Measuring soil water content with time domain reflectometry and ground-penetrating radar
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Abstract

For the measurement of soil bulk electrical conductivity using time domain reflectometry (TDR), it is necessary to determine cable and probe properties. This can be done by direct measurement or by calibration of the TDR-system in salt solutions. For a 3-wire probe system, the results showed that with least-squares fitting, the electrical conductivity of salt solutions could be measured most accurately. Comparison of several calibration techniques suggested that directly measured cable properties deviate from their calibrated (optimal) values. The difference in accuracy between calibration and direct measurements of cable properties could not be explained with overfitting, as has been suggested. It was concluded that a reduction of calibration time by direct measurement of cable and probe properties is not advisable in case of 3-wire probes. When necessary, a reduction of calibration time can be achieved by limiting the calibration procedure to two well-chosen combinations of cable length and solution concentration.
4.1 Introduction

Time Domain Reflectometry (TDR) is used to measure soil bulk electrical conductivity ($\sigma_{soil}$). Giese and Tiemann (1975) suggested to calculate the load resistance $R_L$ [Ω] from the reflection coefficient at long times ($\rho_x$). To avoid overestimation of the sample resistance, $R_L$ should be corrected for resistance of the cable per meter $R_c$ [Ωm$^{-1}$] and the combined extra series resistance $R_0$ [Ω] caused by connectors and cable tester (Heimovaara et al., 1995)

$$\sigma_{soil} = \frac{K_p}{R_L - (CL \times R_c + R_0)}$$  \hspace{1cm} [4.1]

where $CL$ is the cable length [m] and $K_p$ the probe constant [-].

Heimovaara et al. (1995) and Mallants et al. (1996) calibrated cable and probe properties ($R_0$, $R_c$ and $K_p$) using a least-squares fitting of TDR-conductivity measurements in solutions of different concentration to conductivity measurements made with a laboratory conductivity meter (Radiometer Copenhagen CDM83 conductivity meter with CDC314 measurement cell). Recently, Reece (1998) proposed a method to measure $R_c$, $R_0$ and $K_p$ directly. He suggested that direct measurements would eliminate the need for a time-consuming calibration in multiple solutions. His method is based on resistance measurements of a coaxial cable with and without a shorted transmission waveguide. For his 2-wire probes, direct measurement of $R_c$, $R_0$ and $K_p$ resulted in reliable conductivity measurements, but the cable and probe properties obtained with least-squares fitting resulted in even more accurate conductivity measurements. He stated that the higher accuracy using the least-squares fitting method indicated that the fitting procedure adjusts $R_c$, $R_0$ and $K_p$ to account for small measurement errors not necessarily associated with these parameters (overfitting). However, the higher accuracy may also suggest that the theory is incomplete and that the fitting procedure corrects for the deviations from the theory. Besides the comparison of calibration and direct measurements, this 'overfitting'-suggestion of Reece (1998) is also examined in this chapter.

4.2 Methods

There are two approaches to obtain direct estimates of the probe constant $K_p$. For probes correctly emulating a coaxial cable, the probe constant can be calculated from

$$K_p = \frac{\varepsilon_0 c Z_0}{L}$$  \hspace{1cm} [4.2]

where, in case of the 3-wire probes used in this chapter, $Z_0$ can be approximated by (Heimovaara, 1993)
and $\varepsilon$ is the permittivity of the material in the probe $[\text{]}$, $\epsilon$ is the speed of light $(3 \times 10^8 \text{ m/s})$, $L$ is the length of the probe $[\text{m}]$, $Z_0$ is the characteristic impedance of the probe $[\Omega]$, $\varepsilon_0$ is the dielectric permittivity of free space $(8.854 \times 10^{-12} \text{ F/m})$, $a$ is the outer diameter of the inner wire and $b$ is the inner diameter of the outer wires $[\text{m}]$. Alternatively, $Z_0$ can be inferred from measurements of the reflection coefficient ($\rho$) at a time $t$, corresponding to the location of the waveguide in a non-conductive medium of known permittivity, $\varepsilon$, according to

$$Z_0 = Z_a \sqrt{\frac{1+\rho_t}{1-\rho_t}}$$

[4.4]

where $Z_a$ is the characteristic impedance of the cable tester system $(50 \Omega)$. In a lossy or dispersive medium the reflection coefficient will be diminished by conduction thus reducing the ratio in equation 4.4. Generally, it is suggested to measure $\rho$ in a loss-less medium like demineralized water, but the choice of the position of $\rho$ remains arbitrary (Heimovaara, 1992; Baker and Spaans, 1993).

