfully measured water content profiles during the growing season of 2009. During an infiltration experiment it was shown that because of its geometry, the profiling probe over-estimated the wetting-front velocity. At a 0.10-m depth, the over-estimation was almost 30%. The over-estimate will be less significant at greater depths.

Introduction

Time domain reflectometry (TDR) has become an important tool for measurements of dielectric permittivity (ϵ) and bulk electrical conductivity (σ_a) (Robinson *et al.*, 2003). In most applications, small TDR probes containing two or three metal rods, from a few cm up to 0.3–0.5 m in length, have been used. Several small-scale TDR probes have been developed during recent years. An interesting TDR probe design was presented by Nissen *et al.* (1998). This probe was based on the coil principle, which significantly decreased the physical length of the probe without affecting the accuracy. However, the original coil probe design does not allow for σ_a measurements. Persson & Wraith (2002) developed a shaft-mounted probe with a 0.2-m long steel wire coiled around a 0.03-m long shaft capable of taking accurate ϵ and σ_a measurements.

There has been little published on the development of large-scale probes capable of determining the soil moisture profile. In laboratory studies, TDR probes can be placed horizontally into soil columns at various depths and give detailed measurements of water and solute transport. Horizontally installed TDR probes have also been used in field experiments (Das *et al.*, 1999; Persson & Berndtsson, 2002). However, these probes have to be installed by digging a pit or transect and pushing the probes into the soil

wall, creating soil disturbance. This type of installation also limits the depth at which the probes can be buried. Soil water content profiles have also been estimated using inverse modelling of TDR curves from vertically installed TDR probes (Heimovaara *et al.*, 2004; Greco, 2006; Bänninger *et al.*, 2008).

A long TDR probe that can be installed from the soil surface and take measurements at several depth increments is called a profiling probe. Several profiling probes have been developed; however, most of them are only capable of ϵ measurements (Hook *et al.*, 1992; Redman & DeRyck, 1994; Dahan *et al.*, 2003; Laurent *et al.*, 2005; West & Truss, 2006). Ferré *et al.* (1998a, 2003) presented a profiling probe sensitive to electrical conductivity. They did not report the accuracy of their σ_a readings, but it is likely that it was less than for conventional TDR probes because the probe was situated inside a PVC tube. Another disadvantage of existing probes is that they are typically not large and rugged enough to be installed at greater depths.

The objective of the present study was to construct a profiling TDR probe capable of taking both ϵ and σ_a measurements down to a depth of several metres in a soil profile. The probe should be possible to install using a small drilling rig. The probe should allow the user to choose the measurement depths; this can be done by having measurement and extension sections that can be assembled in the desired order. The probe has to be rugged and suitable for long-term field use. The sampling area of the probe should be sufficiently large in order to minimize measurement errors caused by soil disturbance close to the probe.

Correspondence: M. Persson. E-mail: magnus.persson@tvrl.lth.se

Received 14 December 2009; Revised version accepted 2 September 2010

Materials and methods

All TDR measurements performed in the present study were carried out with a Tektronix 1502C (Beaverton, Oregon, USA) cable tester connected to a laptop computer. Estimates of ε and σ_a were calculated from the TDR trace using the WinTDR software (Soil Physics Group, Utah State University, Logan, UT, USA). Reference ε measurements were taken using a 0.2-m long three-rod TDR probe (Soilmoisture Equipment Corp., Santa Barbara, CA, USA).

Profiling probe development

A non-invasive approach allows TDR measurements without inserting the probe into the material of interest. In Persson & Berndtsson (1998) TDR measurements were conducted with half of the TDR measurement volume contained within a PVC block and the other half used to measure θ and σ_a in the soil. Using a similar approach, TDR rods could be placed on the surface of, for example, PVC pipes that can be pushed into the ground. However, PVC pipes lack the rigidity to be used for probes that are several metres long.

Our profiling probe was constructed of a standard 1-m long steel rod with a diameter of 0.04 m, which is hollow and threaded at both ends. The profiling probe had five measurement sections at 0.2-m intervals along the probe. Each measurement section consisted of two stainless steel bands, 0.15-m long, 0.002-m thick and 0.01-m wide. The bands were bent to an almost complete circle with a diameter of 0.052 m, with a gap between the ends of approximately 0.01 m. The two bands were each soldered to the conductors and earths of 10-m long RG58 coaxial cables. The coaxial cable from each measurement section was led through holes drilled through the steel rod, one hole for each measurement section. Five 0.005-m wide and 0.003-m thick rubber strips were glued between the steel rod and the steel bands in order to secure them in place. The centre-to-centre distance of the steel bands was 0.055 m. The entire probe was put in a cylindrical mould with an inner diameter of 0.052 m. The mould was filled with polyurethane (PUR). When the PUR hardened, the probe was removed from the mould and machined in order to achieve a smooth surface. The hollow steel core was also filled with PUR to fix the cables and to prevent water leaks. Two extension sections were manufactured from steel rods that were coated with PUR using the same mould. A schematic design of the profiling probe is given in Figure 1.

