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Borehole-Based TDR Probes in a Layered Sandstone Aquifer: Optimising Data Quality

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Abstract

This paper describes a study where packer-mounted TDR probes arrays were installed in boreholes to monitor water content variations in the vadose zone of a sandstone aquifer. TDR electrodes consisted of flat stainless steel strips, which were pressed against the walls of boreholes on pressurised packers filled with cement grout. TDR traces were collected using an automated multiplexed data logging system, in order to monitor seasonal moisture content variations.

The quality of the water content data obtained varied a lot between individual TDR probes; in general deeper probes performed better, perhaps as a result of the greater grout pressure; these probes tended to produce credible water content values and smoothly varying time series water contents. A large group of probes showed a significant degree of data scatter, i.e. returned apparent probe lengths varied substantially between subsequent daily datasets.

Comparisons of shapes of TDR traces showed that high-scatter probes produced attenuated traces that have a distorted profile compared to ‘good’ traces. This attenuation may be a result of more conductive sediments. Determination of apparent probe length for attenuated traces produces relatively large uncertainty in the position of the probe end, resulting in the observed scatter in the time series water content data. Here we report an alternative method of interpreting the TDR data, based on reflection co-efficient amplitude, which produces more consistent water content data for our probe arrays.

Key words: Flat probes, water content, sandstone rock aquifer, trace picking

Introduction

Over the previous 25 years the technique of time domain reflectometry has been developed as a highly accurate method for measuring water content in soils to an accuracy within 1-2% of the true volumetric water content (Topp et al, 1980, Jones et al, 2002). TDR hardware is relatively inexpensive and may easily be automated (Huang & Dowding, 1994) and so it has gained wide acceptance as a useful technique for monitoring moisture levels in unconsolidated sediments, particularly by soil scientists (Wraith & Das, 1998, Jones et al, 2002. Ferré & Rudolph, 1998; Al

Hagrey & Michaelson, 1999; Robinson et al, 1999), and many systems and probe designs are now commercially available for use in soils. However, application of TDR for monitoring water content in cemented media such as sedimentary rocks is less well developed, because of the difficulty in inserting the waveguides into pre-drilled holes without air gaps (Hokett et al., 1992; Sakaki et al., 1998). Previous attempts to solve this problem have focussed on the use of flat electrodes which are pressed against the measurement medium (Selker et al, 1993; Nissen et al, 1999, West et al., this volume). For example, a short inflatable packer with TDR waveguides embedded in its walls, which is then inserted in uncased boreholes on a temporary basis, the Time Domain Reflectometry with Intelligent Micromodule Elements (TRIME) system, is described by Stacheder et al (1994). However, such systems may produce significant errors when used to collect time-series water content data, due to the repeated repositioning of the TDR waveguides between subsequent readings. Also, the need to manually reposition the packer between readings limits the potential for automatic data collection.

A new borehole packer system was developed in which flexible packers with multiple TDR waveguides attached to the outside skin were permanently installed in 4 boreholes by filling with cement grout (Truss et al., 2001, Truss 2004; West and Truss, 2006). The aim of the TDR system was to provide time series water content data at a range of depths, to track lateral and vertical water and pollutant movements within the vadose zone of the Triassic Sherwood Sandstone, a consolidated fluvial sandstone aquifer in the United Kingdom. Improved understanding of water behaviour within the vadose zone is required for land use planning purposes. A fully automated TDR installation consisting of 54 TDR probes, mounted upon 4 packers collected daily datasets, in order to monitor the response to individual rainfall events.

Analysis of the data from the TDR system showed that most of the TDR probes returned smoothly varying, credible water content values. However, there were two groups of probes that returned less credible values: one group which consistently returned unrealistically low water contents (i.e. below the specific retention of the sandstone), and another group of probes that exhibited a high degree of data scatter (i.e. inconsistent water content values from consecutive days). Low-reading TDR probes were found to have coaxial cables from deeper probes lying between the two skins of the packer, directly behind the affected probe. The reasons for the high degree of scatter returned by some probes proved to be more problematical to trace, and are discussed below. In this paper, the design of the TDR packers, and their installation is described, and a data processing method that improves data quality for the high-scatter probes is presented. The implications of the data for the interpretation of hydrological processes in the unsaturated zone, and the interpretation other geophysical datasets collected from the field sites, are discussed by West and Truss (2006).