To compare calibration with direct measurement (Reece, 1998), a total of 25 measurements were made in demineralized water and 4 KCl-solutions with conductivities of 0, 11, 119, 232 and 439 mS/m for 5 cable lengths (ranging from 5 to 25 m of RG58 C/U coaxial cable). We used a 3-wire probe (Heimovaara, 1993) and a Tektronix 1502C cable tester (Beaverton, OR, USA). The methods to obtain $R$, $R_0$ and $K_p$ directly ($K_p$ with equation 4.2 and 4.3 (Method 1) or equation 4.2 and 4.4 (Method 2)) are compared with results of least-square fitting of $K_p$ with directly measured cable properties (Method 3), and with least-square fitting of both $K_p$ and cable properties (Method 4). Measurements were randomly separated in a calibration (12) and a validation set (13). Subsequent calibration and validation were repeated 150 times for different sets.

### 4.3 Results and Discussion

Resistance measurements with shorted coaxial cables, as proposed in the method of Reece (1998), resulted in a cable resistance $R_c$ of 0.050 $\Omega$ and an internal cable tester and connector resistance of 0.080 $\Omega$ (figure 4.1). Resistance measurements with shorted probes attached to the cables resulted in an upward resistance shift, which resulted in a probe resistance of 0.373 $\Omega$ and a total internal resistance $R_0$ of 0.453 $\Omega$. This confirms Reece's (1998) speculation that the probes used by Heimovaara et al. (1995) had a relatively high $R_p$. Validation of the methods to obtain $R$, $R_0$ and $K_p$ (table 4.1) showed that probe constants estimated from either equation 4.3 or 4.4 resulted in less reliable conductivity measurements. Apparently, both methods of obtaining $K_p$ directly should be applied with care in...
Table 4.1. Results of calibration and validation for five procedures for obtaining cable ($R_c$ and $R_0$) and cable properties ($K_p$). Results presented are mean and standard deviations (in parentheses) of Root Mean Square Error (RMSE) for 150 randomly selected calibration and validation sets. If no calibration was performed, the methods were validated on 150 randomly selected validation sets consisting of 13 measurements each. Results of direct measurements are given in italics.

<table>
<thead>
<tr>
<th>Method</th>
<th>$K_p$</th>
<th>$R_0$</th>
<th>$R_c$</th>
<th>RMSE (cal.) ($\text{mSm}^{-1}$)</th>
<th>RMSE (val.) ($\text{mSm}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Probe dimensions (eq. 4.3)</td>
<td>3.670</td>
<td>0.453</td>
<td>0.050</td>
<td>-</td>
<td>51.53</td>
</tr>
<tr>
<td>2 Reflection at $t$ (eq. 4.4)</td>
<td>5.560</td>
<td>0.453</td>
<td>0.050</td>
<td>-</td>
<td>37.85</td>
</tr>
<tr>
<td>3 $K_p$ fitted</td>
<td>4.773</td>
<td>0.453</td>
<td>0.050</td>
<td>2.883</td>
<td>3.658</td>
</tr>
<tr>
<td></td>
<td>(0.027)</td>
<td>(-)</td>
<td>(-)</td>
<td>(-)</td>
<td>(4.81)</td>
</tr>
<tr>
<td>4a $K_p$ and $R_0$ fitted</td>
<td>4.668</td>
<td>0.740</td>
<td>0.050</td>
<td>2.305</td>
<td>3.702</td>
</tr>
<tr>
<td></td>
<td>(0.046)</td>
<td>(0.178)</td>
<td>(-)</td>
<td>(0.792)</td>
<td>(0.964)</td>
</tr>
<tr>
<td>4b $K_p$ and $R_c$ fitted</td>
<td>4.664</td>
<td>0.453</td>
<td>0.070</td>
<td>0.715</td>
<td>1.379</td>
</tr>
<tr>
<td></td>
<td>(0.014)</td>
<td>(-)</td>
<td>(0.004)</td>
<td>(0.252)</td>
<td>(0.675)</td>
</tr>
<tr>
<td>4c All parameters fitted</td>
<td>4.657</td>
<td>0.479</td>
<td>0.070</td>
<td>0.590</td>
<td>1.712</td>
</tr>
<tr>
<td></td>
<td>(0.019)</td>
<td>(0.096)</td>
<td>(0.005)</td>
<td>(0.222)</td>
<td>(0.939)</td>
</tr>
<tr>
<td>4 specific measurements$^1$</td>
<td>4.633</td>
<td>0.522</td>
<td>0.067</td>
<td>-</td>
<td>1.152</td>
</tr>
<tr>
<td></td>
<td>(-)</td>
<td>(-)</td>
<td>(-)</td>
<td>(-)</td>
<td>(0.309)</td>
</tr>
</tbody>
</table>