Calibration

The measurement volume of the profiling probe contained not only the media of interest, the material surrounding the probe (ε_{ref}), but also PUR. Thus, the profiling probe measured ε and σ_a , and cannot be directly used. In dielectric mixing models describing the contribution from x different compounds with different ε values to the equivalent ε of the mixture ε_{eq} , the contribution from the components is assumed to be constant if the geometrical positions

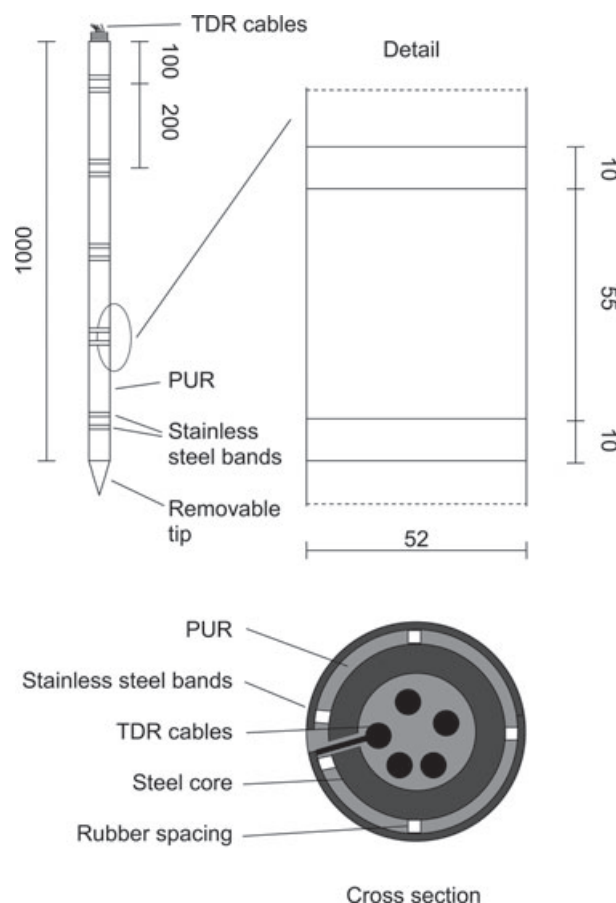


Figure 1 Schematic design of the profiling probe; all measurements are in millimetres.

and volume fractions of the x components are constant within the applied field (Ferré *et al.*, 1996). In the probe design described above, two different materials will be present in the measurement volume, PUR and the surrounding material. Thus, it is possible to describe the contribution of these media using a two-phase dielectric mixing model:

$$\varepsilon_{\text{eq}}^n = w_{\text{PUR}} \varepsilon_{\text{PUR}}^n + (1 - w_{\text{PUR}}) \varepsilon_{\text{ref}}^n, \quad (1)$$

where w_{PUR} is a weighting factor describing the fractional contribution of the PUR. The exponent n summarizes the geometry of the medium in relation to the applied electrical field.

In order to relate ε_{eq} measured by the profiling probe to ε measured by the reference TDR probes, measurements were made in air and several fluids. The fluids were n-paraffin, inverted sugar syrup (a mixture of glucose and fructose), ethanol, 70% ethanol mixed with 30% water (vol:vol), 50% ethanol in water, and water. A 1-m long PVC cylinder with an inner diameter of 0.25 m was used for the measurements in liquids. Twenty measurements were completed and averaged with the reference probe and each of the five measurement sections of the profiling probe in all fluids. The measurement with the reference probe was used as reference ε

values to optimize w_{PUR} and n in Equation (1) for each section of the profiling probe. Measurement of ε_{PUR} was taken on a small PUR cube that was manufactured for this purpose using an E5061A ENA Network Analyzer with a 85070E Dielectric Probe Kit (Agilent Technologies, Santa Clara, CA, USA). The measured ε_{PUR} was 2.8 at 1 GHz; this value was used in the optimization.