Probe and packer design

It has been shown (Persson and Berndtsson, 1988, Selker et al, 1993, Marheshwarla et al., 1995) that TDR probes do not need to be inserted into the matrix under investigation. Although insertion is the normal method of emplacement into soils, this poses severe problems when the material under investigation is a rock. Provided account is taken of the dielectric properties of the backing medium behind the TDR probes, it is possible to place the probes in contact with the medium under investigation and still get good water content results. Here, a vertically mounted, 2 electrode waveguide, with the electrodes mounted on 1mm thick neoprene backing attached to inflatable borehole packers was used; the selection of this probe design is described by Truss et al. (2001). The neoprene backing served to maintain the electrodes in a parallel planar configuration despite deformation of the borehole packer.

The depth to the water table is typically about 14m at the packer installation site (Heck Quarry, Selby, West Yorkshire, UK. SE588 213). Packers acted to seal the borehole so it does not act as a preferential pathway for water flow, maintain borehole stability, provide a secure mounting point for accurate location of TDR waveguides, ensure that the waveguides maintain intimate contact with the surrounding rock, and limit air gaps behind and adjacent to the waveguides. Each packer consisted of a 12-15 metre long, 125mm diameter, double-skinned tube of impermeable, flexible and elastic material (Chlorino material DP205, manufactured by Chlorino Ltd, Italy), sealed at both ends with metal caps, with the upper cap drilled and tapped to allow grout injection and pressurisation (Figure 1). The packers were designed to deform to account for irregularities in the cylindrical boreholes. Each packer was fitted with up to sixteen TDR vertical waveguide assemblies before being lowered into the borehole, pressurised to 2 bar using compressed air, and injected with pressurised cement grout to hold the waveguides in contact with the rock in a permanent installation.

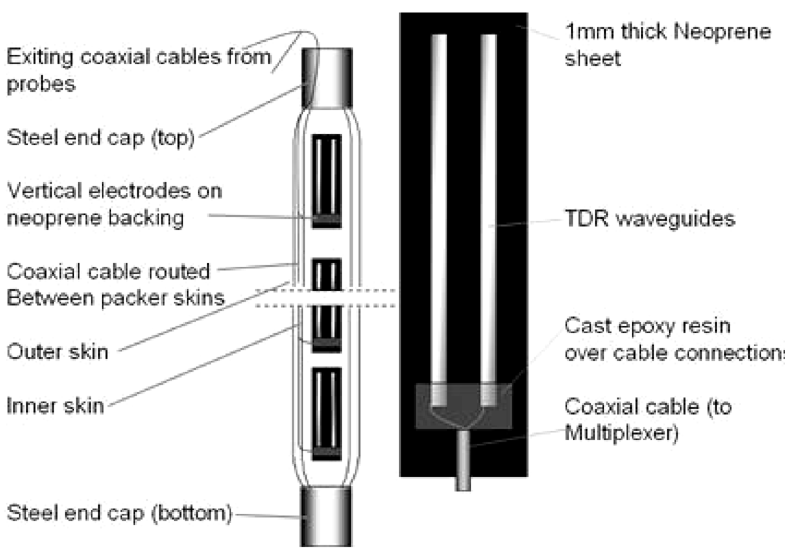

Figure 1 Details of packer showing possible electrode orientations, packer design, and waveguide assembly design.

Cement shrinks upon curing, typically by approximately 0.7%, so to prevent the waveguides moving away from the borehole wall and introducing air gaps, a shrinkage reducing agent (Eclipse, manufactured by W.R. Grace & Co. Cambridge, Connecticut, USA) and a plasticising agent (Advil, also manufactured by W.R. Grace & Co.) was added to the grout mixture according to manufacturers recommendations. The use of compressible neoprene in the waveguide assemblies protected the packer from being punctured by sharp-edged electrodes, allowed some cement shrinkage to be accommodated, while allowing the waveguides to mould to fit any minor irregularities in the borehole wall.

Installation

A total of fifty-two individual TDR probes were installed on four packers at the test site. A cased access hole suitable for a neutron probe (Bell, 1987) and an uncased hole suitable for the TRIME mobile packer system (Stacheder et al, 1994) were also drilled (Figure 2). Results from the TRIME system are presented in West & Truss 2006, and the neutron probe results provided data from the near subsurface to compliment the deeper TDR and TRIME datasets.

