# Observation of water movement in soil with electric resistivity tomography

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## 1 INTRODUCTION

Considerable attention has been given to the role of unsaturated zone in water storage and contaminant transport. The ability of the soil to infiltrate water is important for moisture availability to crops, ground water recharge or estimations of surface and subsurface runoff rates during heavy rainstorms. Most often contaminants reach groundwater aquifers after first moving through the vadose zone. The soil serves as a natural filter, which is able to slow down, transform, or even totally eliminate some hazardous solutes.

The soil is rather complicated system of non-uniform soil particles, organic matter and pores, which are filled with air and water. Good physical description of the unsaturated (vadose) zone and understanding the water flow regime are the key elements to solve many environmental problems.

It has been a great challenge to observe the spatially and temporary heterogeneous physical conditions of the subsurface on a fairly easy way. The traditional methods rely on analyses made on disturbed or undisturbed soil samples. Such procedures are costly, time consuming and provide the information from small discrete volumes only. Indispensable disadvantage of the soil sampling is the disturbance of the soil profile resulting in creation of preferential paths and modification of soil structure.

The spatiotemporal heterogeneity of soil moisture distribution in a soil profile, including the groundwater table position, causes significant uncertainties in modelling predictions. It holds especially for infiltration processes involving soils exhibiting the preferential flow phenomenon (Beven & German 1982, Císlerová 2005). So far it is very difficult to describe the irregularities of soil moisture distribution and soil moisture propagation during infiltration in bigger scales by means of non-destructive techniques.

Electrical Resistivity Tomography (ERT) is frequently used to remotely characterize subsurface features in many settings, including the vadose zone (Daily et al. 1992). Recent studies have shown that ERT can be used to obtain quantitative information about the structure of solute transport (Yeh et al. 2008, Koestel et al. 2009), water front plume development (Battle-Aguilar et al. 2009, Schwarz & Schreiber 2009), water flow in fractures (Daily et al. 1987) or irregular subsoil settlement (Pícha & Jančovič 2004).

To obtain the moisture distribution below the area of infiltration we proposed a combination of non-invasive monitoring and numerical simulations with inversely optimized parameters, which are difficult to measure directly (Zumr et al. 2009). Electric resistivity tomography (ERT), time domain reflectometry (TDR) and standard tensiometers were tested and calibrated to be able quantitatively determine basic hydraulic characteristics and initial moisture content distribution on given soils.

## 2 MATERIALS AND METHODS

### 2.1 *Electrical resistivity tomography*

Noninvasive and nondestructive techniques are increasingly used in soil science. Electrical resistivity tomography is a common geophysical survey tool to determine the resistivity distribution within the soil profile. The resistivity is related to various parameters (temperature, mineralogical composition) but the primary factors are porosity, moisture content and concentration and chemical composition of solutes (Archie 1942, Battle-Aguilar et al. 2009).

Two-dimensional and three-dimensional electrical tomography surveys are carried out using a large number of electrodes connected to multi core cable. Electronic switching unit is used to automatically select two potential and two current electrodes for each measurement of apparent resistivity. The measured apparent resistivity pseudosections are converted into a modeled distribution of inverted resistivity values via inversion algorithm.

In this study, the automated resistivity system ARES (GF Instruments, Brno, Czech Republic) was used for 2D and 3D resistivity tomography and software Res2DInv and Res3DInv (Geotomo Software) for the processing of raw ERT data.

Figure 1 shows an example of the application of ERT at the mine dump Hájek, close to Ostrov nad Ohří, Czech Republic. The locality is considered as an environmental thread, since the waste materials with high concentrations of HCH and PCB were deposited at the site in late 1960s. To be able to identify the water regime and the transport domain, the 2D ERT across the whole dump was conducted. The light grey zone at the top half of the figure represents the area with low electrical resistivities and stands for soil profile, the dark area with high electrical resistivities represents the bedrock.