The resistive load (R_L) across a TDR probe may be measured and related to σ_a of the target medium (Heimovaara *et al.*, 1995). The profiling probe R_L measurements were calibrated to σ_a by comparing the measured R_L to σ_a measured by the reference electrical conductivity meter in salt solutions. Ten NaCl solutions with σ_a over a range of 0.0–6.0 dS m⁻¹ were used; 10 profiling probe measurements were obtained in each solution. It should be mentioned that the range in σ_a of the calibration fluids should match the range expected in the field. We chose the range in our calibration fluids because we plan to use the probe in a saline environment in the future. We also wanted to test if the profiling probe could take ε measurements under these very saline conditions. Reference electrical conductivities were taken with a digital conductivity meter. In a similar manner to Nissen *et al.* (1999) in calculating σ_a for their printed circuit board TDR probes, we used the method suggested by Heimovaara *et al.* (1995):

$$\sigma_a = K_p / (R_L - R_{\text{cable}}), \quad (2)$$

where K_p is the probe cell constant and R_{cable} is the contribution to R_L from the combined series resistances of the cable tester, cables, connectors, and the probe head.

Sampling area

Knight *et al.* (1994) showed that the spatial weighting function $w(x, y)$ of a TDR probe in an arbitrary electrostatic potential field Φ can be calculated by:

$$w(x, y) = \frac{|\nabla\Phi|^z}{\int \int |\nabla\Phi_0|^z dx dy}, \quad (3)$$

where Φ_0 is the potential field in a homogeneous field where ε is constant in the area surrounding the probe. Assuming that the probe geometry is constant along the rods and that end effects can be neglected, the TDR measured equivalent permittivity ε_{eq} when the probe is surrounded by a heterogeneous ε distribution $\varepsilon(x, y)$ can be calculated by:

$$\varepsilon_{\text{eq}} = \int \int \varepsilon(x, y) w(x, y) dx dy. \quad (4)$$

When calculating Φ , the potentials of the probe rods were set to 1 and -1 for the rod connected to the conductor and the shield, respectively. Our probe had a steel core completely covered in PUR, thus its potential was set to 0. This makes Φ change rapidly over the small distance (0.003 m) between the steel bands and the steel core. Because the sampling area of the TDR probe is proportional to the square of the gradient of Φ , ε_{eq} will be much affected by ε_{PUR} . We calculated ε_{eq} using Equations (3) and (4) for the 10 calibration fluids described above.

Field test

A field test of the profiling probe was conducted near the Löddeköpinge field station, 15 km northwest of Lund, Sweden. The soil at the site is a loamy sand; more information about the site can be found in Persson & Berndtsson (2002) and Öhrström *et al.* (2004). The profiling probe was installed using a hand auger in early summer 2009. No extension parts were used, thus the top of the probe was situated at the soil surface. The centres of the measurement sections were situated at 0.1, 0.3, 0.5, 0.7 and 0.9-m depths. The probe was left in place until the end of October 2009. The purpose of this experiment was to test the reliability and consistency of the profiling probe during long-term measurements. Three dielectric permittivity and σ_a measurements were taken and averaged once daily during this period.

At the end of the growing season an infiltration experiment was conducted. The purpose of this was to compare the response of the profiling probe and horizontally-installed TDR probes subjected to a sharp wetting front. Three TDR probes were installed at 0.15 m from the profiling probe by digging a hole, 0.15-m deep, and installing the probes horizontally into the soil wall. After installation the hole was backfilled using the original soil. The probes were installed at 0.0675, 0.10 and 0.1325-m depths; this corresponds to the centres of the top and bottom steel bands and the centre of the most shallow measurement section of the profiling probe. The probes used were 0.04-m long with a wire diameter of 0.001 m and a wire spacing of 0.005 m, similar to those used by Persson & Haridy (2003), but with a longer rod. These probes are referred to as P1–P3, with P1 being at the most shallow depth.

During the infiltration experiment an area of 0.6 × 0.6 m, with the profiling probe in the middle, was ponded to a depth of 0.001–0.005 m by adding water every 10 minutes for a period of 250 minutes. The average infiltration rate during this period was 0.00018 m per minute. During the experiment the uppermost sections of the profiling probe and P1–P3 were connected to a SDMX50 multiplexer (Campbell Scientific Ltd., Shepshed, UK) controlled by the WinTDR software. Measurements were taken every 2.5 minutes. Measured ε values were converted to θ using the Topp equation (Topp *et al.*, 1980).

