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Comparison of Three Methods to Calibrate TDR for Monitoring Solute Movement in Undisturbed Soil

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ABSTRACT

Time domain reflectometry (TDR) is rapidly becoming a popular method for measuring solute concentrations in the laboratory as well as in the field. Success or failure of TDR to represent solute resident concentrations depends on the accuracy of the invoked calibration. In this study, we compared three commonly used calibration methods that relate the impedance, Z_0 as measured with TDR, to the solute concentration such as the inlet concentration, C_0. The comparison was carried out using solute transport data obtained from l-m-long, 0.3-m-diam. undisturbed saturated soil columns. The first method comprised the application of a long enough solute pulse such that the concentration in a soil column became equal to the input concentration. The second method involved numerical integration of the observed response to a tracer pulse input function from which Z_0 could be obtained. The third method determined Z_0 using an independently measured relationship between the impedance and the solute concentration. The three calibration methods gave approximately the same results for the first observation depth at x = 0.05 m. However, the presence of heterogeneous transport processes involving solute diffusion from mobile to immobile water regions predicated the use of excessively long solute pulses in order to equilibrate the entire soil column to the input concentration. The first method hence was useful only for the shallower depths. The second method could be applied throughout the soil profile, provided impedance measurements were made for a reasonable time period, especially in the case of nonequilibrium transport. The procedure using an independently measured Z-C relationship underpredicted Z_0 in about 50% of the cases, presumably because of the use of repacked soil in the calibration.

SEVERAL STUDIES have recently demonstrated the potential of TDR for measuring solute transport in laboratory soil columns as well as field soil profiles (e.g., Kachanoski et al., 1992; Wraith et al., 1993; Vanclooster et al., 1993, 1995; Mallants et al., 1994; Ward et al., 1994). Potential advantages of TDR have been discussed at length in the above literature, and are not repeated here. A possible disadvantage of TDR is its usefulness primarily for nonreactive tracers and low EC soils.

Success or failure of TDR to accurately measure solute concentrations depends strongly on the appropriateness of the calibration procedure being used. The assumed calibration is also important for EC measurements using conventional four-electrode salinity probes (Rhoades et al., 1989). Since TDR measures the total resistance or impedance, Z, of a soil to the flow of electromagnetic energy, solute concentrations can be inferred from impedance readings if a particular value of the impedance, Z_0, can be related to a known value of the concentration, such as the concentration of the inlet solution, C_0. A linear relationship between Z and C has been observed for instance by Ward et al. (1994) for different values of water content, θ, although at higher values of θ some nonlinearity exists for low concentrations. By means of such Z-C relationships, impedance distributions can subsequently be translated back to solute distributions. The three most commonly used calibration methods are: TDR measurement of a continuous solute application until some constant value Z_0 is obtained (referred to hereafter as Method 1), TDR measurement of a pulse-type solute application using the concept of convolution (Method 2), and determination of an independent Z-C calibration using disturbed or undisturbed soil (Method 3). Any of these three methods works well for relatively homogeneous sandy soils or repacked soil columns (Kachanoski et al., 1992; Vanclooster et al., 1993; Ward et al., 1994). However, calibrations may become problematic for soils exhibiting small-scale heterogeneities due to the presence of macropores, immobile water regions, or low-permeability zones. This problem was demonstrated by Mallants et al. (1994), who used TDR to measure solute concentrations in a sandy loam soil containing a large number of macropores. They showed that the TDR sampling volume for their macroporous soil may have been too small to yield accurate values

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Abbreviations: TDR, time domain reflectometry; EC, electrical conductivity; PVC, polyvinyl chloride; BTC, breakthrough curve.

of the average concentration across the soil column. Mallants et al. (1994) subsequently employed Method 1 by adding a very long solute pulse so that the conditions that C = Co (or Z = Z_0) at the detection volume was satisfied. This method, however, also has problems if zones of low permeability and/or stagnant water are present within the sampling volume of the TDR probe; the solute may then require an inordinate amount of time in order to spread uniformly by diffusion across the entire cross-section of the column.

In this study we compared these three calibration methods for relating TDR impedance readings to solute concentrations using data measured at six different depths in 1 -m-long, 0.3-m-diam. water-saturated undisturbed soil columns. First, we evaluated the accuracy of Method 1 to calibrate the Z-C relationship from a very long tracer pulse, i.e., until Z becomes constant and equal to Z_0. Second, the results from a numerical convolution of the solute pulse response was investigated (Method 2). Next, we examined the applicability of an independently measured relationship between the bulk soil EC (EC,) and the EC of the soil liquid phase (EC,) as a function of the soil water content, θ (Method 3). Values for the calibration constant, Z_0, obtained with Methods 2 and 3 were compared with impedance data obtained using Method 1.

