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COMPARISON OF EFFLUENT AND TDR BREAKTHROUGH CURVES OF ELECTRICAL CONDUCTIVITY IN A LABORATORY COLUMN EXPERIMENT*

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A b s t r a c t. Steady state downward flux was carried out in laboratory for 2 soil columns containing sand and aggregated loam. The bulk elekrical condictivity (EC) was measured at the bottom of the column by horizontally installed TDR probes. The bulk EC data were evaluated by continuous flow and convolution method and they were converted to relative concentrations, as were the effluent EC data. For sand, the relative concentrations obtained from the effluent were similar to those for TDR, while for aggregated loam there were significant discrepancies. The results were explained by the different pore distribution of the soils.

K e y w o r d s: TDR (Time Domain Reflectometry), BTC (Breakthrough Curve), soil column, effluent

INTRODUCTION

Time domain reflectometry (TDR) method is widely used to measure volumetric water content *(θ)* and bulk soil electrical conductivity *(EC_a)* of the soil. To calculate the resident solute concentration *(c_r)* of the soil, first the pore water electrical conductivity *(EC_w)* has to be determined from EC_a of the soil. For this purpose several salt calibration methods are introduced. Ward *et al*. [4] divided them into two main groups.

Indirect methods can be applied in the case of steady state flow through disturbed and undisturbed soil samples. At constant water content relative *EC* values are calculated from EC_a values. These are equal to the relative solute concentrations.

Direct methods are used under transient flow conditions as well in the case of steady state flow for homogenised disturbed soil columns. The relationship between EC_a, EC_w and θ is determined in separate measurement series. The experiments are carried out on soil columns with nearly the same structure.

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In this study we evaluate TDR data with *indirect methods*. Our aim is to compare resident solute concentration obtained for horizontally installed CAMI/RS TDR probes (Easy Test Ltd., Poland) with the effluent concentration (c_f) of two laboratory experiments with disturbed loam and sand texture soil columns.

MATERIAL AND METHODS

Theory

The relationship between EC_a, EC_w and θ was expressed by the following empirical formula for soils having EC_w between 4-20 *dS/m* [3].

$$EC_a = EC_s(\theta) + T(\theta)\theta EC_w \tag{1}$$

where $EC_s(\theta)$ is the EC of the solid phase of the soil, $T(\theta)$ is the transmission coefficient accounting for tortuosity of the pore system of the soil. At constant soil water content both EC_s and T are constant.

The applied indirect methods: According to eq (1) at constant soil water content EC_a is linearly related to EC_w as well as to the resident solute concentration (c_r).
The resident solute concentration (c_r) can be expressed using the following relative expressions:

$$c_{r,rel}(x,t) = \frac{c_r(x,t) - c_{r,i}}{c_{r,o} - c_{r,i}} = \frac{EC_a(x,t) - EC_{a,i}}{EC_{a,o} - EC_{a,i}} \tag{2}$$

where $c_{r,o}$ is a reference concentration (e.g. the input solute concentration), $c_{r,i}$ is the initial resident concentration, $EC_{a,o}$ is the bulk EC associated with $c_{r,o}$ and $EC_{a,i}$ is the initial bulk EC.

Under steady state conditions $c_r(x,t)$ can be calculated indirectly by using continuous flow* or convolution** methods [4,2].

* If the applied pulse with c_o concentration is long enough, after the solute dispersion front passes through the horizontally installed TDR probes at depth x, the resident concentration equals the input (reference) concentration that is related to the measured EC_a value. Thus $EC_{a,o}$ can be read directly.

** If the applied pulse with c_o concentration is not long enough, the resident concentration does not equal the input concentration at depth x, therefore $EC_{a,o}$ cannot be measured directly.

Assuming mass conservation of solute pulse $EC_{a,o}$ can be calculated.

$$c_{o,rel}t_o = \frac{1}{EC_{a,o} - EC_{a,i}} \int_o^{\infty} (EC_a(x,\tau) - EC_{a,i})d\tau \tag{3}$$

$$c_{r,rel}(x,t) = \frac{c_r(x,t) - c_{r,i}}{c_{r,o} - c_{r,i}} = \frac{EC_a(x,t) - EC_{a,i}}{EC_{a,o} - EC_{a,i}} \tag{4}$$

where $c_{o,rel}$ = 1, t_o is the period of pulse application.

Under steady state flow, the resident solute concentration in a soil column experiment can be determined from the experimental data and separate calibration measurements are not necessary.

Experimental method

Steady state downward flux was conducted through 2 soil columns containing sandy and loam soil with an aggregate size of 0.2-2 mm. Table 1 shows the particle size distribution, and Figure 1 presents the retention curves of the soil samples.