Results and discussion

Sampling area

The 90 and 70% sampling areas calculated according to the procedure described by Ferré *et al.* (1998b) are presented in Figure 2. The 90% sampling area extends only approximately 0.01 m from the surface of the probe. This means that the probe is very sensitive to air gaps close to the probe surface. Therefore care should be taken when installing the probe. Clearly the steel core leads to a steep gradient of the potential lines near the probe rods and, especially, between the rods and the core. Because the sampling area of the TDR probe is proportional to the square of the gradient of the potential lines the sampling area is restricted close to the surface of the probe. If instead a non-conducting material had been chosen

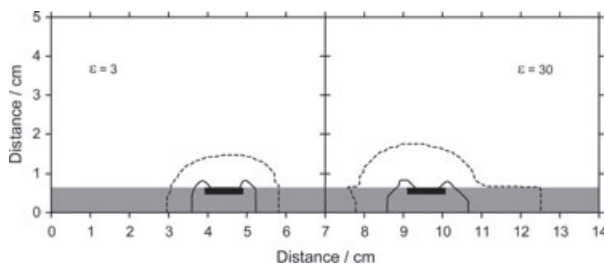


Figure 2 The 90% (dashed) and 70% (solid line) sampling areas of the profiling TDR probe surrounded by dry ($\epsilon = 3$) and wet ($\epsilon = 30$) soil. Grey is PUR and black is the steel bands; the metal core is situated at $y = 0$.

as a core material, the sampling area would have been extended further from the probe surface. The probe geometry would then be similar to the surface probe of Persson & Berndtsson (1998). Furthermore, the measured ϵ_{eq} would be greater, which would lead to improved accuracy of the ϵ_{ref} estimate. On the other hand, a PVC core would mean a less rigid probe. Another way of increasing the sampling area would be to increase the distance between the steel core and the steel bands. We carried out a numerical simulation of the sampling area for an alternative probe design with a 0.004-m thick PUR layer between the core and steel bands. This led to a 90% sample area extending almost 0.02 m from the probe surface. A larger-diameter probe would, however, be more difficult to install and would cause greater soil disturbance. Furthermore, the maximum diameter of our probe was restricted by the specifications of the drilling rig that we used. Future designs will instead have a smaller-diameter steel core in order to have a thicker PUR layer while keeping the same total diameter of the probe.

Calibration

When the soil is in parallel with the electric field, $w(x, y)$ does not change with ϵ_{ref} . Theoretically, this is the only case where Equation (1) is valid; in other cases the parameters in Equation (1) depend on $\epsilon(x, y)$. From Figure 2 it can also be seen that the sampling area changes with ϵ_{ref} , which means that the soil is not perfectly in parallel with the electrical field. Theoretically, Equation (1) is thus not valid; however, it can still be used as an empirical relationship between ϵ_{ref} and ϵ_{eq} .

Figure 3 shows three TDR traces obtained in air, distilled water and a 2.0 dS m⁻¹ NaCl solution. From all three traces ϵ values can easily be determined even if the long cable flattens the signal somewhat. Even at the largest σ_a level used during calibration, a clear end reflection was visible and ϵ measurements could be taken.

The best fit parameters of Equation (1), w_{PUR} and n , for the five measurement sections were in the range 0.62–0.73 and 0.61–0.90, respectively. These values were close to previously published parameters for probes with a similar geometry, $w = 0.68$, $n = 1.0$ (Persson & Wraith, 2002). It should be noted that the observed large variation, especially in the n parameter, for

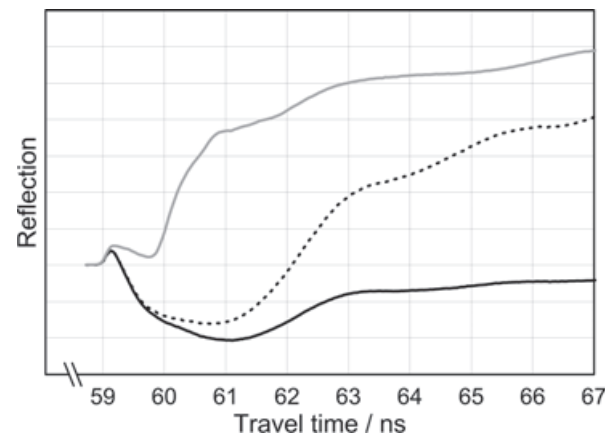


Figure 3 TDR traces of the profiling probe measured in air (grey), distilled water (dashed line) and a 2 dS m⁻¹ salt solution (black).

probes with seemingly identical geometries also has been found in other studies. Apparently Equation (1) is very sensitive to small changes in the parameters. The root mean square error (RMSE) of the ϵ_{ref} prediction was small: in the range of 0.1–0.3 for the different sections. The variability of the ϵ_{ref} and prediction was also investigated. It was found that the standard deviation of the ϵ_{ref} prediction in water was 0.30–0.55 for the different probe sections. This is around 10 times larger than the reference 0.2 m TDR probes (Persson & Wraith, 2002; Persson & Haridy, 2003).