MATERIALS AND METHODS

Solute transport processes were examined on 30 undisturbed soil columns taken 1 m apart at the Bekkevoort experimental field, east of Leuven, Belgium. Details of the experimental design and the transport experiments can be found in Mallants et al. (1995, unpublished data). Soil water contents, θ, and bulk soil electrical conductivities, EC, were monitored by means of TDR probes installed horizontally at six different depths (0.05, 0.15, 0.30, 0.45, 0.60, and 0.80 m) under constant temperature conditions. Time-averaged water contents based on all 30 columns were 0.37, 0.34, 0.33, 0.33, 0.33, and 0.35 $m^3 m^{-3}$ for the six observation depths mentioned above. Standard errors of observed θ are very small ranging from 0.002 to 0.004, which is within the range of TDR instrument variability. The mean water flux was 0.0078 m h^{-1}, with a standard deviation of 0.0064 m h^{-1}. After establishing steady-state saturated flow using solute-free water, long-duration solute pulses containing 7 $\times 10^{-3}$ M $CaCl_2$ were applied in order to "saturate" the soil column with the applied tracer solution (i.e., until C = C_0 in the columns). Solute application times (t_0) ranged from 79 h for 14 columns to more than 660 h. Measurements were made with a Tektronix cable tester (Tektronix 1502B, Beaverton, OR) and the channels were multiplexed manually. Values of Z were obtained for 0.25-m-long two-rod TDR probes (0.005-m diam. and 0.02-m spacing). The travel time of the electromagnetic wave and the impedance Z were taken from the screen of the cable tester. Values of Z are calculated by taking the reflection coefficient, ρ, at long times ($t \rightarrow \infty$) on the reflected wave form (see Fig. 1). The impedance where the wave form has reached a stable level, Z_∞ is calculated from:

$$Z_\infty = Z_c \frac{(1 + \rho_\infty)}{(1 - \mathrm{Pm})} \qquad [1]$$

where Z_c is the impedance of the coaxial cable (50 Ω), and ρ_∞ is the reflection coefficient at long times (Fig. 1).

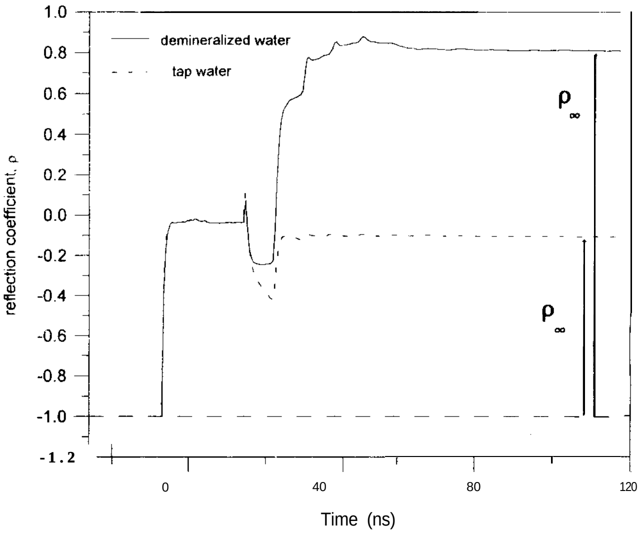

Fig. 1. Typical wave form of a two-rod TDR probe without balun inserted in demineralized water and tap water (electrical conductivity = 0.75 dS m^{-1}) at 20°C. Values of the reflection coefficient at long times, ρ_∞, were obtained by positioning the screen cursor at long times when all multiple reflections had disappeared.

Calibration of the Solute Concentration-Impedance Relationship

As shown by several researchers (e.g., Kachanoski et al., 1992), solute concentrations may be deduced from TDR-based estimates of the EC,. A linear relationship is generally observed between the resident solute concentration, C, and EC, for constant water contents ranging from relatively low to saturation, and for salinity levels ranging from 0 to approximately 50 dS m^{-1} (Diels et al., 1994, unpublished data; Ward et al., 1994):

$$C = \alpha + \beta \, \mathrm{EC_a} \qquad [2]$$

where a and β are calibration constants. The EC, (dS m^{-1}) can be related to the impedance, Z (Ω), of an electromagnetic wave that travels through the soil using (Topp et al., 1988 and references herein; Heimovaara et al., 1995):

$$\mathrm{EC,} = \frac{K_c}{Z - Z_{\mathrm{cable}}} \qquad [3]$$

where K_c is the cell constant of the TDR probe (m^{-1}), and Z_{cable} (Ω) is the resistance associated with cable, connectors, and cable tester. For salinity levels less than ≈0.3 S m^{-1}, $Z_{\mathrm{cable}} << Z$ in Eq. [3] and is therefore omitted in the following discussion. When the cable resistance, Z_{cable} = 0.2 Ω, was accounted for (using a 50 Ω coaxial cable of approximately 2 m), a perfect linear relationship was found between solution EC and TDR-measured EC, with the slope K_c = 2.937 m^{-1} (see Fig. 2). It is evident from Fig. 2 that TDR measurements not corrected for cable resistance underestimate conductivity when EC > -0.3 S m^{-1}. The cell constant K_c was obtained by measuring Z when immersing the TDR probe in five different salt solutions of known conductivity ranging from 0 to 1.2 S m^{-1} (see also Nadler et al., 1991; Heimovaara et al., 1995). Electrical conductivity measurements were carried out with a laboratory four-electrode EC meter (WTW, Weilheim, Germany, LF 92 conductivity meter with TetraCon 96 measurement cell). We note here that calibrations based on Eq. [2] and/or [3] are not a unique issue for TDR, but a general

