ABSTRACT

A system for the application of time domain reflectometry (TDR) to cemented lithologies has been developed. Specially designed TDR probes will be mounted onto borehole packers that are filled with grout and pressurised to force the probes against the walls of the borehole. The system will allow automatic moisture content and electrical conductivity monitoring in the vadose zone of a sandstone aquifer during both natural rainfall events and infiltration experiments, to provide data for fluid flow and solute transport modelling, and ultimately the assessment of groundwater vulnerability to pollution.

The design, calibration and proof testing of the time domain reflectometry borehole packer probes is described in this paper. The optimisation of the geometry and configuration of the packer-mounted waveguides is described. The aims were to produce good reflections from the start and end of the waveguides over the range of dielectric constants seen in the field, thus allowing the two way travel time to be determined accurately, and to maximise sensitivity to the dielectric constant of the rock. Calibration of the packer-mounted waveguides for both moisture content and electrical conductivity is reported. In both cases the calibration is linear which indicates that the packer influence on the waveguide response is a constant and easily removed from the results. Experimental investigation indicates that most of the sensitivity is within ¼ of the waveguide separation distance from the packer. Proof testing in a sand tank shows that volumetric moisture contents accurate to within 0.025 can easily be obtained.

1. INTRODUCTION

Over the previous two decades the technique of time domain reflectometry has been developed for measuring moisture content in soils, and has been widely applied by soil scientists. However, its application for monitoring moisture content in rocks is less well developed, because of the difficulty in inserting the waveguides to the required depths and without air gaps (Hokett et al., 1992; Sakaki et al., 1998). Previous attempts to solve this problem have focussed on the use of short borehole packers with TDR waveguides embedded in their walls that are inserted in uncased boreholes on a temporary basis. However, such systems produce significant errors when used to collect time-series moisture content data, due to the repeated repositioning of the TDR waveguides between subsequent readings. Furthermore, open boreholes may act as preferential flow paths for water. A new borehole packer system is being developed in which packers with multiple TDR waveguides are permanently installed in boreholes by filling with grout. The aim is to provide time series of moisture contents and electrical conductivities at a range of depths in boreholes, to track lateral and vertical water and pollutant movements within the vadose zone of the Sherwood Sandstone aquifer in the UK. The Sherwood Sandstone, a consolidated fluvial sandstone of Permo-Triassic age, is the second most important aquifer in the UK in terms of the amount of groundwater abstracted, and improved understanding of its vadose zone is required for land use planning purposes. TDR data will complement those already obtained using cross hole radar to inform groundwater vulnerability assessment and the development of stochastic models of vadose zone flow (Binley et al. in press; Binley et al. 2001a&b). In this paper, the design of the packers and the TDR waveguides, and the laboratory calibration, spatial sensitivity and proof testing of the waveguides are described.
2. PACKER DESIGN

The depth to the water table is typically between 10-20m at the proposed packer installation sites (Hatfield and Eggborough in West Yorkshire, UK) and the rock is often poorly cemented and weak, which may lead to caving of the borehole sides. The packer design must therefore:

- Assist in maintaining 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.
- Seal the borehole so it does not act as a preferential pathway for moisture flow.

Several methods of achieving these aims have been considered, including mechanical devices to force the waveguides into contact with the rock, but the inflatable packer design shown in Figure 1 was selected due to simplicity and ease of manufacture.

Each packer consists of a 12-18 metre long, 125mm diameter 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. Each packer will be fitted with up to sixteen TDR waveguide assemblies before being lowered into the borehole where it will be filled with cement grout pressurised to force the waveguides into contact with the rock.

Use of large (10m+) inflating packers does present some problems:

- During inflation packers will expands vertically as well as laterally. Any waveguides mounted directly to the packer would be put under tension and risk damage. The spacing between the waveguides could also increase, altering the probe impedance characteristics. Hence, TDR waveguides are mounted on neoprene backing rather than directly on the packers themselves (see Figure 1).
- Cement shrinks upon curing, typically by approximately 0.7%. 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) is added to the grout mixture. The use of compressible neoprene in the waveguide assemblies also allows some cement shrinkage to be accommodated, while allowing the waveguides to maintain contact with and mould to fit any minor irregularities in the borehole wall.