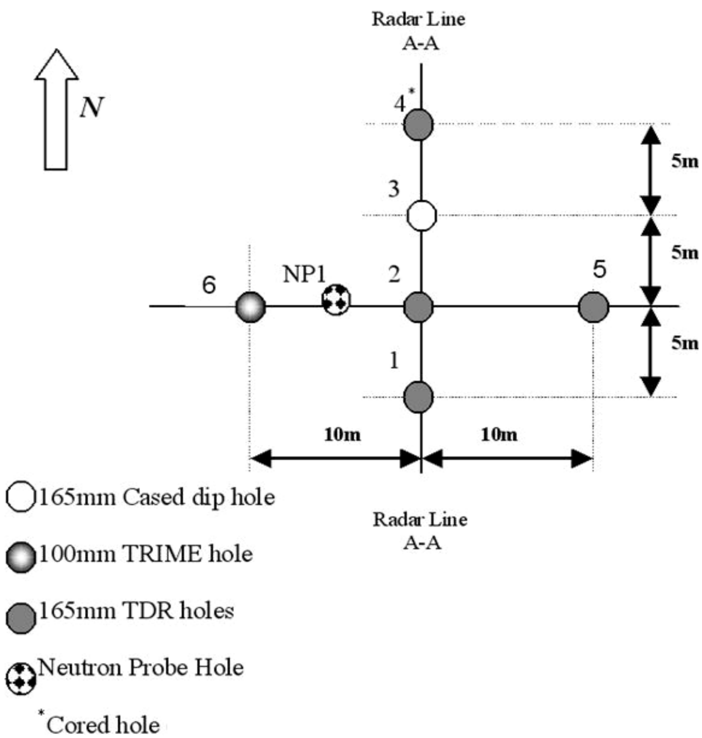

Figure 2 Borehole installation

The TDR system was automated using a series of Campbell Scientific SDMX50 multiplexers and a Campbell Scientific CR10X datalogger allowing daily readings to be taken. Water content profiles were collected using the TRIME mobile packer and neutron probe and these were used to validate the permenant TDR packer results. In order to convert apparent probe lengths and reflection coefficients into permittivity values a probe calibration was undertaken using liquids of known dielectric constant (Table 1).

Table 1. Dielectric properties of standard liquids

Material	Relative dielectric constant	Source
Acetone	(200C) 21	http://www.ctennant.co.uk/proddata/tp00001a.htm
Methanol	(250C) 32.6	http://www.asiinstr.com/dc1.html
Cyclohexane	(200C) 2	http://www.asiinstr.com/dc1.html
Air	1	http://www.asiinstr.com/dc1.html

Cement grout identical to used for the field packers was cast into a 15-litre container, and coated with epoxy resin to reduce any tendency to absorb fluid (Figure 3).

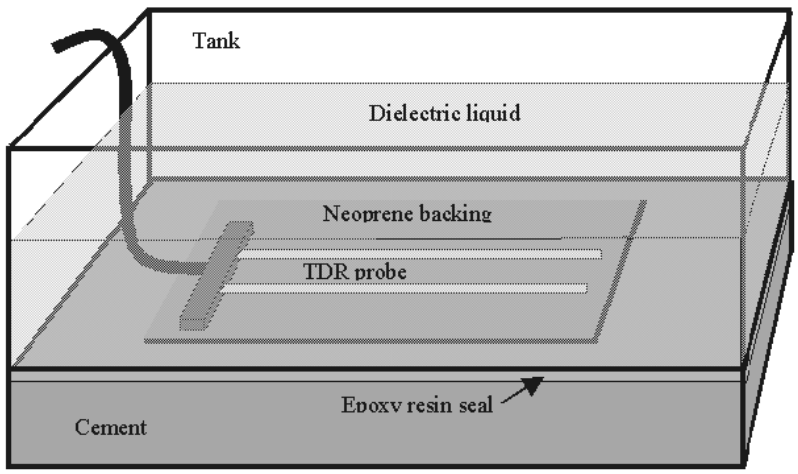

Figure 3. Calibration cell layout

A TDR probe assembly was affixed in the epoxy coated cement to simulate a packer-mounted array. The container was filled with liquids of known permittivity and TDR traces and apparent water content recorded for each fluid. All calibration tests were carried out at 20°C using a Campbell Scientific TDR 100 unit, using Campbell Scientific PC TDR 2.0 software. Because the waveguides are mounted on the packer assembly, the measured permittivity will depend partially on the dielectric properties of the neoprene/cement behind the waveguides and partially on the dielectric properties of the measurement medium. The permittivities returned by the TDR software were plotted against the known permittivity of the standard liquid used, and a calibration formula which took account of the permittivity of the packer was determined. The measured relative dielectric constant K_{exp} was given by

$$K_{exp} = K_{medium}(1-w) + K_{packer}.w \qquad (1)$$

where w is a weighting factor between 0 and 1 (Truss et al., 2001), determining the relative contribution of the packer materials. The purpose of calibration was thus to determine both K_{packer} and the weighting factor w using liquids with a range of dielectric constants.