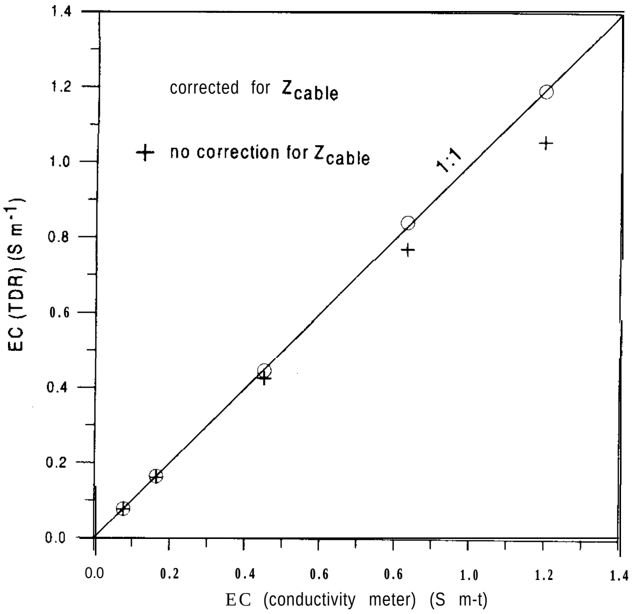

Fig. 2. Electrical conductivity, EC, measured with a conductivity meter vs. EC calculated from two-rod TDR probes in five different KCl solutions. Open circles represent TDR measurements corrected for cable resistance.

problem for any EC measurement device, whether TDR, an electrical conductivity probe, or electromagnetic induction.

Relative solute concentration, $c(x,t)$, can be expressed as

$$c(x,t) = \frac{C - C_i}{C_0 - C_i} \qquad [4]$$

where C_0 is a reference concentration such as the input concentration during miscible displacement, and C_i is the background concentration. Inserting Eq. [2] into Eq. [4] and using Eq. [3] leads to

$$c(x,t) = \frac{Z_{x,t}^{-1} - Z_i^{-1}}{Z_0^{-1} - Z_i^{-1}} \qquad [5]$$

where Z, is the impedance before application of the tracer solution, and Z_0 is the impedance associated with the reference concentration, C_0. Equation [5] shows that, under steady flow conditions (i.e., constant soil water content) the relative solute concentration c at a particular depth, x, and time, t, can be derived from the measured impedance $Z_{x,t}$ if appropriate values of Z, and Z_0 are available. In this study, values for Z_i and Z_0 were determined for each depth and column separately because of local variations in water content and soil texture. Values for the background impedance Z_i at concentration C_i are readily obtained from the initial condition while, for homogeneous soils, values for Z_0 can be related to the reference concentration C_0 using one of the following three methods.

Method 1: Continuous Solute Application

The impedance, Z_0, can be immediately related to the input solution concentration C_0 by applying a long enough (continuous) solute pulse until the solutes have distributed uniformly throughout the soil profile. This method is most commonly used for TDR calibration. The procedure was previously used by Rhoades (1981) and Rhoades et al. (1989), among others, to establish relationships between ECa, ECw and θ of field soils using four-electrode salinity probes. Ward et al. (1994) found for their loamy sand that essentially the same impedance Z_0 was obtained when such a step increase of tracer solution was compared with the convolution of a pulse application (Method 2) with the same concentration C_0.

Method 2: Convolution Method

When a continuous tracer solution ($t_0 \rightarrow \infty$) is applied during steady-state flow to a soil profile having background concentration C_i, the local concentration C in the soil can remain less than Co for relatively long periods of time, especially at large depths in structured soils exhibiting nonequilibrium transport. Rather than assuming that C = C_0 at a TDR detection point, Method 2 assumes mass conservation of a solute pulse (t_0 finite) passing through the detection volume for a uniform velocity field, i.e., the amount of solute passing the detection volume should be equal to the amount (Cot,) applied to the soil surface. Integrating Eq. [5] between times 0 and ∞ yields, for a linear system:

$$c_0 t_0 = \frac{1}{Z_0^{-1} - Z_i^{-1}} \int_0^{\infty} (Z_{x,\tau}^{-1} - Z_{x,i}^{-1}) d\tau \qquad [6]$$

where τ is time. As long as t_0 and Z, are known, Z_0 can be determined from the convolution integral in Eq. [6] using the measured impedance curve Z(t) (see also Ward et al., 1994). Strictly speaking, the above equation is valid for flux-averaged concentrations (Kreft and Zuber, 1978) whereas TDR detects total resident concentrations. We assume, however, that the difference between resident and flux-averaged concentrations is relatively minor compared with the mass balance error due to local fluctuation of flow velocity. Equation [6] is incorrect when the pore-water velocity at the TDR detection point is different from the inflow velocity.