![Figure 1 a) packer design b) waveguide assembly design](image-url)
3. Waveguide arrangement

Commonly TDR probes of either a 2 or a 3-waveguide design are used for determination of soil moisture contents. Several probes with flat waveguides suitable for mounting on packers were constructed for testing and it was found that 2-waveguide designs performed well. There was no appreciable differences in moisture content values between a 3-prong Campbell Scientific CS605 probe and the various 2 waveguide designs constructed in house. Therefore, it was decided in the interests of simplicity to utilise a 2-waveguide design for the long packers.

Experimental investigation of both vertically and circumferentially mounted waveguides (Figure 2) was carried out using waveguides width of 3mm, separation of 30mm and width of 4mm, separation of 40mm (in accordance with the optimum separation to width ratio of 10, described below). The circumferential waveguide configuration posed problems – e.g. difficulties in mounting thin, flexible waveguide assemblies on an expanding packer, limitation of waveguide length to the circumference of the packer, and reduced sensitivity to the dielectric constant of the rock compared with vertically mounted waveguides. The latter effect is the result of the electrical field lines in the circumferential arrangement penetrating further into the packer, and therefore being more influenced by the materials used in packer construction. To avoid these difficulties vertically mounted waveguides were selected.

![Figure 2. a) Vertical electrode arrangement b) circumferential electrode arrangement](image)

With the vertical waveguide arrangement, smaller waveguide separations provided better sensitivity to the moisture content of the rock. This is because of the curved nature of the packer surface, which leads to greater influence of the packer materials at greater waveguide separations. In practice, this is not a major problem unless the penetration of the packer by the electric field is sufficient to ‘see through’ the neoprene layer allowing water content of the cement in the packer to affect the readings. A waveguide separation of 30mm was decided upon as the best compromise between sensitivity to the packer material and adequate penetration into the rock.

Waveguide impedance

Probe impedance needs to be optimised so that both the first and second reflections can be distinguished clearly over the range of moisture content and salinity expected in field conditions, thus facilitating the determination of the two-way travel time for the signal within the waveguides. Assuming that the transmission line formed by the waveguides has zero loss, that changes in impedance happen abruptly where the coaxial cable is joined to the waveguides, and that the coaxial cable has impedance of 50Ω, the reflection co-efficient for the first reflection, $R$, (see Figure 6) is given by:

$$R = \frac{Z - 50}{Z + 50}$$  (1)
where $Z$ is the impedance of the waveguide. The second reflection co-efficient $T$, which is a result of two transmissions (cable $\Rightarrow$ waveguides and waveguides $\Rightarrow$ cable) plus the reflection from the waveguide tips is given by:

$$T = \frac{200Z}{(Z + 50)^2}$$

(2)

The dependence of $R$ and $T$ on $Z$ is illustrated in Figure 3 below.

![Figure 3. Dependence of reflection co-efficients on probe impedance](image)

Figure 3 shows that as $R$ increases, $T$ decreases. A $Z$ nears 50$\Omega$ the first reflection becomes small, hence the TDR waveguides need to have a characteristic impedance greater than 50$\Omega$. The intersection where both jumps are equal can be found by equating (1) with (2) giving a result $Z$ of 211.8$\Omega$. Hence, the optimum probe impedance is 211.8$\Omega$. However, probe impedance depends on the dielectric properties of the medium as well as probe geometry, with increasing dielectric constant leading to reduced probe impedance. Hence in practice a range of probe impedances will occur, according to the dielectric constant of the rock. In order to investigate this, the characteristics of the system were modelled at the Department of Electrical Engineering at the University of Liverpool using the ‘LC’ software for electromagnetic simulation. The results of this modelling showed that in order to provide detectable first and second reflections over the range of dielectric constants expected in the field (3 for dry rock to 37 for saturated rock), the impedance of the packer-mounted probe in air needs to be greater than 250$\Omega$. This ensures the impedance of the probe remains above 50$\Omega$, and the first reflection, $R$, remains detectable even in saturated rock conditions. However the $Z$ value in air should not be too large so as to reduce the second reflection, $T$, to small values. As a compromise an impedance of 275$\Omega$ in air was selected.

The next step in waveguide design was to identify a waveguide geometry that would produce a characteristic impedance of 275$\Omega$ in air, when placed on an appropriate backing material. Further simulation with the ‘LC’ software showed that for thin waveguides mounted on thick plastic backing, an impedance of 275$\Omega$ in air was attainable when the ratio of waveguide separation to waveguide width was equal to 10, regardless of the actual dimensions of the waveguides.