Figure 4 shows a plot of the relative dielectric constants of the standard liquids against the relative dielectric constants measured by the packer assembly immersed in these liquids. Also shown is a plot of equation (1) with the parameters K_{packer} and w optimised for best fit to the data. The calibrated values of w and K_{packer} for this range are 0.37 and 8.65 respectively.

This calibration was applied to the field data returned from the automated TDR system. However, some probes returned high levels of scatter in the calibrated data, i.e. time series water contents fluctuated sharply between subsequent days, in a physically unrealistic way. Such probes are referred to as ‘high scatter’ probes. The reasons for this behaviour are discussed below.

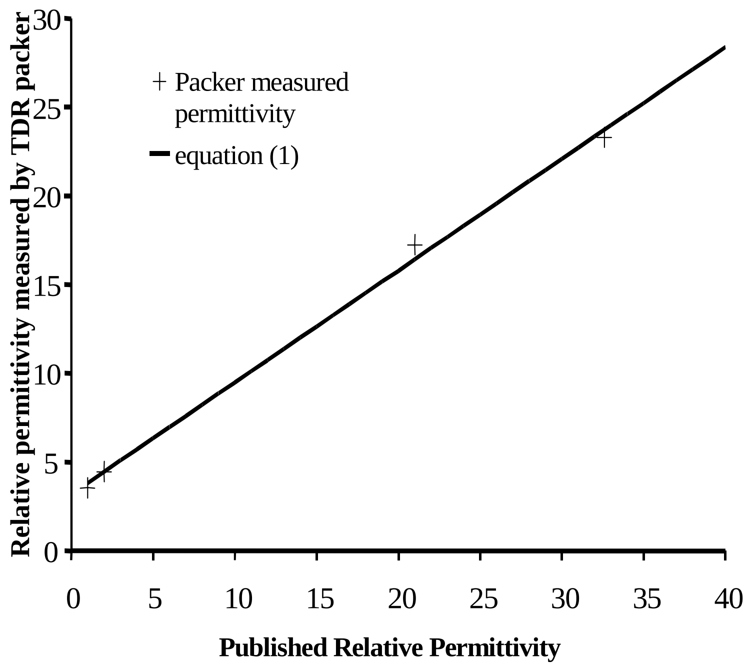

Figure 4. Packer mounted waveguide calibration using liquids of known dielectric constant (Truss et al., 2001)

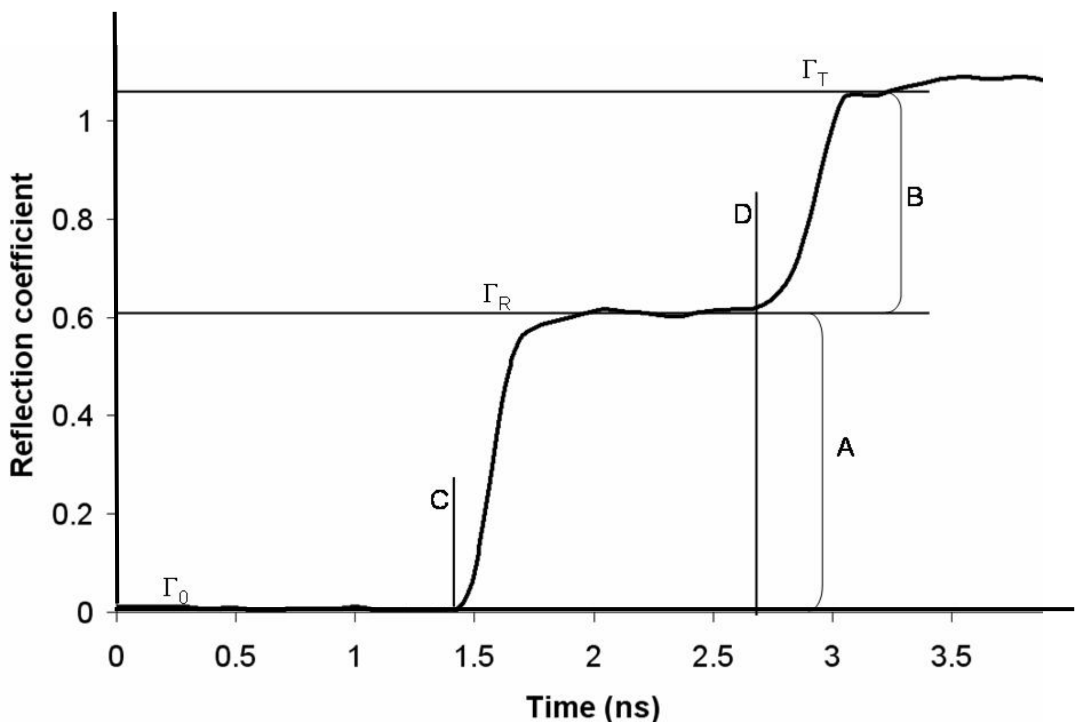

Figure 5 Typical TDR trace

Figure 5 shows an actual TDR trace from the calibration rig shown in Figure 3, taken in air. A reflection occurs every time the impedance of the system changes abruptly. The first step (A) is the reflection as the pulse reaches the waveguide electrodes. The second step (B) is the reflection from the ends of the electrodes. Most traditional picking methods use the time gap (C-