The ϵ_{eq} calculated by Equation (4) using the ϵ_{ref} for the calibration fluids resulted in slightly smaller values than the measurements. Figure 4 shows the ϵ_{eq} calculated by Equation (4) with measured values from one of the measurement sections. Equation (4) is actually only valid for an infinite probe length with a constant geometry along the rods. The reason for the observed difference probably depends on the finite length of the rods, which might lead to unaccounted-for end effects, and the fact that the modelled and actual probe geometry is not identical and constant along the probe length.

Ferré *et al.* (1996) defined the sensitivity of a TDR probe as the change in the measured response per unit change in the property of interest. The sensitivity of the profiling probe was calculated following the procedure described in Ferré *et al.* (1996, 2000) and the result is shown in Figure 5. As a comparison, the sensitivity of a traditional geometry (two- or three-rod TDR probe without coating) is also included in Figure 5. As can be seen, the sensitivity was smaller compared with the traditional geometry and it increased with water content. This increase will lead to an over-estimate of the measured water content if the water content varies along the probe rods. Because the long axis of the rods was in the horizontal plane, this will have had little effect on the measurements. The sensitivities of many other probe geometries can be found in Ferré *et al.* (2000).

Equation (2) gave good results with a RMSE for the σ_a prediction of 0.048–0.073 dS m⁻¹. These values are around 10 times greater than probes with a traditional geometry (Persson & Haridy, 2003). The parameters K_p and R_{cable} were in the range

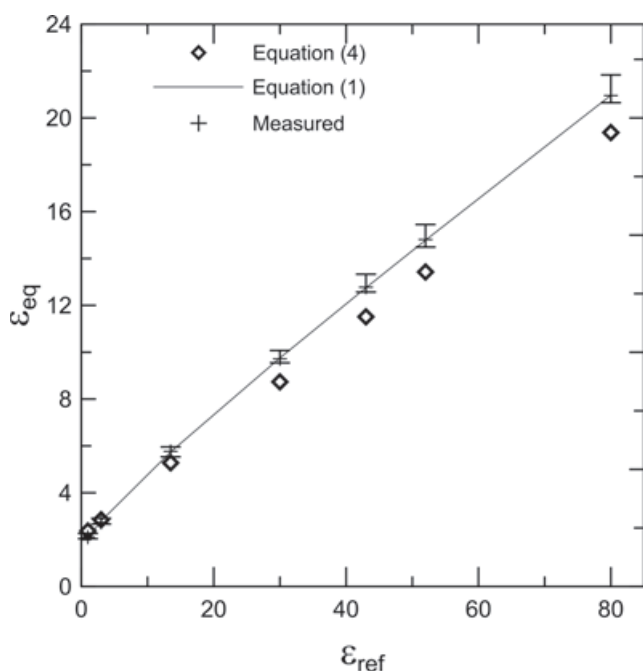


Figure 4 Measured ϵ_{eq} from one of the measurement sections along with predicted values using Equations (1) and (4). The error bars indicated the standard deviation of the five different sections.

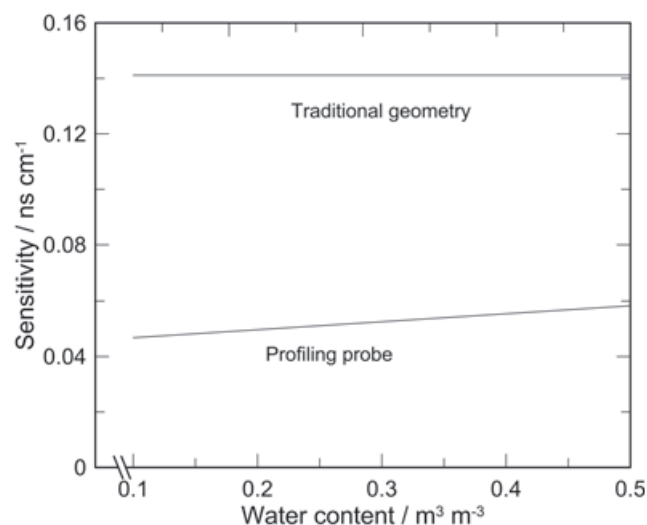


Figure 5 Sensitivity of the profiling probe compared with a TDR probe of traditional geometry.