As equations 1 and 2 do not account for losses in the coaxial cable or the BNC connector, it was considered necessary to measure the impedance of a probe constructed to the above specifications, as a check. A prototype field probe was constructed from aluminium of thickness 0.5mm, consisting of 250mm long waveguides, 3mm in width, separated by a 3cm gap, and attached to 6mm thick neoprene backing material with adhesive. A typical TDR trace obtained using the Campbell
Scientific TDR 100 unit for this probe arrangement in air is shown in Figure 4. Assuming no loss in the probe itself (essentially correct for the air/backing material combination seen by the probe), the impedance may be calculated using the ratio of T/R, which we shall call $\beta$.

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

From Figure 4, the first reflection coefficient R is 0.6 and the second T is 0.45, so $\beta$ is 0.783, and using equation (3) gives Z of 275.73 $\Omega$. This is very close to the theoretical value predicted from the LC software (275 $\Omega$).

4. CALIBRATION AND SENSITIVITY ANALYSIS

Moisture content calibration

Probe calibration was undertaken using liquids of known dielectric constant. Cement grout identical to that intended for field use was cast behind a prototype probe assembly to simulate a packer-mounted array. After the cement had set, the probe assembly was removed, voids in the cement were filled, and the cement coated with epoxy resin and silicone sealant to reduce a) voids and b) any tendency of the packer to absorb fluids from its surroundings. The test packer was fixed into a 20-litre container, which was filled with liquids of known permittivity (see Table 1). All calibration tests were carried out at 20°C using a Campbell Scientific TDR 100 unit, using Campbell Scientific PC TDR 2.0 software.

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative dielectric constant</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetone</td>
<td>(20°C) 21</td>
<td><a href="http://www.ctennant.co.uk/proddata/tp00001a.htm">http://www.ctennant.co.uk/proddata/tp00001a.htm</a></td>
</tr>
<tr>
<td>Methanol</td>
<td>(25°C) 32.6</td>
<td><a href="http://www.asiinstr.com/dc1.html">http://www.asiinstr.com/dc1.html</a></td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>(20°C) 2</td>
<td><a href="http://www.asiinstr.com/dc1.html">http://www.asiinstr.com/dc1.html</a></td>
</tr>
<tr>
<td>Water</td>
<td>(20°C) 80.4</td>
<td><a href="http://www.asiinstr.com/dc1.html">http://www.asiinstr.com/dc1.html</a></td>
</tr>
</tbody>
</table>
As the waveguides are mounted on the packer assembly, the measured dielectric constant 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 measured relative dielectric constant $K_{exp}$ will thus be given by

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

(4)

where $w$ is a weighting factor between 0 and 1, determining the relative contribution of the packer materials. The weighting factor $w$ for TDR probes attached to a backing material is independent of the dielectric constant of the measurement medium, provided that the backing material is uniform and thick. This assumption is valid here as the neoprene backing contains most of the rearward sensitivity volume of the probe (see below). The purpose of calibration is thus to determine both $K_{packer}$ and the weighting factor $w$ using liquids with a range of dielectric constants.

Figure 5 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 (4) 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.

**Figure 5. Packer mounted waveguide calibration using liquids of known dielectric constant**

**Electrical conductivity calibration**

The electrical conductivity of the medium surrounding a TDR probe can be determined from the ratio of the applied to the reflected voltage after the first reflection from the probe end, $\rho$,

$$\sigma = \frac{k_p(1-\rho)}{Z_c(1+\rho)}$$

(5)

where $Z_c$ is the cable impedance ($50\Omega$) and $k_p$ is a probe constant (dimensions $L^{-1}$). The probe constant depends on the geometry of the waveguides, and in the case of the packer-mounted probe, on the electrical conductivity of the packer assembly. Here, the probe constant was determined for the test packer by measuring $\rho$ in sodium chloride solutions with a range of salinity. The electrical conductivity of the solutions was measured independently using a Jenway 340 Electrochemistry analyser and conductivity probe. Temperatures were monitored throughout the procedure and all conductivities reported are corrected to those at 10°C.

The TDR traces (Figure 6a) show that the signal travel time is independent of ionic concentration, but that the reflected signal is increasingly attenuated at high salinity. Figure 6b shows a plot of TDR measured conductivity (i.e. found using
equation 5 with $k_p$ equal to unity) against that measured by the conductivity probe. Linear regression analysis gives a probe constant of $8.96 \text{ m}^{-1}$ for this probe arrangement.