Method 3: Experimentally Determined EC_a-EC_w-θ Relationship

Equation [3] shows that the EC, may be calculated directly from the TDR-measured Z if the cell constant for the TDR probe, K_c, and Z_{cable} are known. In order to relate Z with C, it is further necessary to describe EC, as a function of the EC, and θ. This is because θ was found to fluctuate between the soil columns used for our transport experiments, as well as vs. depth within some of the columns. For a given θ, the relation between EC, and EC, may be given in a linear form (Rhoades et al., 1976):

$$EC, = EC; + T\theta EC_w \qquad [7]$$

in which EC,' is apparent electrical conductivity of the solid phase of the soil, and T is a transmission coefficient accounting for the tortuosity of the current flow. In a more recent study, Rhoades et al. (1989) interpreted T as the mobile water fraction (soil water in the large pores). The EC_a-EC_w relationship for this study was determined using repacked sandy loam soil taken from the upper Ap horizon (O-O.25 m) of the same transect as used for the soil columns. Particle-size distribution of the soil is 12.65% clay, 13.10% silt, and 74.25% sand. Calibration experiments were carried out by mixing dry soil material with known volumes of water containing eight different concentrations of $CaCl_2$ (ranging from 0 to 32 g L^{-1}). The soil packed into PVC boxes (0.32 m long, 0.25 m wide, and 0.21 m high) had a uniform bulk density of 1.4 Mg m^{-3} with θ of 0.12, 0.24, and 0.38 $m^3 m^{-3}$. Calibration experiments were carried out for eight different concentrations of $CaCl_2$ (ranging from 0 to 32 g L^{-1}). Upon application of Eq. [3], all readings of Z were transformed to ECa, using a previously determined value for K_c.

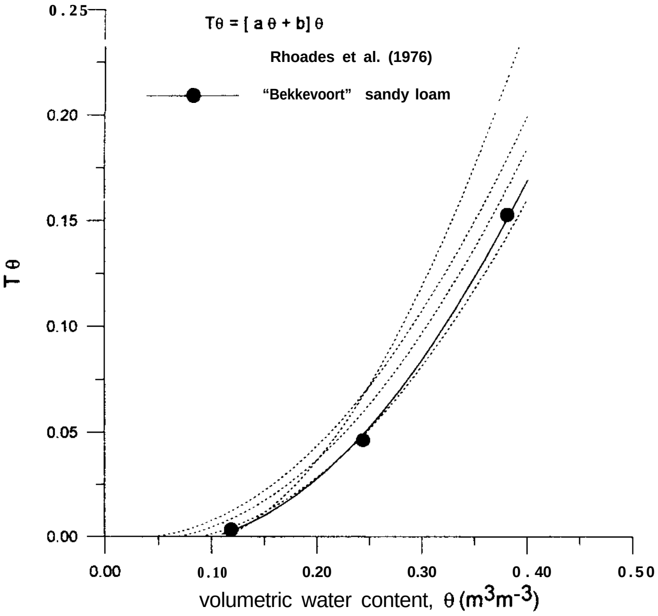

Fig. 3. Relation between the slope of Eq. [7], $T\theta$, vs. volumetric soil water content, θ.

RESULTS AND DISCUSSION

The intercept and slope of Eq. [7] for three different water contents (0.12, 0.24, and 0.38 $m^3\,m^{-3}$) and eight different salt concentrations (0, 0.5, 1, 2, 4, 8, 16, and 32 g L^{-1}) were determined using linear regression analysis (Diels et al., 1994, unpublished data). Linear relationship between EC, and EC, were found for all three water contents using salinity levels from 0 to 50 $dS\,m^{-1}$, with r^2 ranging from 0.81 (θ = 0.12) to 0.99 (θ = 0.38). The estimated values for the intercept $T\theta$ were used to relate the transmission coefficient T to θ by using the expression $T = a\theta + b$. Best-fit parameters were a = 1.421 and b = -0.146 (r^2 = 0.997). Figure 3 is a plot of $T\theta$ *vs.* θ using the estimated values of a and *b*, together with curves obtained by Rboades et al. (1976) for a variety of soils. Estimated values for the intercept of Eq. [7], ECs', were found to increase with water content. Although originally Rhoades et al. (1976) reported that EC,' was essentially independent of water content, their later model (Eq. [5] from Rhoades et al., 1989) shows a dependency of the intercept on the water content:

$$EC_a = \left[\frac{(\theta_s + \theta_{ws})^2}{\theta_s}\right. EC_s + T\theta\, EC_a \qquad [8]$$

where EC, is electrical conductivity in the solid phase, θ_s is the volumetric content of the solid phase, and θ_{ws} is water content in the fine pores. The latter parameter is a linear function of the total soil water content, θ (see Fig. 6 and 7 of Rhoades et al., 1989). Thus, the increasing values of the intercept of Eq. [7] as observed in this study are due to increasing values of θ_{ws} when total soil