D) between the first and second reflections to calculate the apparent length of the waveguide electrodes (L_a). This is then divided by the true electrode length (L) to obtain the relative dielectric permittivity, which may be used to calculate the volumetric water content using one of the many equations in the literature such as the Topp equation (Topp, 1980). Identification of the start and end of the TDR probes in the recorded signal presents little difficulty for traces with steep reflections, such as that shown in Figure 5. However, traces from the 'high scatter' probes installed at our field site were distorted, making it difficult to accurately pinpoint inflexion points corresponding to the start and end of the probe. This distortion is likely to be a result of long cable lengths. For example, Figure 6 shows a trace from TDR borehole 5, probe 7 which was one of the probes that yielded high scatter water content values; i.e. large random fluctuations between consecutive days, when picked using a conventional method based upon calculation of the apparent waveguide electrode length from the timing of the TDR trace 'jumps'.

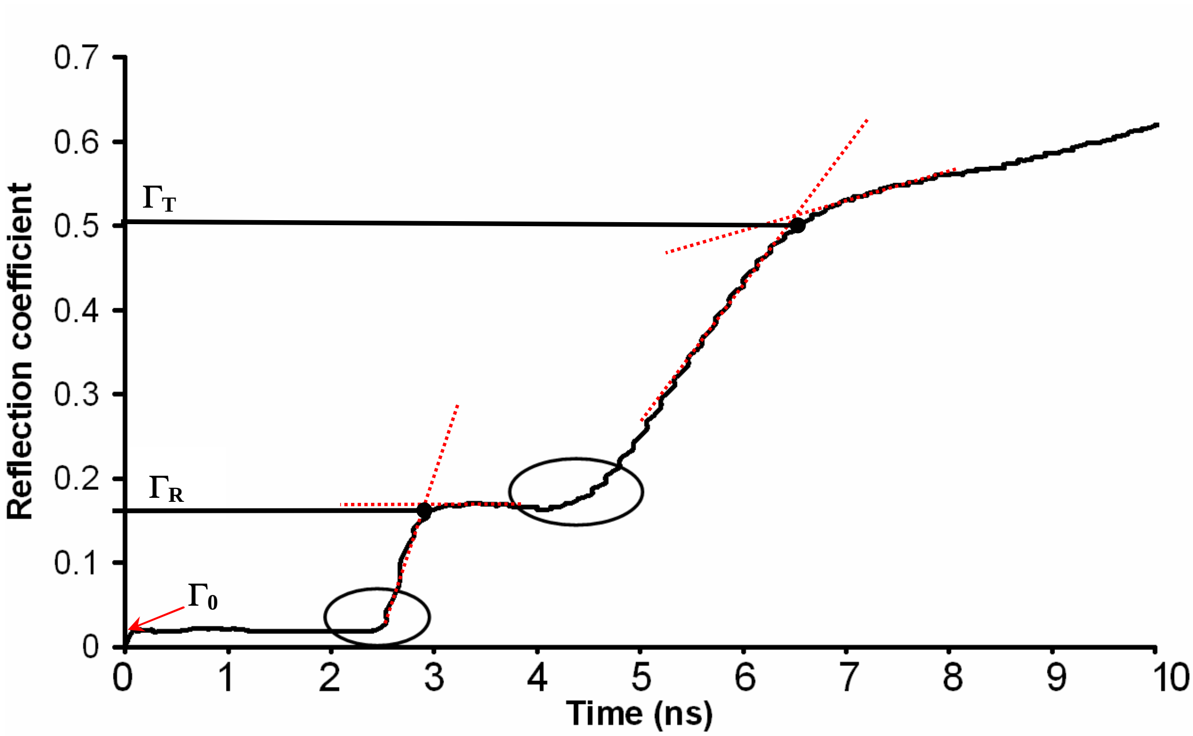

Figure 6. A high scatter probe trace from Borehole TDR 05, Probe 7. The circled areas show where there is an indistinct reflection which would be hard for the software to accurately pick. The locations of Γ_0 Γ_R and Γ_T were picked using the first breaks in slope using tangents as shown.