Table 1. Particle size distribution of soils (%)

Soil type	Particle size						
	<0.002	0.002-0.005	0.005-0.01	0.01-0.02	0.02-0.05	0.05-0.25	>0.25
	mm						
Sand	7.84	0.64	0.4	1.12	3.44	49.08	37.48
(Chernozem) Loam	21.79	9.03	8.35	12.95	36.35	11.55	–

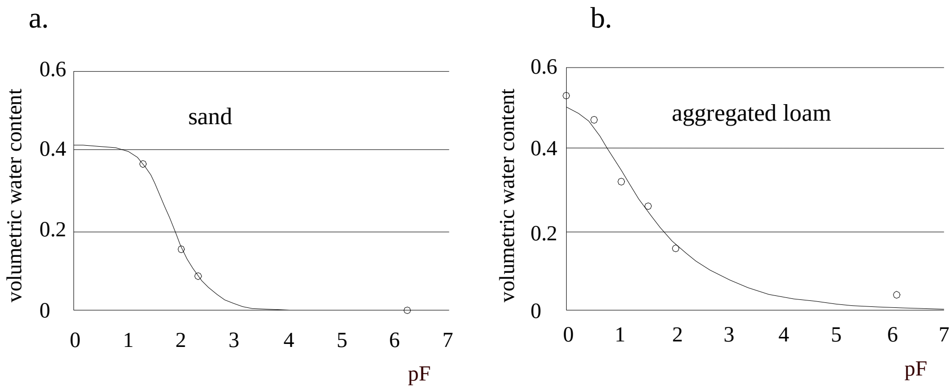


Fig. 1. Retention curves a. for sand b. for aggregated loam soils

The experiment was similar of that described by Wraith et al. [5]. Initially, the columns were saturated by 0.01 M $CaCl_2$ solution. Then volume of 0.035 M $CaCl_2$ solution was added on to the top of the column and displaced with two pore volumes of 0.01 M $CaCl_2$ solution. The columns were 10 cm long and had 6 cm inner diameter. The lower end of the column was supported with a screen such that water could flow out freely under atmospheric pressure. In the case of sand, 1 cm pressure head was used at the top of the column. In the case of the loam texture soil, an unsaturated flow with 0.18 cm h^{-1} rate was applied. The effluent solutions were analysed for electrical conductivity *(EC)*, EC_a and θ was also measured by TDR probes (Easy Test) horizontally installed at 9.5 cm depth of the soil column. A schematic of the experiment is represented in Figure 2.

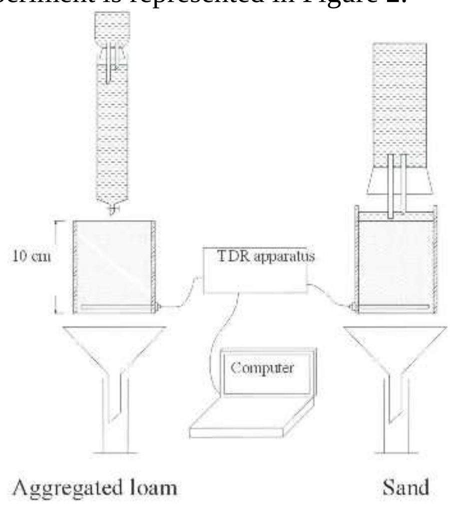


Fig. 2. Schematic presentation of the experiment

RESULTS AND DISCUSSION

To evaluate the experiment we used convolution and continuous flow methods. The effluent solution breakthrough curves were compared to the TDR BTC's (Fig. 3).

In the case of sand, the effluent BTC was very similar to the BTC obtained by TDR probes at the bottom (9.5 cm) of the soil column (Fig. 3a.). After adding 1.8 pore volume of 0.035 M $CaCl_2$ solution to the top of the column there was equilibrium in the system, thus continuous flow method was used for calibration. For loam soil, the slope of the TDR BTC was less steep than the slope of the effluent BTC (Fig. 3b.). As after adding two pores volume of $CaCl_2$ there was not equilibrium in the column, the convolution method was used for calculating the TDR BTC.

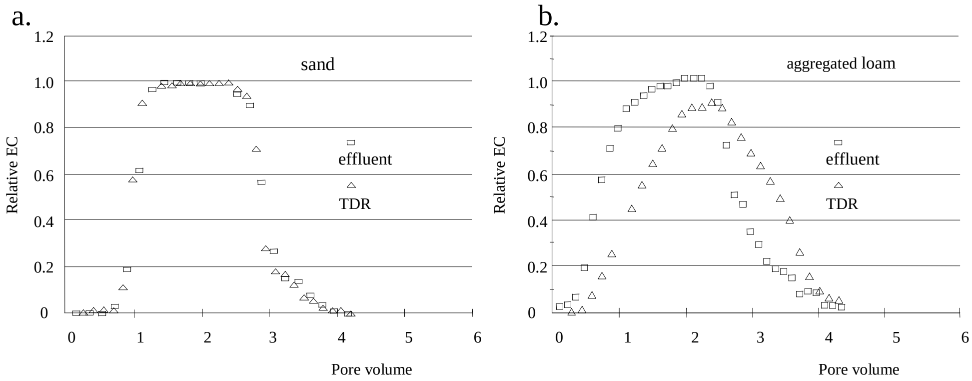


Fig. 3. Comparison of effluent BTC with TDR BTC a. for sand b. for loam soils

The results can be explained with the difference between the so called resident concentration and flux average concentration as defined by Kreft and Zuber [1].