**Figure 6.**  

*a) TDR traces from packer mounted probe in salt solutions of various conductivity  
b) Determination of probe constant for packer mounted probe.*
Spatial sensitivity (moisture content)

Knight (1992) investigated the dependence of the spatial sensitivity of TDR probes on waveguide geometry. For typical waveguide geometries with waveguide separation ratios of around 10, sensitivity is focussed in the immediate proximity to the waveguides, but with some sensitivity in an ellipse around the waveguides in plan. A variation on the method described by Baker and Lascano (1989) was used to investigate the sensitivity of packer-mounted electrodes here. A test packer segment with waveguide assembly was attached to a frame that allowed accurate and controlled movement of a row of glass tubes filled with water. These tubes were moved laterally past and away from the waveguides, with the two-way travel times in the probe being measured for each position. Two-way travel times were converted to apparent moisture content in the sensed volume using the equation of Topp et al (1980). The results were normalised to express sensitivity as a percentage of the total probe response along each transect. The results of the sensitivity analysis are shown in Figure 7., two-thirds of the sensitivity occurs within 6mm of the waveguides (i.e. the thickness of the neoprene).

![Graph](image)

**Figure 7. Spatial sensitivity of packer mounted probe to moisture content**

5. PROOF TESTING

The prototype packer-mounted probe was proof tested in sand derived from the Sherwood Sandstone aquifer, to investigate the accuracy in determination of volumetric moisture content using the calibration derived above. A sample of Sherwood Sandstone sand was oven dried at 105°C for 24 hours, and sieved through a 1.8mm sieve to remove any cemented lumps.
Approximately 11kg of oven dried sand was tamped into a large tray (the volume occupied by the sand was recorded in order to obtain the dry density). The volumetric moisture content was determined by pressing the packer-mounted probe onto the surface of the sand. Tap water was progressively added to the sand, 0.5 litres at a time, mixing to ensure homogeneity of moisture content and re-tamping as far as possible into the same volume (some difficulties were experienced in compacting the sand down to the same volume, which may have affected the calculation of volumetric moisture content). A TDR volumetric moisture content was recorded for each moisture increment by applying the Topp equation (Topp et al., 1980) to the dielectric permittivity of the sand found using the probe calibration parameters in equation (4). The Topp equation is known to accurately relate dielectric constant to moisture content for Sherwood Sandstone at TDR frequencies (West et al., 2001). The results of proof testing are presented in Figure 8 below.

![Figure 8. Results of proof testing borehole TDR packer in Sherwood Sandstone sand](image)

The probe mounted packer measures volumetric moisture content remarkably well, to within 0.025 of the values estimated from the mass of water added. The accuracy of the TDR packer itself is probably even better than this, as most of the scatter shown is probably the result of actual volumetric moisture content variation in the sand rather than error.

### 6. SUMMARY AND CONCLUSIONS

A borehole packer-mounted TDR system for measuring the moisture content and electrical conductivity of rock has been designed, calibrated and proof tested. The system is designed to be installed in the vadose zone of a consolidated sandstone aquifer, to monitor water and pollutant migration. The packer consists of a flexible plastic tube with metal end caps, which can be grouted into a borehole using non-shrinkable grout. TDR waveguide assemblies are mounted onto the packer and pressed against the borehole walls. The geometry and configuration of the waveguides was selected to ensure that the reflections from the start and end of the waveguides would be significant over the range of dielectric constant values encountered in field conditions, and to maximise sensitivity to the dielectric constant of the borehole walls. The resulting design consisted of waveguides which were 0.5mm thick, 3mm wide and 30mm apart, and 250mm long, mounted vertically on the packer. The measured impedance of the waveguides closely matched that predicted from theoretical modelling.
The packer mounted TDR waveguides were calibrated using liquids of known dielectric constant and aqueous solutions of known electrical conductivity. The calibrations are essentially linear which indicates that the proportion of the sensed volume that resides inside the packer assembly does not depend on the dielectric constant of the surrounding medium. Experimental investigation using water filled glass tubes indicates that 90% of the sensitivity to moisture content is focused within 7.5mm or so of the waveguides, which illustrates the importance of eliminating air gaps between the packer and the borehole walls. It also shows that the probes are not sensitive to the properties of the grout in the packer because of the intervening backing materials. A prototype packer was proof tested in a tank containing sand at varying degrees of saturation. It performed well despite difficulties in maintaining constant sand density, giving moisture content readings within ±0.025 of the bulk value.

7. ACKNOWLEDGEMENTS

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8. REFERENCES