Figure 7 shows two TDR traces, from borehole TDR 05, probe 7, taken on consecutive days. When superimposed the plots look identical, but the PC208 software returned L_a/L values of 3.353 for trace A and 3.554 for trace B using a tangent picking algorithm. Upon conversion to calibrated moisture contents this resulted in a 5% increase in volumetric moisture content from 0.2 to 0.25 in a single day. This level of increase is typical of high-scatter probes and is very unlikely to be a result of a genuine moisture content change. The traces were manually picked using the tangent and first break methods, to eliminate any possibility that the variation might be due to a data handling error, and the tangent lines are shown on Figure 7. Manually picked L_a/L values using the tangent method yielded values of 3.333 for trace A and 3.560 for trace B, almost identical to those automatically picked using PC208W software. Thus, identification of probe ends using the conventional method proved very difficult.

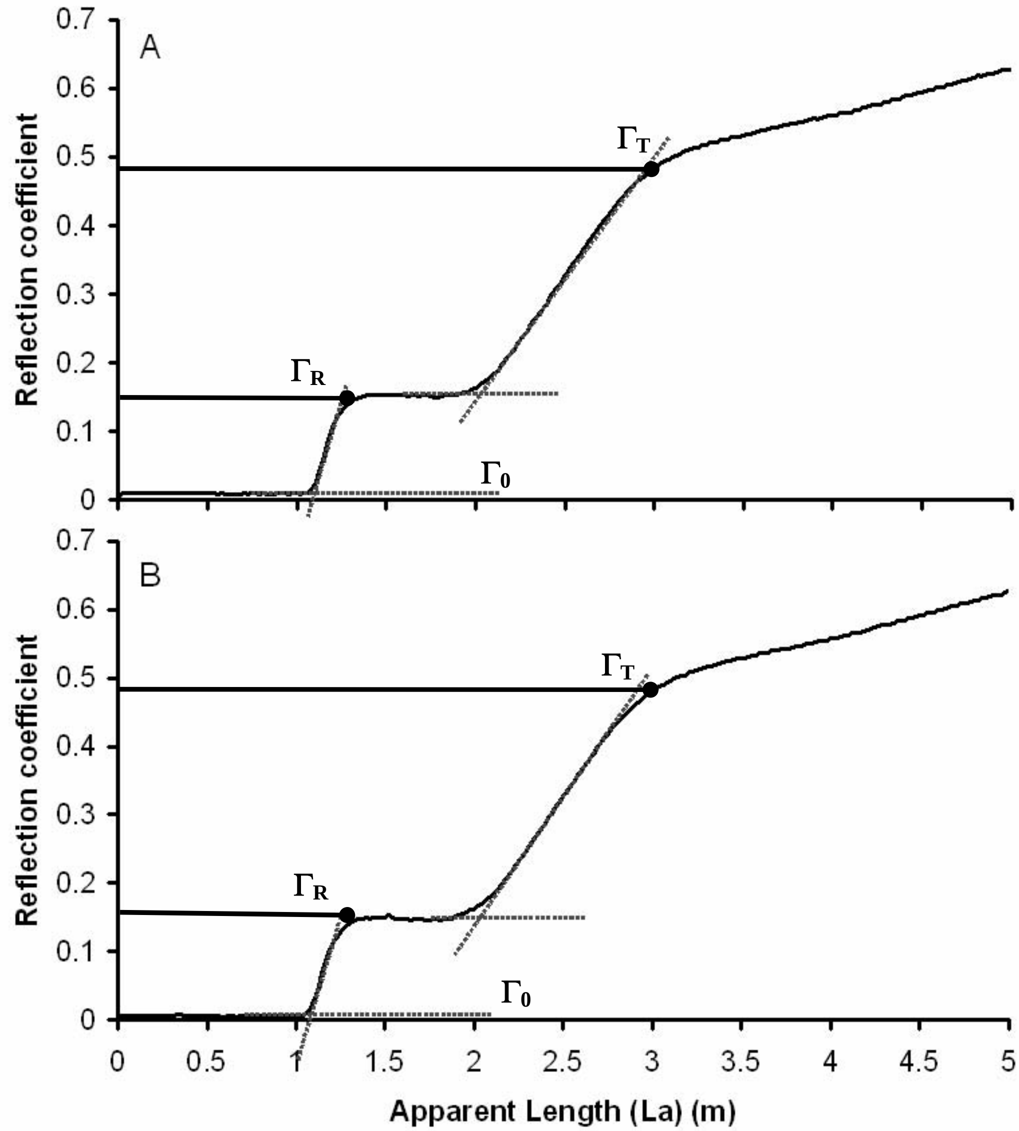

Figure 7. Traces from consecutive days for high scatter probe (Borehole TDR 05, Probe 7). The dotted lines show the tangents used to calculate L_a/L values. The locations of Γ_0 Γ_R and Γ_T were manually picked using tangents (not shown) to determine the first breaks in slope.