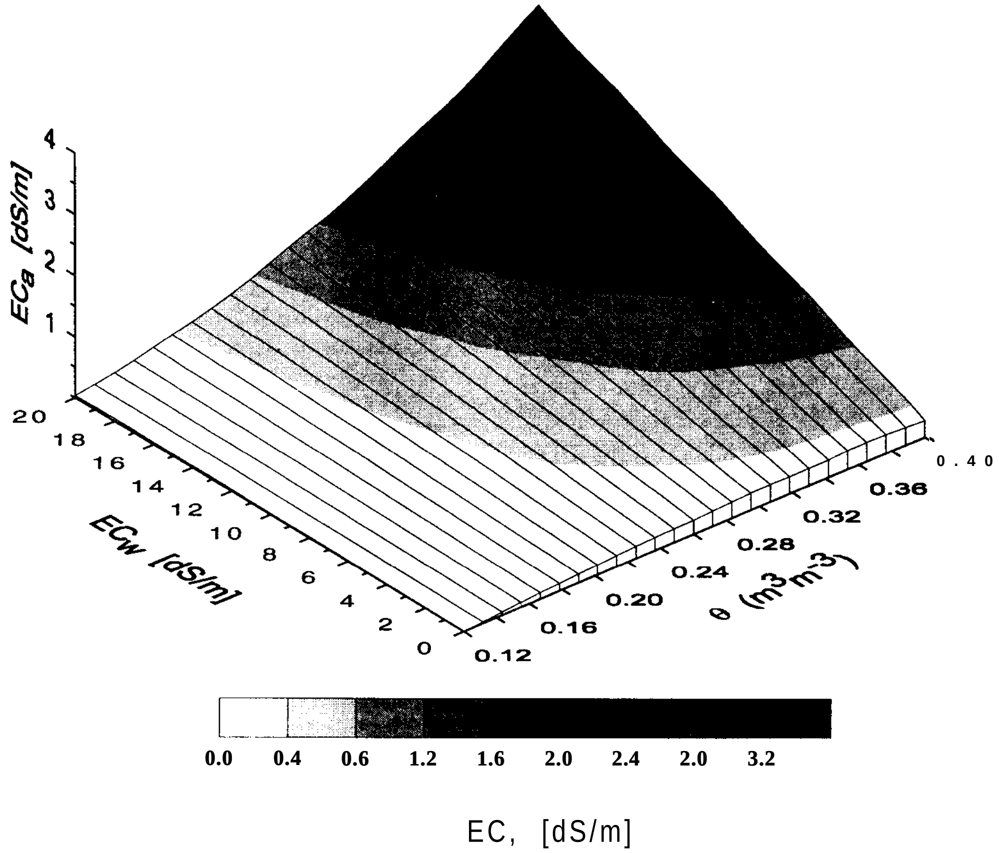

Fig. 4. Bulk soil electrical conductivity, EC., of Bekkevoort sandy loam soil as a function of the water content, θ, and the electrical conductivity of the soil water, EC,.

water content increases. A linear relationship of the form A + $B\theta$ was used to relate ECs' to θ. The data was represented well for A = -0.1094 and B = 1.249 (r^2 = 0.981). The resulting EC,-EC,-8 relationship thus obtained was used to construct a smooth EC,-EC,-8 surface as shown in Fig. 4.

The continuous solute application Method 1 is very simple and attractive as long as the soil can be equilibrated with the input solution within a relatively short time period. Figure 5 shows typical distributions of the impedance vs. time at six depths following the application of a 79-h solute tracer pulse. The soil solution concentration should reach the input concentration, C_0, when the impedance achieves a constant minimum value, Z_0. Notice, however, that the observed Z in Fig. 5 keeps decreasing during the application period for al cases except the shallower 0.05-m depth location. As discussed by Mallants et al. (1994), the relatively quick and early decrease in Z is most likely due to the presence of macropores, which cause solutes to move quickly downward while bypassing much of the soil matrix liquid phase. Concomitant tailing is caused by slow diffusion of solutes from the larger pores to the less permeable soil matrix. Several of our soil columns could not be quickly saturated with the