22–25 and 1.1–1.9 Ω , respectively. In Figure 6, the measured and modelled σ values are shown: the measured electrical conductivity is presented as $1/R_L$ in order to have the same units on both axes. It can be seen that the accuracy of the σ_a measurement is less at small values of σ_{ref} . Huisman *et al.* (2008) showed that the accuracy of a TDR system can be as accurate as 0.6–1.2% of the measured σ_a , provided that the reflection coefficient is in the range -0.75 to 0.75 . Our probe had an accuracy of around 1.5%

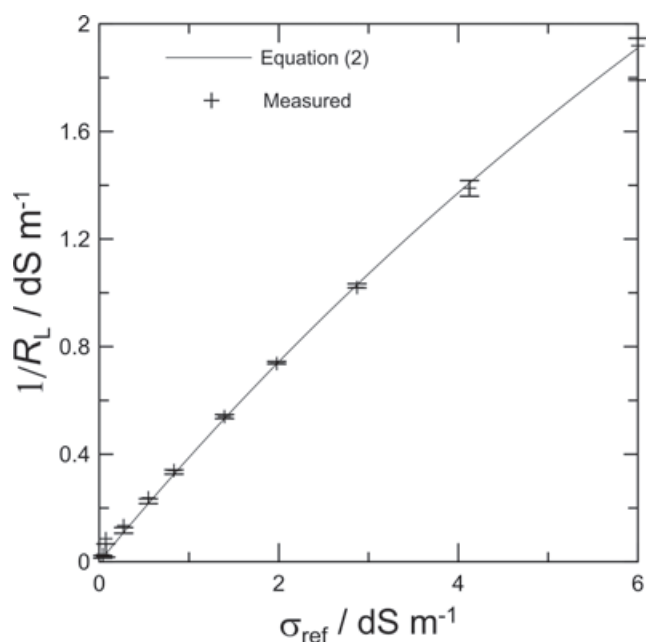


Figure 6 Measured $1/R_L$ from one of the measurement sections along with predicted values using Equation (2). The error bars indicate the standard deviations of the five different sections.

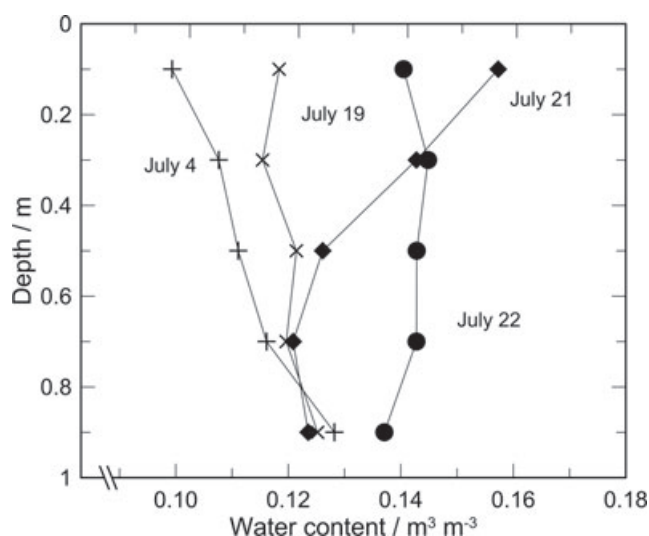


Figure 7 Measured water content profiles for 4 days during July 2009.

for σ_{ref} larger than about 0.8 $dS m^{-1}$. It should be noted that the accuracy can be improved by using a smaller range in σ_{ref} during calibration.

Field test

The profiling probe successfully measured ϵ and σ_a during the growing season of 2009. No drift in the measurements occurred, indicating that there were no water leaks into the probe. As an example, four measured water-content profiles are presented

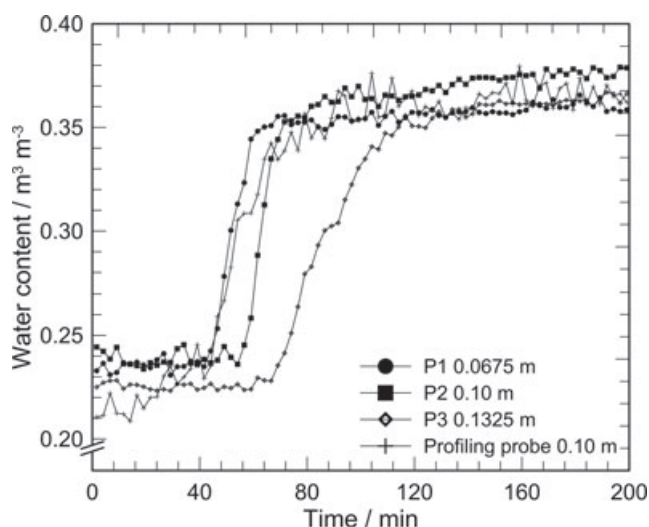


Figure 8 Measured water content during the infiltration experiment using three miniature probes (P1–P3) and the uppermost section of the profiling probe. The measurement depths are given in the legend.

in Figure 7. The first (4 July) represented the driest condition, with only 1.1 mm of rain during the preceding 15 days. A heavy rainfall, 24.4 mm, occurred on 20 July. The measured θ profiles the preceding and the two following days are also presented in Figure 7. A water-balance calculation shows that the increase in θ during this event is realistic. The soil profile contained 14 (21 July) and 22 mm (22 July) more water compared with 19 July. The under-estimate on 21 July probably depended on a larger θ in the topsoil (above 0.1 m depth). The small value on 22 July was because of infiltration below 0.9 m.