$^1$ All parameters fitted, only 4 cable length $\times$ solution concentration combinations.

Figure 4.1. Resistance as a function of cable length measured by a cable tester on coaxial cables terminating in a short (with and without a probe). Fitted regression lines are $Y=0.080+0.050X$ ($R^2=0.997$) for the shorted cables and $Y=0.453+0.050X$ ($R^2=0.997$) for the shorted probe with cables.
Comparison of Calibration and Direct Measurement

the case of 3-wire probes. For the probe constant calculated from probe dimensions (equation 4.3) this was expected, because it is well established that 3-wire probes do not behave as coaxial probes and tend to underestimate true probe constants (Zegelin et al., 1989). Direct estimation of \( K_p \) from TDR waveforms (equation 4.4) did not result in reliable conductivity measurements either, because \( Z_0 \) was overestimated. Again, an explanation for this overestimation can probably be found in the non-coaxial behavior of 3-wire probes.

Acceptable conductivity measurements were obtained when directly measured cable properties were combined with a probe constant fitted to measurements in multiple solutions (Method 3). This illustrates that calibration with measurements in multiple solutions improves the accuracy of conductivity measurements with TDR in case of 3-wire probes. However, table 4.1 also shows that an even higher accuracy of conductivity measurements for both calibration and validation was easily achieved by optimizing all three parameters (Method 4c). This improvement in accuracy was accompanied by a greater magnitude of fitted \( R_p \) as can be seen from the partial optimization of cable properties (Method 4a and 4b). Apparently, direct measurements of cable properties do not result in the most accurate conductivity measurements. The fact that the improvement in accuracy was seen in both the calibration and validation set indicates that overfitting is not the primary explanation for the higher accuracy of the fitting procedures, as has been suggested by Reece (1998).

A reduction of calibration time by direct measurement of \( R_s, R_0 \) and \( K_p \) does not appear feasible in the case of 3-wire probes. A simplification of the calibration procedure might be considered when extensive calibration in multiple solutions is a problem. One possibility is to reduce the fitting procedure to only two cable lengths and two solution concentrations. For the validation set this approach resulted in a low RMSE of 1.152 when cables of 25.6 and 4.1 m and solutions of 120 and 439 mSm\(^{-1}\) were used. Other calibration sets of four measurements also resulted in accurate conductivity measurements, provided that the selected cable lengths and solution concentrations covered the range of expected values. This illustrates that only four well-chosen measurements contain all the information needed to obtain \( R_s, R_0 \) and \( K_p \), as can be expected from the simple nature of the underlying equations.

In summary, although the methods presented by Reece (1998) do have the advantage of being direct measurements, care should be taken when these methods are applied to 3-wire probes. For a 3-wire probe system, least-squares fitting of cable and probe properties resulted in the most accurate conductivity measurements. Comparison of several calibration techniques suggested that directly measured cable and probe properties deviate from their calibrated (optimal) values. It is certainly important (and curious) to note that there are unexplained differences
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between direct and empirical methods. Furthermore, it was suggested that a reduction of calibration time could be achieved by limiting the calibration procedure to two well-chosen cable lengths and solution concentrations.