In order to obtain water content values from our data, we developed an alternative approach that does not rely on the identification of the exact position of probe ends in the trace. The alternative method described here depends instead upon the reflection coefficient data within the TDR traces. The reflection coefficient (Γ) for each reflected wave may be defined as the ratio between the transmitted and reflected voltages or currents, Rizzi, 1988). The first reflection coefficient (Γ_R) is given by:

$$\Gamma_R = \frac{Z - 50}{Z + 50} \qquad (2)$$

where Z is the probe impedance(Truss et al., 2001). The second reflection co-efficient (Γ_T), which is a result of two transmissions (cable $\Rightarrow$ waveguides and waveguides $\Rightarrow$ cable) plus the reflection from the waveguide tips is given by:

$$\Gamma_T = \frac{200Z}{(Z + 50)^2} \qquad (3)$$

(Truss et al., 2001). Combining eqns (2) and (3) yields and explicit expression for Z in terms of the ratio of Γ_T/Γ_R, which we shall call β.

$$Z = 50\frac{2 + \sqrt{4 + \beta^2}}{\beta} \qquad (4)$$

(Truss et al., 2001). In order to obtain β, three reflection co-efficient values were recorded from each trace, the initial (zero) value (Γ_0), the reflection coefficient of the first step, Γ_R and the reflection coefficient of the second step Γ_T (Figure 5). The Γ_0 value was subtracted from the other values to find β using Eqn (3). Probe impedance itself depends on the permittivity of the rock medium surrounding the electrodes, with increasing permittivity leading to reduced probe impedance, but as there is no analytical expression linking dielectric constant of medium, electrode spacing and width to probe impedance for flat probes, an empirical equation was determined that produced a best fit curve to the calibration data. Values of β determined for traces collected from the calibration liquids were plotted against the known permittivity values for the liquids, and the data were fitted using a 2nd order polynomial expression (Figure 8). The calibration data show that there is a strong relationship between permittivity of the material in front of the probe and β.

The expression relating K and β is given by:

$$K = 242\beta^2 - 264\beta + 72 \qquad (5)$$

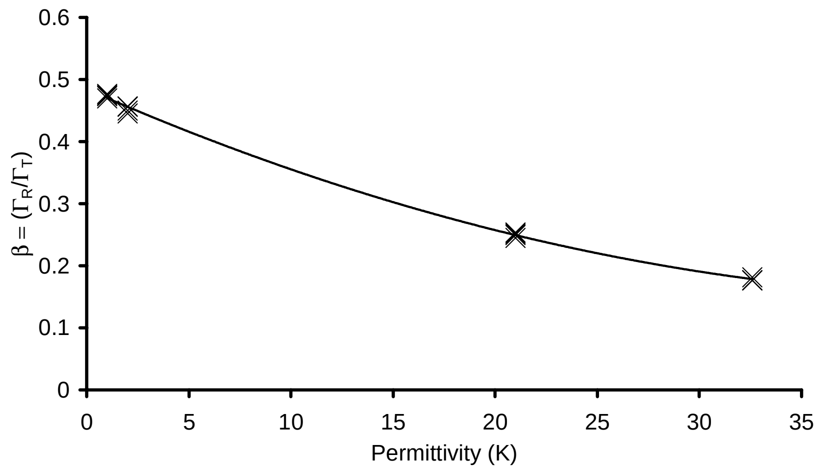

Figure 8. Calibration plot in standard fluids for Γ_R and Γ_T from TDR traces.

Field Validation

The TDR traces were picked manually for Γ0. Γ_R and Γ_T, for both a low-scatter probe (Borehole TDR5 probe 6) and a high-scatter probe (Borehole TDR5 probe 7) over a 28 day period. Plotting the reflection co-efficient derived water contents against those derived using the tangent method (Figure 9) showed values from the low scatter probe plotted very close to the 1:1 line in a tight group approximately 2% water content in diameter. However, the high-scatter probes showed over 5% water content variation in the values obtained using the tangent picking method, but only 2% variation when picked using the reflection co-efficient approach.