The measured water content during the infiltration experiment is given in Figure 8. Because of the rod placement of the profiling probe, it is likely that the arrival time and the sharpness of the wetting front were difficult to estimate correctly: this is indicated in Figure 8. The wetting front velocities (v_w) were calculated for each probe. The arrival time of the wetting front was calculated as the time when ε reached the average θ of the start and end of the experiment. The wetting front velocities of the three miniature TDR probes were 1.3, 1.5 and 1.5 mm per minute for the 0.0675, 0.10 and 0.1325 m depths, respectively. For the profiling probe the calculated v_w was 1.8 mm per minute. The theoretical wetting front velocity can be calculated as:

$$v_w = \frac{J_w}{\theta_{end} - \theta_{start}}, \quad (5)$$

where J_w is the average water flux at the soil surface. The theoretical v_w was calculated to be 1.4 mm per minute, showing that P1–P3 gave accurate results whereas the profiling probe over-estimated v_w by almost 30%. Apart from the probe geometry this over-estimate could also be the result of preferential flow along the profiling probe; this would also explain the increase in ε already occurring after around 25 minutes.

Conclusions

A large profiling TDR probe for σ_a and ε measurements was developed. The probe is rugged and suitable for long-term field measurement. It was shown that the probe gave accurate ε and σ_a measurements, even though the standard deviation of the ε measurement was significantly larger compared with a 0.2-m long standard TDR probe. A numerical analysis showed that the 90% measurement area only extended to about 0.01 m from the probe surface, indicating that the probe was sensitive to air gaps forming during the installation. A non-metallic core would have given a larger sampling area; however, the probe would have been less rigid. The present probe has five measurement sections: the number of measurement sections was limited by the number of coaxial cables that could fit inside the hollow steel rods.

An infiltration experiment showed that wetting-front velocities are likely to be over-estimated using the profiling probe. The main reason is that the wetting front is moving along the plane of the probe 'rods', perpendicular to the long axis of the probe. If more exact estimates of wetting-front velocities or breakthrough curves are needed, spatial sensitivity modelling of the TDR sampling area can be performed (see Ferré *et al.*, 2002). Because the profiling probe was designed primarily for measurements at depth, where sharp and rapid changes in θ and σ_a are unlikely, this over-estimation has little practical significance.

One alternative to our suggested profiling probe is horizontally installed two- or three-rod TDR probes installed in the walls of trenches or pits in the soil. This is, however, not practical when measurements are to be made at depths of several metres. Furthermore, the trench or pit has to be backfilled carefully in order not to change the flow paths in the soil. Our profiling probe is easy to install; on the other hand, the accuracy is reduced. The accuracy and sensitivity can be improved if a non-metallic core is used, but this will make the probe less rigid and, thus, less suitable for deep measurements.

Acknowledgements

This study was funded by the Swedish Research Council through the grant 'Geoelectrical measurements of soil water content and pollutant concentration over multiple scales'. Experimental equipment was also purchased through a grant from the Crafoord foundation.

References

- Bänninger, D., Wunderli, H., Nussberger, M. & Flühler, H. 2008. Inversion of TDR signals – revisited. *Journal of Plant Nutrition & Soil Science*, **171**, 137–145.
- Dahan, O., McDonald, E. & Young, M. 2003. Development of a flexible TDR probe for deep vadose zone monitoring. *Vadose Zone Journal*, **2**, 270–275.
- Das, B.S., Wraith, J.M. & Inskeep, W.P. 1999. Nitrate concentrations in the root zone estimated using time domain reflectometry. *Soil Science Society of America Journal*, **63**, 1561–1570.