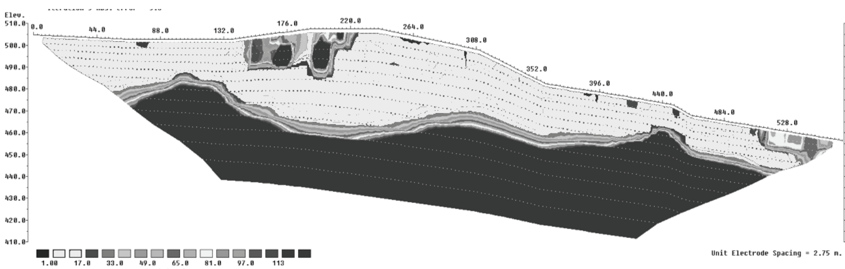


Figure 1. Two dimensional electrical resistivity array at mine dump Hájek

### 2.2 *Conversion of electrical resistivity to moisture content*

To convert geophysical images into two-dimensional cross sections or three-dimensional volumes of quantities such as porosity, moisture content, solute concentration or permeability, various petrophysical formulas have been used (Day-Lewis et al. 2005, Ewing & Hunt 2006).

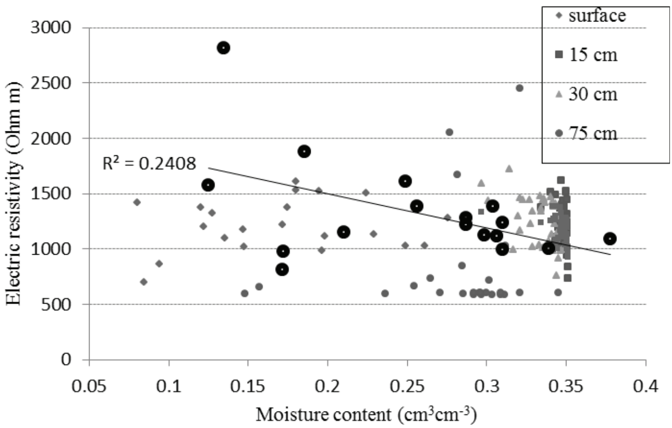


Figure 2. Linking 2D ERT measurement with moisture content measured gravimetricaly and with the use of TDR

We linked the ERT data with moisture content values measured by TDR. As figure 2 shows, there is no clear relationship between them. The main difficulties to define the relationship include spatially heterogeneous organic matter content, different chemical and physical properties of soil and the scale issues related to TDR and ERT techniques. The ERT resolution decreases with the depth, the TDR moisture content values are related to a relatively small volume in the vicinity of the TDR probe.

To convert the electrical resistivity to the moisture content we used a modified form of Archie's Law as described by Schwartz (2008):

$$\rho_b = c \cdot \rho_w \cdot \theta^m \tag{1}$$

where $\rho_b$ (Ohm m) is bulk conductivity obtained with ERT, $\rho_w$ (Ohm m) is pore water conductivity, $\theta$ (cm$^3$ cm$^{-3}$) is soil moisture content, $c$ and $m$ are fitting parameters that depend primarily on clay content in the soil (Shah & Singh 2005).

During the experiments it was concluded that 2D tomography does not give the results of the sufficient accuracy. Therefor the full 3D ERT was performed to calibrate electrical resistivity and moisture content.

## 2.3 *Tension infiltration experiment*

The disk tension and ring ponded infiltration experiments are relatively simple methods of measurements of effective infiltration properties of soil. The conventional evaluation methods, such as Green Ampt or a numerical solution of Richards equation, usually estimate a homogeneous development of the spherical water plum. To put the evaluation of the experiment more precisely, the 3D ERT imaging of the water front movement was employed. The plot of the size of 2.2 m to 1.4 m, where 96 electrodes were installed in a regular perpendicular grid with the 20 cm offset, was monitored. Solution of KBr was added into infiltrating water to increase the electrical conductivity and enhance the ERT results.

The field infiltration experiment was carried out in a shallow pit for a period of three days. The upper boundary condition was controlled by the tension disk infiltrometer (Soil Measurement Systems, Tuscon, Arisona, USA), the propagation of a water front was monitored by two T4 tensiometers (UMS GmbH, Munich, Germany) and nine TDR probes (Campbell Scientific Inc., UK) installed in two depths below the infiltration disc (Sněhota et al. 2008).

## 3 RESULTS

The propagation of the wetting front below the infiltration disc is illustrated in figure 3. The ERT captures the moisture and KBr distribution during the experiment with reasonably good resolution. A significant part of the infiltrated water volume flows below the monitored domain, which makes it difficult to quantify water and solute volumes at discrete points of the soil profile.