- Resident or volume average concentration *(c_r)* is the mass of the solute per unit volume of fluid contained in an elementary volume of the system.
- Flux average concentration *(c_f)* is the mass of the solute per unit volume of fluid passing through a given cross-section of soil during an elementary time interval.

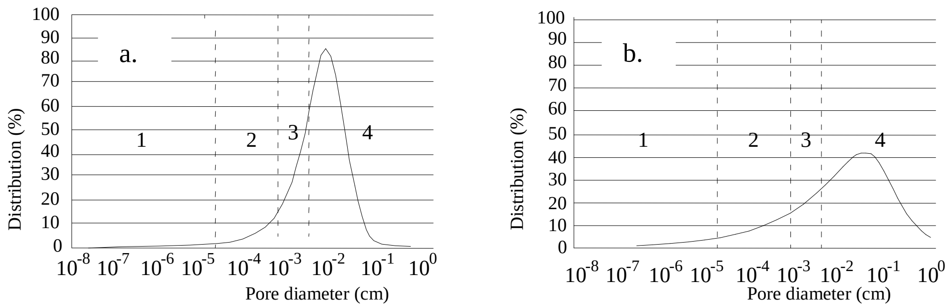
The TDR equipment measures resident concentration that is added from all of the pores solute concentration in the soil column. The effluent concentration, however, is a flux average concentration, thus it is described by the solute concentration of the large pores.

The difference between c_r and c_f of soils can be explained by their pore size distribution. To compare the pore size distribution of the soil samples, pore size density functions were calculated from the water retention functions (Fig. 4).

The large steepness of the function shows that the diameter of pores differs only in 1-2 orders of magnitude. Thus, there is only one unit stream front in the column. In this case c_r is characterised mainly by the concentrations of the large pores as well as c_f, therefore the TDR and effluent BTC's are similar.

In the case of the aggregated loam, the steepness of the function is smaller, which means that large diameter gravitation pores ($d > 10^{-1}$cm) and adsorption pores ($d < 10^{-4.7}$cm) are present in the column at the same time. Preferential flow plays a significant transportation role in the system while conductance of smaller pores is negligible.

The effluent concentration c_f is characterised mainly by the solute concentrations of very large pores, while resident concentration is contributed to the whole pore water concentration. In small diameter pores the soil solution mixes slower than in large pores, which causes less steep slope of the TDR BTC.



1: adsorption pores, 2: capillary pores, 3: capillary-gravitation pores, 4: gravitation pores

Fig. 4. Pore size density function a. for sand b. for loam soils

CONCLUSION

The effluent concentration depends mainly on the solute concentration of large pores, while TDR concentration depends on the solute concentration of large and small pores. In the case of sand, large pores are dominant, therefore the TDR and effluent BTC's are similar. As in aggregated loam large pores and very small pores are present at the same time under the applied flux velocity there was preferential flow in the column. In small pores the solutions mix slower, therefore TDR and effluent BTC's cannot have the same shape.

In those cases where preferential flow occurs, TDR and effluent BTC's are expected to differ from each other.

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PORÓWNANIE KRZYWYCH PRZEWODNICTWA ELEKTRYCZNEGO GLEB W KOLUMNOWYM DOŚWIADCZENIU LABORATORYJNYM PRZY WYKORZYSTANIU TECHNIKI TDR

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Streszczenie. W warunkach laboratoryjnych prowadzono doświadczenie nad ustalonym przepływem grawitacyjnym przy użyciu 2 kolumn wypełnionych piaskiem oraz zagregowaną gliną. Wartość przewodnictwa elektrycznego mierzono przy dnie kolumn za pomocą zamocowanych poziomo sond TDR. Dane z pomiarów poddawano ocenie metodą przepływu ciągłego oraz konwolucyjną, oraz przekształcano na wartości stężenia względnego, podobnie jak dane przewodnictwa elektrycznego dla wypływu. Dla piasku wartości stężenia względnego otrzymane z wypływu były podobne do wartości otrzymanych metodą TDR, podczas gdy dla zagregowanej gliny wytępowały znaczące różnice. Otrzymane wyniki wyjaśniono poprzez różnice w rozkładzie wielkości porów badanych gleb.

Słowa kluczowe: TDR, BTC, kolumna glebowa, wypływ