- Ferré, P.A., Rudolph, D.L. & Kachanoski, R.G. 1996. Spatial averaging of water content by time domain reflectometry: implications for twin rod probes with and without dielectric coatings. *Water Resources Research*, **32**, 271–279.
- Ferré, P.A., Rudolph, D.L. & Kachanoski, R.G. 1998a. Water content response of a profiling time domain reflectometry probe. *Soil Science Society of America Journal*, **62**, 865–873.
- Ferré, P.A., Knight, J.H., Rudolph, D.L. & Kachanoski, R.G. 1998b. The sample areas of conventional and alternative time domain reflectometry probes. *Water Resources Research*, **34**, 2971–2979.
- Ferré, P.A., Knight, J.H., Rudolph, D.L. & Kachanoski, R.G. 2000. A numerically based analysis of the sensitivity of conventional and alternative time domain reflectometry probes. *Water Resources Research*, **36**, 2461–2468.
- Ferré, T.P.A., Nissen, H.H. & Šimůnek, J. 2002. The effect of the spatial sensitivity of TDR on inferring soil hydraulic properties from water content measurements made during the advance of a wetting front. *Vadose Zone Journal*, **1**, 281–288.
- Ferré, T.P.A., Rudolph, D.L. & Kachanoski, R.G. 2003. The electrical conductivity response of a profiling time-domain reflectometry probe. *Soil Science Society of America Journal*, **67**, 494–496.
- Greco, R. 2006. Soil water content inverse profiling from single TDR waveforms. *Journal of Hydrology*, **317**, 325–339.
- Heimovaara, T.J., Focke, A.G., Bouten, W. & Verstraten, J.M. 1995. Assessing temporal variations in soil water composition with time domain reflectometry. *Soil Science Society of America Journal*, **59**, 689–698.
- Heimovaara, T.J., Huisman, J.A., Vrugt, J.A. & Bouten, W. 2004. Obtaining the spatial distribution of water content along a TDR probe using the SCEM-UA Bayesian inverse modeling scheme. *Vadose Zone Journal*, **3**, 1128–1145.
- Hook, W.R., Livingston, N.J., Sun, Z.J. & Hook, P.B. 1992. Remote diode shorting improves measurement of soil water by time domain reflectometry. *Soil Science Society of America Journal*, **56**, 1384–1391.
- Huisman, J.A., Lin, C.P., Weihermüller, L. & Vereecken, H. 2008. Accuracy of bulk electrical conductivity measurements with time domain reflectometry. *Vadose Zone Journal*, **7**, 426–433.
- Knight, J.H., White, I. & Zegelin, S.J. 1994. Sampling volume of TDR probes used for water content monitoring. In: *Proceedings of the Symposium and Workshop on Time Domain Reflectometry in Environmental, Infrastructure and Mining Applications*, Special Publication SP, (eds K.M. O'Connor & L.V. Wade), pp. 19–94. Bureau of Mines, U.S. Department of the Interior, Minneapolis, MN.
- Laurent, J.P., Ruelle, P., Delage, L., Zaïri, A., Ben Nouna, B. & Adjmi, T. 2005. Monitoring soil water content profiles with a commercial TDR system: comparative field tests and laboratory calibration. *Vadose Zone Journal*, **4**, 1030–1036.
- Nissen, H.H., Moldrup, P. & Henriksen, K. 1998. High-resolution time domain reflectometry coil probe for measuring soil water content. *Soil Science Society of America Journal*, **62**, 1203–1211.
- Nissen, H.H., Moldrup, P., Olesen, T. & Raskmark, P. 1999. Printed circuit board time domain reflectometry probe: measurements of soil water content. *Soil Science*, **164**, 454–466.
- Öhrström, P., Hamed, Y., Persson, M. & Berndtsson, R. 2004. Characterizing solute transport in the unsaturated zone by simultaneous use of dye and bromide. *Journal of Hydrology*, **289**, 23–35.
- Persson, M. & Berndtsson, R. 1998. Noninvasive water content and electrical conductivity laboratory measurements using time domain reflectometry. *Soil Science Society of America Journal*, **62**, 1471–1476.
- Persson, M. & Berndtsson, R. 2002. Transect scale solute transport measured by time domain reflectometry. *Nordic Hydrology*, **33**, 145–164.
- Persson, M. & Haridy, S. 2003. Estimating water content from electrical conductivity measurements with short time-domain reflectometry probes. *Soil Science Society of America Journal*, **67**, 478–482.
- Persson, M. & Wraith, J.M. 2002. Shaft-mounted time domain reflectometry probe for water content and electrical conductivity measurements. *Vadose Zone Journal*, **1**, 316–319.
- Redman, J.D. & DeRyck, S.M. 1994. Monitoring non-aqueous phase liquids in the subsurface with multilevel time domain reflectometry probes. In: *Proceedings of the Symposium on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications*, Evanston, Illinois, (eds K.M. O'Connor & L.V. Wade), pp. 7–9. Bureau of Mines, U.S. Department of the Interior, Minneapolis, MN.
- Robinson, D.A., Jones, S.B., Wraith, J.M., Or, D. & Friedman, S.P. 2003. A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry. *Vadose Zone Journal*, **2**, 444–475.
- Topp, G.C., Davis, J.L. & Annan, A.P. 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *Water Resources Research*, **16**, 574–582.
- West, L.J. & Truss, S.W. 2006. Borehole time domain reflectometry in layered sandstone: impact of measurement technique on vadose zone process identification. *Journal of Hydrology*, **319**, 143–162.