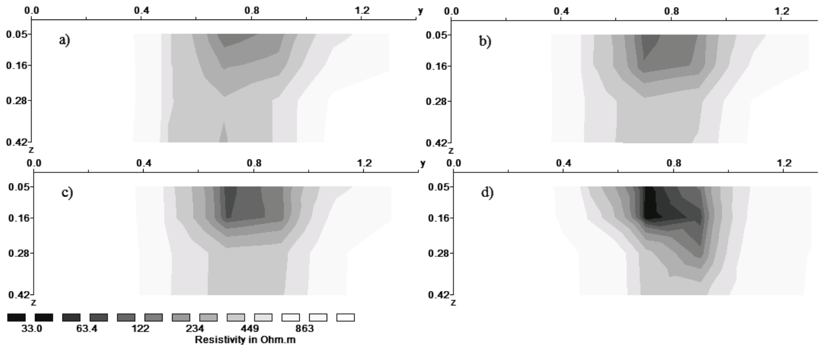


Figure 3. The propagation of wetting front during tension infiltration experiment as measured with ERT

A comparison of the electrical conductivity distribution measured with ERT and TDR, the soil moisture pattern obtained by the TDR and the visualization of the wetting front at the surface is given in figure 4. The both, ERT and TDR measurements were done immediately after the end of the infiltration experiment. The TDR measurements were done in a 20 cm by 20 cm grid at the depth of 5 cm, the values in between were interpolated by kriging. All the methods result in a qualitative agreement with the same position of the center of infiltration and a similar shape of the wetting front.

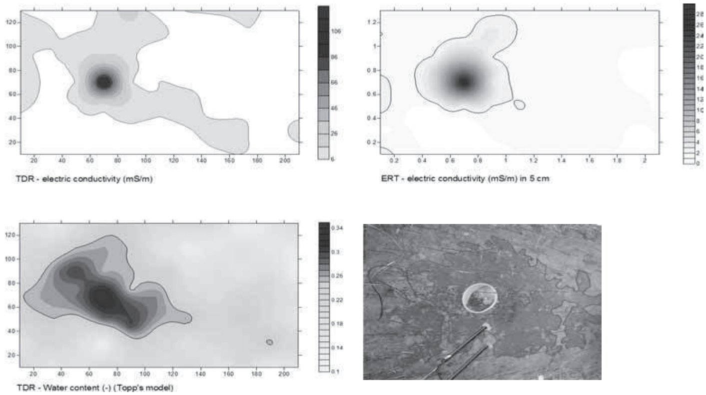


Figure 4. Electric conductivity and moisture content at the surface measured with ERT and TDR compared to wetting front after the infiltration experiment

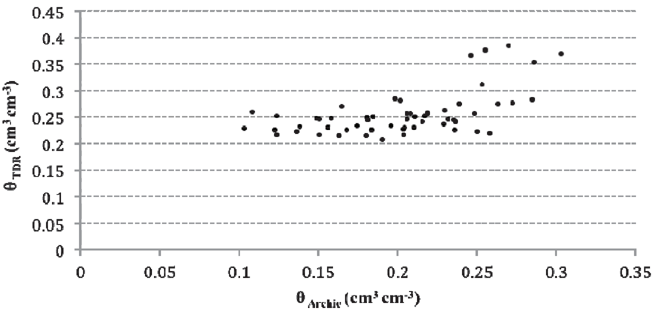


Figure 5. Calculated soil moisture content using ERT with modified Archie's Law and TDR soil moisture content

Quantitative evaluation of the measurements was done by means of modified Archie's Law as presented in equation 1. Figure 5 shows the relationship between the inverted electrical resistivity and the moisture content. The resulting coefficient of determination is 0.31.

## 4 CONCLUSIONS

Soil water content was monitored during the infiltration experiment. A new approach of the quantitative evaluation of infiltration pattern on heterogeneous soil that exhibits preferential flow was tested.

The resulting coefficient of determination is lower than in similar studies in literature, where the $R^2$ are about 0.67 (Zhou et al. 2001), 0.46 (Michot et al. 2003) or 0.57 (Schwartz 2008). The main reasons for poorer results are the high heterogeneity of the soil under the study and unknown spatial distribution of concentration of KBr in soil.

There is still high uncertainty contained in the ERT derived water contents. But ERT can be reliably used to provide the information about qualitative behavior of the infiltration process.

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