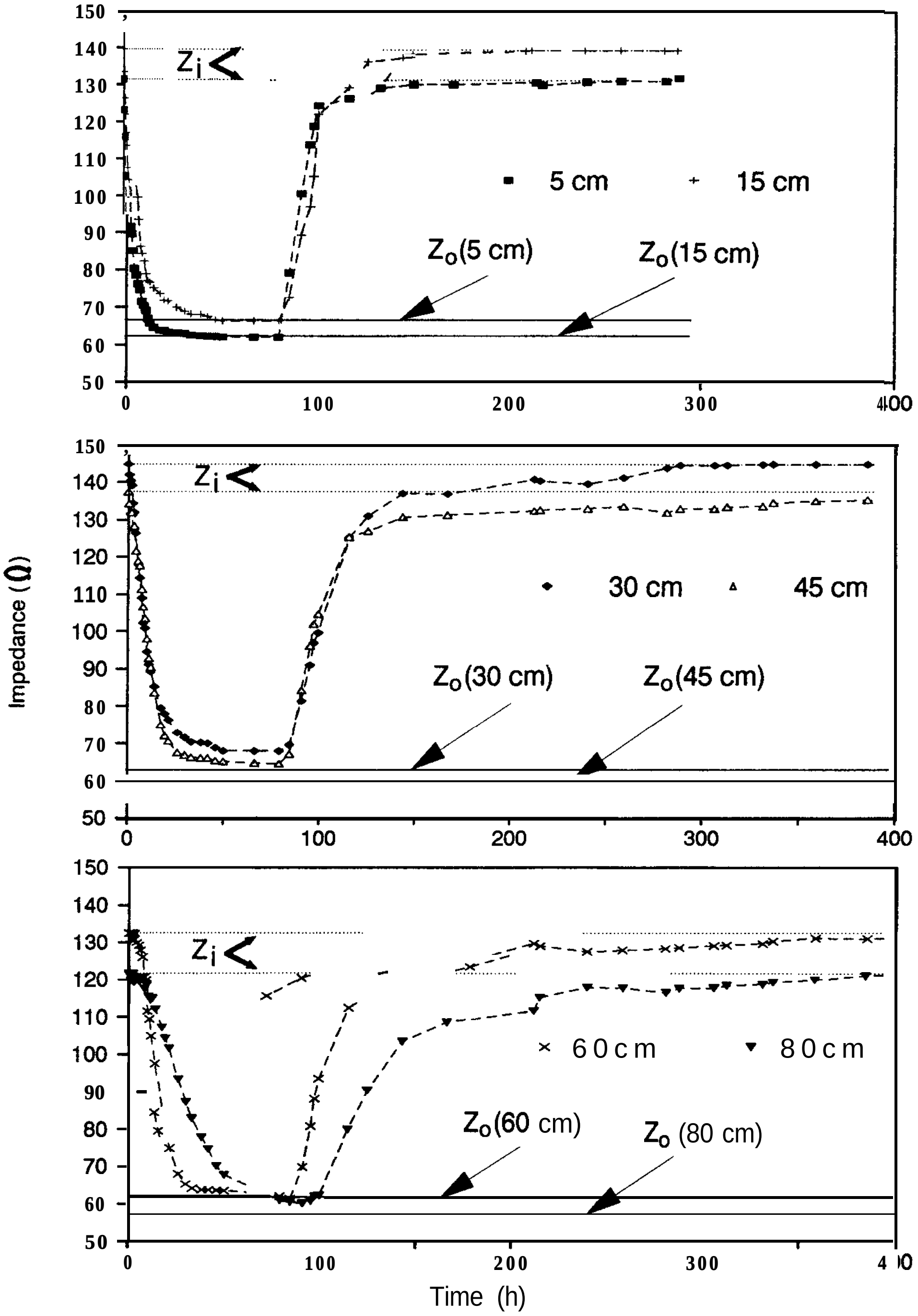

Fig. 5. Impedance vs. time readings at six depths in one soil column measured with TDR for a solute application where t_0 = 79 h.

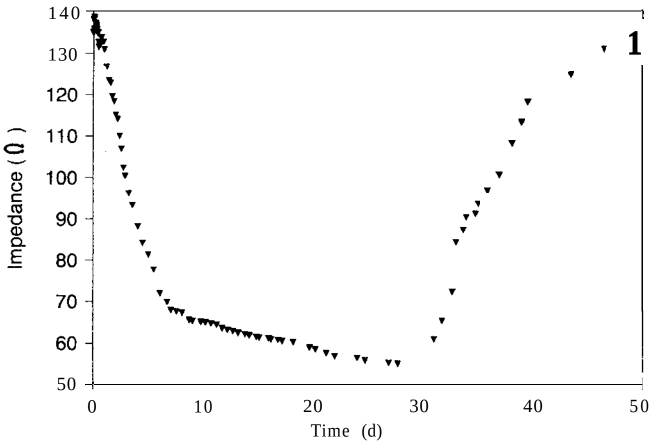

Fig. 6. Measured impedance vs. time at 0.80-m depth in one soil column for the tracer pulse (t_0) of 664 h.

applied solution, even after continuing ponded infiltration with the tracer solution for 600 h. This is demonstrated in Fig. 6, which shows that the impedance Z at x = 0.80 m in one soil column still decreased after applying the tracer solution for 664 h. Hence, the solute concentration in this soil remained less than Co, and the final impedance Z_0 could not be determined accurately.

Applying long-duration (large t_0) solute pulses to structured soils exhibiting nonequilibrium transport is important since TDR-measured breakthrough curves are very susceptible to the value of the reference impedance, Z_0, assumed in the calibration process. Figure 7 shows an example Z(t) curve obtained at x = 0.05 m for 664 h. In this example it took 664 h to completely equilibrate the soil with the input solution, leading to a final Z_0 of 56 Ω. By comparison, the impedance after 400 h was 57.2 Ω, a value close to Z_0, while after t = 300 and 200 h, the impedance values were 58 and 61.2 Ω, respectively. Note that water content is constant throughout the experiment (θ ranged from 0.312 to 0.317, which is within the range of measurement error of TDR). Using these values for Z_0 in Eq. [5] reveals the significance of the effects of having incorrectly estimated Z_0 values on the "measured" BTCs. Results in Fig. 8 show that cutting off the Z(t) distribution too early (i.e., before equilibrium is reached) leads to roughly the same early breakthrough times, but with considerably less tailing in the BTC. Using inaccurately measured BTCs in turn will lead to incorrect transport parameter values when the TDR data are subsequently analyzed with transport models. For instance, Table 1 gives estimated parameters v (pore water velocity) and D (dispersion coefficient) for the convection-dispersion equation obtained for the four BTCs and Fig. 8. The parameter values for the reference case are considerably different in comparison with the three other cases (representing inappropriate calibrations) .

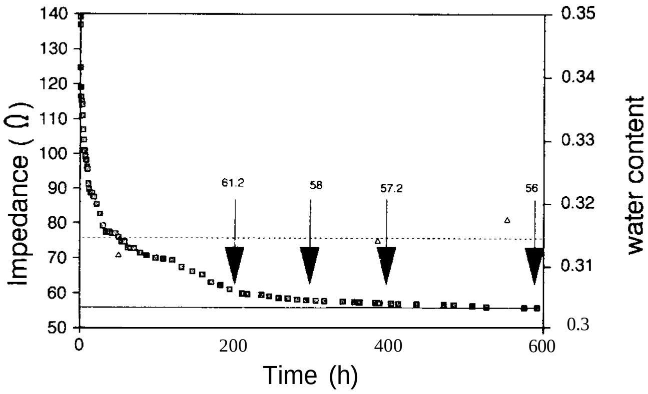

Fig. 7. Measured impedance vs. time readings at 0.05-m depth for a tracer pulse (t_0) of 664 h; vertical arrows indicate different impedance (Z_0) values used for calibration purposes. Triangles represent TDR-measured water content and dashed line is mean water content.