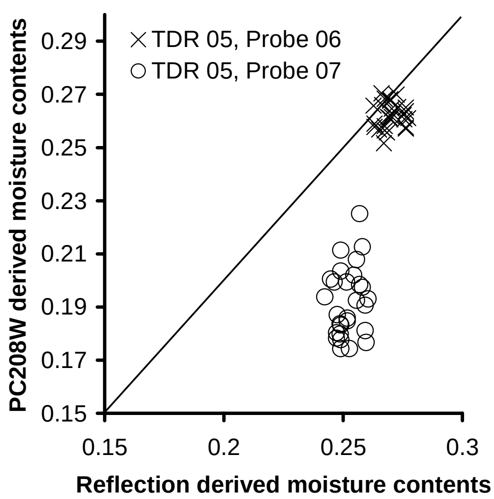

Figure 9. Crossplot of reflection derived moisture contents / moisture contents from PC208W software. Solid line is a 1:1 plot

Furthermore, the reflection co-efficient method returned water content values much closer to the values obtained from probe 6, which was located 1.5m above. Figure 10 shows variation in water content over time changes using both approaches. This plot illustrates both the reduction in 'noise' (i.e. day to day variation) in water content values from the 'high scatter' probe (probe 7) and the shift in water content values that occurs when the reflection co-efficent approach is applied. Application of the reflection co-efficient approach to data from further high-scatter probes, yielded similar results. Hence it can be concluded that the reflection co-efficient method represents a superior approach for obtaining water contents for our data.

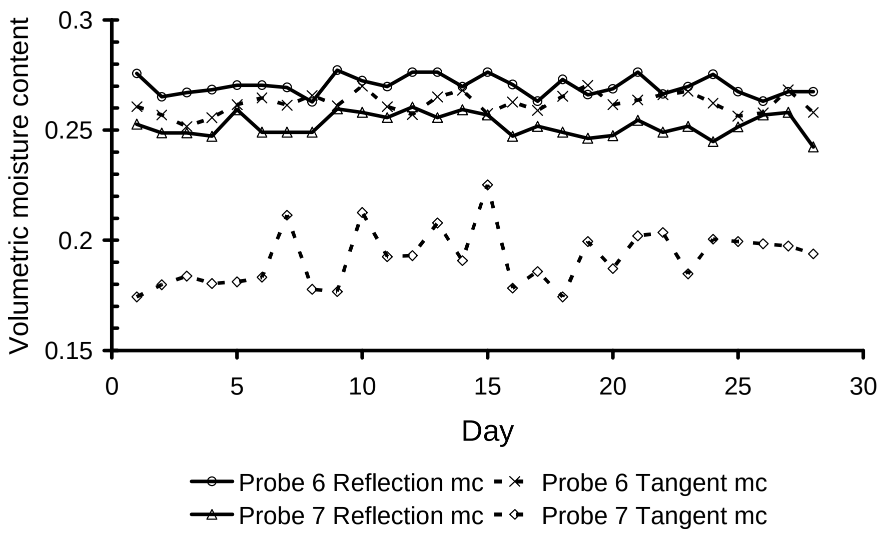

Figure 10. Time-series moisture content data showing reduction in scatter between the reflection and PC208W picking methods.

Summary and conclusions

A borehole packer-mounted TDR system has been installed in the vadose zone of a consolidated sandstone aquifer, to monitor water migration. The packers consisted of dual skin, flexible plastic tube with metal end caps, grouted into boreholes using non-shrinkable grout. TDR waveguide assemblies, consisting of pairs of parallel stainless steel electrodes were mounted vertically on the packer, and held under pressure against the borehole walls.

Field results for a 14m long packer installed in the vadose zone of the Sherwood Sandstone aquifer in the UK are presented. Some probes showed a high degree of scatter between water contents obtained on consecutive days, when traces were picked to obtain probe two way travel times. The primary reason for the high scatter is strongly related to the trace geometry returned by the offending TDR probes, which made accurate picking of the inflexion points corresponding to the probe ends difficult. An alternative method using reflection coefficients to obtain dielectric permittivity and hence water content data was developed. The new method improved data quality for the 'high-scatter' probes while giving the same results as the conventional method for other probes that yielded sharper end-of-probe reflections. These results will be of interest to those attempting to analyse data from TDR installations in conductive environments where end-of-probe reflections are not sharply defined.

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Biography

Steven Truss gained his first degree in Earth Sciences with the Open University in 2000, and was awarded a PhD by the University of Leeds in 2004. Since then he has worked at the University of Miami as a visiting academic researcher and in various roles at the University of Leeds.

Jared West gained his first degree in Natural Sciences from the University of Cambridge in 1988, and was awarded a PhD by the University of Leeds in 1992. Since then he has worked at the University of Leeds in various roles, and is currently a Senior Lecturer in Hydrogeology.

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