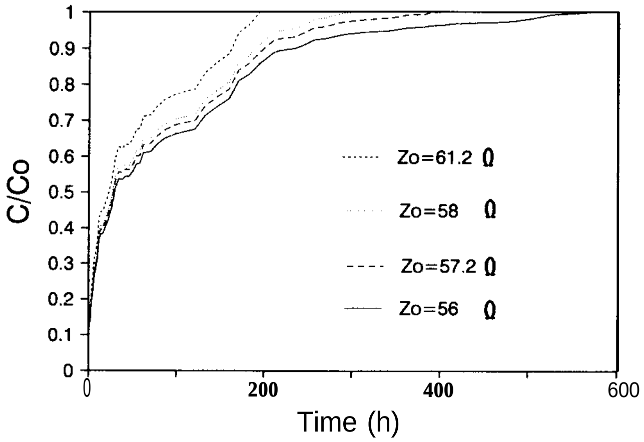

Fig. 8. Effect of incorrectly determined values for impedance Z_0 (Fig. 4) on calculated solute breakthrough curve (Z_0 = 56 Ω is the reference value).

The alternative calibration Method 2 avoids the need for solute concentrations to reach the final equilibrium value, Z_0. We tested this calibration procedure for 18 soil columns by comparing estimates of Z_0 based on Eq. [6] with values of Z_0 measured at 0.05 m where the soil had already equilibrated with the applied solution. The results in Fig. 9a show that estimates of Z_0 obtained with Method 2 only minimally deviate from Z_0 values based on Method 1, with a coefficient of determination, r^2, of 0.994. Method 2 is based on the assumption that the convolution of the TDR-measured impedance equals C_0t_0 (Eq. [6]). Therefore, Method 2 requires that measurement times are long enough to ensure that all solute passing the measurement window of the TDR probe will be detected. This is especially true at larger depths in structured soils where long equilibration times to capture the low-concentration tails can be very extreme.

Furthermore, pore-water velocity needs to be homoge-

Table 1. Estimated convection-dispersion equation transport parameters for different values of impedance Z_0.

Z_0	v	D	r^2
	cm $\mathrm{h^{-1}}$	cm2 $\mathrm{h^{-1}}$	
56†	6.2	3790	0.992
57.2	3.4	992	0.987
58	3.3	884	0.985
61.2	3.8	897	0.987

† Considered as reference value.

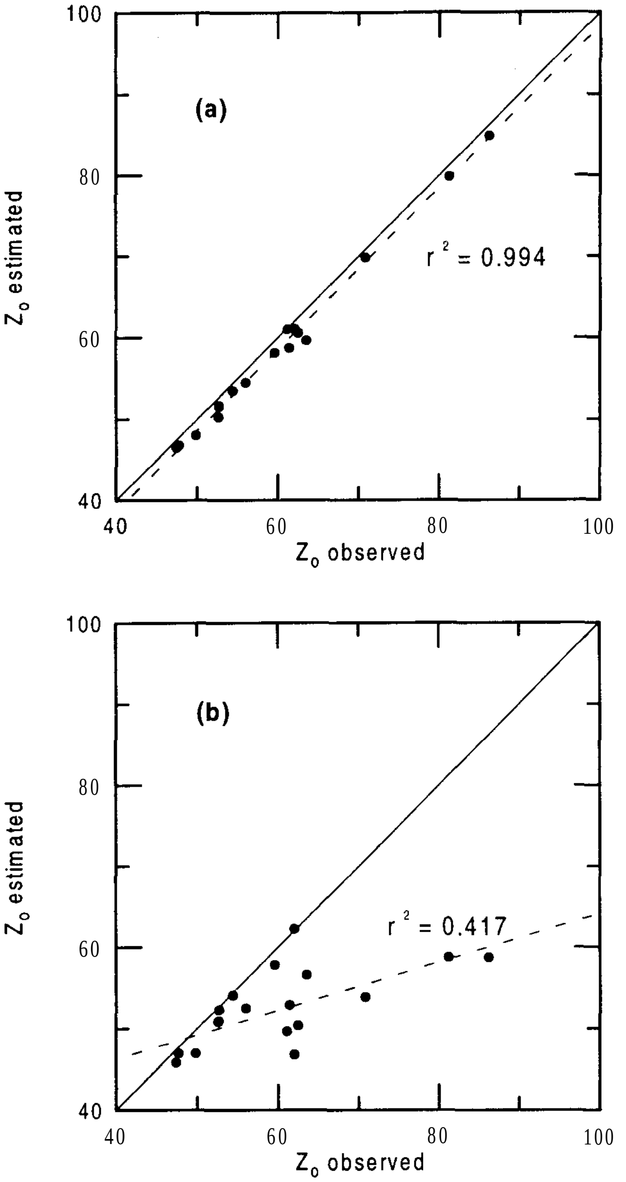

Fig. 9. Observed (Method 1) vs. estimated values for impedance Z_0 based on (a) Method 2 and (b) Method 3. The solid line represents perfect agreement. Also shown are linear regression lines (dashed) and the coefficient of determination (r^2).

neous to ensure proper mass recovery for Method 2. As discussed by Mallants et al. (1994), the TDR sampling volume might be too small compared to the spatial variation of pore-water velocity in undisturbed soils. In this case, the solute mass detected by TDR could be different locally across the entire cross-sectional area. Evidence from dye stains (Mallants et al., 1993) and field observations of macropores indicated that macropores in our experiments existed and functioned mainly near the soil surface, while the subsurface was found to be more homogeneous. This finding would suggest a somewhat more uniform transport process in the subsurface once the solute front had passed the surface layers. If this assumption is correct, convolution of the TDR-measured pulse response should result in C_0t_0 for a given detection point in the deeper soil layers as long as the measurement time is long relative to the nonequilibrium time scale for detection points in the upper part of the soil column. As shown in Fig. 5, the observed impedance returned to the background impedance, Z_i, within 400 h, even at the deeper depths. Hence, we conclude that for those depths were the soil cannot be easily equilibrated with the inlet solution, Method 2 provides a possible alternative for estimating Z_0 provided the final Z is close to Z_i. An advantage of method 2 is the fact that field-scale leaching experiments with solute-free water (or locally available water with a relatively low background concentration) are generally easier to execute than experiments requiring large amounts of a tracer solution of constant C_0.

Calibration Method 3 is based on an independently determined EC,-EC, relationship for different water contents, θ. The reference impedance, Z_0, at known concentration, Co, was obtained by first computing EC, for a given EC, and θ, using Eq. [7] with calibration constants previously determined. Next, the value of EC, was transformed to Z_0 according to Eq. [3]. Since the EC,-EC,-8 relationship was determined only for soil taken from the upper Ap horizon (O-O.25 m), we computed Z_0 at C_0 only for the first observation depth, 0.05 m. Similar to Fig. 9a, estimates of Z_0 from the calibration were compared with measured values of Z_0 obtained using the continuous application approach (Fig. 9b). Although nine out of 18 values were close to the measured Z_0, the overall agreement was poor, yielding an r^2 of 0.417. Since the EC_a–EC_w–θ relationship was determined on a repacked soil, soil structure differences (including the destruction of macropores) are a likely cause for the deviation. The effect of soil structure on current flow through the void space of the soil matrix is described by the transmission coefficient T (see Eq. [7]). Rhoades et al. (1989) interpreted T as the fraction of the total soil water that is mobile and resides in the large pores. It is thus reasonable to assume that T will be different between undisturbed and repacked soil. Moreover, the EC_a–EC_w–θ relationships may have been different for other soil layers due to different physico-chemical properties. Especially the higher clay content in the deeper layers, i.e., 23% clay in the 0.55 to 1.00-m layer vs. 13% clay in the surface Ap horizon, may have affected the electrical conductivity of the solid phase (EC, in Eq. [8]), as Rhoades et al. (1989) demonstrated that EC, could be linearly related to clay content. Hence, it may be necessary to determine the EC_a–EC_w–θ relationships using undisturbed soil taken from a location close to the measurement point.

CONCLUSIONS

Impedance data measured with TDR in l-m-long undisturbed soil columns were evaluated using three different calibration procedures. In order to relate Z with the concentration, C, it was necessary to determine the reference impedance, Z_0, associated with the reference concentration, C_0. Although the continuous application Method 1 is simple in concept, widely used, and should be generally applicable, results in this study indicate that this method may be problematic, especially for undisturbed or structured soils exhibiting nonequilibrium solute transport. This is because the method may require an inordinate amount of tracer solution to ensure proper equilibration of the soil solution with the input concentration. For example, some of our columns required solute applications for more than 660 h in order to reach equilibrium. Proper equilibration with the input solution is critical since, as demonstrated in this study, the tail of a TDR-measured BTC can change significantly if the reference impedance, Z_0, is incorrectly determined.

The convolution Method 2 is based on the assumption that all the mass of solute applied to the soil surface during a relatively short pulse time (t_0) will pass by and be monitored by the TDR probes. This method agreed well with the continuous application method at 0.05 m where the soil was completely saturated with the applied solution. Since the subsurface layers of the soil columns used in this study were more homogeneous than the soil layers near the surface, we assumed that the TDR probes at the deeper depths eventually could detect all of the solute passing through the surface layers, provided enough time is allowed for the TDR measurements. Moreover, it may generally by much easier to measure for a long period of time than to keep applying a tracer solution for a long period of time to ensure reaching the input concentration, C_0. Hence, we believe that for those depths where the soil cannot be easily and quickly equilibrated with the input solution, the convolution method will provide an attractive alternative for estimating Z_0.

We also compared the calibration method using an independently determined EC,-EC,-8 relationship with the continuous application method at 0.05 m. The agreement was relatively poor, in part because of the use of repacked soil for the independent calibration. Accurate calibration probably will require that the EC,-EC_w–θ relationship be determined using undisturbed soil taken from a location close to the measurement point.

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