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Estimation of unsaturated hydraulic parameters in sandstone using electrical resistivity tomography under a water injection test

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ABSTRACT

Hydraulic conductivity is an important soil property when determining the potential for water movement in top-soil and in spite of its importance; soil hydraulic conductivity remains one of the most difficult of soil properties to assess. Laboratory methods have limitations due to the size of the samples and taking undisturbed soil samples is usually difficult in sandy soil and in-situ methods are required to estimate hydraulic conductivity.

This study was conducted to estimate saturated hydraulic conductivity in unsaturated sandstone using the ground surface electrical resistivity tomography (ERT). The site is characterized by a deep Arenosol soil with high permeability and a low water retention capacity located at the Semora-Correia, the east of Lisbon. Eight ERT snapshots were collected during a water injection test to produce a sequence of 2D resistivity images. Time-lapse ERT data were inverted using independent data inversion, the difference inversion and simultaneous space–time inversion methods. Afterward, using an in-situ approach resistivity variation models were converted to water content images. By comparing first and second spatial moments of water movement images inferred from the ERT method with unsaturated flow simulation predicted from a numerical solution of Richards' equation, the range of saturated hydraulic conductivity is estimated to be in 0.5–0.7 (cm/min).

The evaluation of ERT approach was made using a synthetic test. The results of synthetic test showed that the estimated parameters were significantly influenced by the ERT inversion method and an overprediction of spatial moments and consequently saturated hydraulic conductivity was observed in all inversion methods; however the resistivity models obtained by simultaneous space–time inversion method was more successful in water movement monitoring.

1. Introduction

Improved understanding of unsaturated flow and identifying hydraulic parameters is limited by the lack of appropriate in situ measurement techniques. Traditional methods are usually invasive, sometimes requiring boreholes, covering only a small and localized investigation and may not be representative of the soil properties at the management scales.

Recent research has shown that ERT surveys as non-invasive and cost-effective method is a promising alternative to traditional techniques for unsaturated zone characterization. The capability of ERT surveys have been demonstrated in many studies (e.g. Kemna et al., 2002; Looms et al., 2008a, 2008b; Daily et al., 1995; Müller et al., 2010). Time-lapse ERT survey is a popular tool for unsaturated zone monitoring to determine those hydrologic variables that are time dependent, such as soil water content variations. The dependence of electrical resistivity variations on changes in soil water content through empirical or semi-empirical relationships (e.g., Archie, 1942) or established in-situ relationships (e.g., Farzamian et al., 2015) is the key mechanism that permits the use of time-lapse ERT to monitor water movement in time-lapse mode. Several studies have been conducted to monitor salt tracer tests or water infiltration through the unsaturated zone using ground surface ERT (e.g., Barker and Moore, 1998; Park, 1998; Hayley et al., 2009) and crosshole ERT (e.g., Slater et al., 1997; Daily et al., 1992; Binley et al., 2002a, 2002b; Deiana et al., 2007). Also, ground surface ERT (e.g., Robert et al., 2012; Cassiani et al., 2006) and crosshole ERT (e.g., Binley et al., 1996; Slater et al., 2000, 2002; Singha and Gorelick, 2005) are extensively used in saturated zone study.

ERT approach has several limitations in unsaturated zone characterization. These limitations are partly due to technical limitations of the ERT method associated with resolution and inversion artifacts reported in many studies (e.g., Deiana et al., 2007; Cassiani et al., 2006). Inadequate petrophysical relationship to convert electrical resistivity values to soil water content is another source of uncertainty and necessity of determining site-specific relationships was discussed in several studies (e.g., Looms et al., 2008a). The temperature dependence of electrical

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resistivity is also a source of error for time-lapse resistivity monitoring and the effect of temperature changes over ERT images must be taken into account (Hayley et al., 2007).

Since the most unsaturated zone studies focused mainly on crosshole ERT, we performed an experiment to explore the potential of ground surface ERT in capturing water movement during a water injection test in order to estimate the saturated hydraulic conductivity. We also measured the subsurface temperature variations during the water injection test using suitably placed sensors for temperature correction over time-lapse ERT models.

In this study, we examined several time-lapse inversion methods and attempted to evaluate the artifacts associated with each inversion method by performing a synthetic test. In addition, we established an in-situ approach based on resistivity and volumetric water content variations as proposed by Farzamian et al. (2015) to convert resistivity variations to water content distribution images. The method we used in this study is similar to Farzamian et al. (2015) work, which used time-lapse ERT and multi-height EM38 data collected under natural condition for unsaturated hydraulic parameters characterization. They compared the unsaturated flow simulation predicted from a numerical solution of Richards' equation with equivalent statistics from 2D resistivity images inferred from ERT and multi-height EM38 data to estimate the saturated hydraulic conductivity. To improve this comparison, we used moment analysis (Ye et al., 2005) in this study to estimate the first and second spatial moment of the water tracer. This method is widely used in hydrogeophysical study. One of the first applications of moment analysis was described by Binley et al. (2002b). They calculated first and second spatial moments of changes in moisture content predicted from a numerical simulation of vadose zone flow with two- and three-dimensional ERT and cross-borehole radar profiles to estimate hydraulic conductivity. Singha and Gorelick (2005) also used the moment analysis to estimate horizontal and vertical hydraulic conductivity. More recently, Looms et al. (2008a) calculated the zeroth, first, and second moments to estimate the water loss and illustrate how small structural changes in layered sediments can result in capillary barriers and affects the downward migration.

2. Field site and field experiment

2.1. Study area

The study area is located at the state of Campanhia das Lezirias — Samorra Correia, approximately 50 km east of Lisbon. The soil is a deep Arenosol (FAO, 1988) with high permeability and a low water retention capacity. A field site with 40 m length and 6 m width was established to conduct the experiment, on a 2 m unsaturated soil, consisting mainly of sands. Also, an experimental transect with 12 m length was designed in the middle of the filed site for geophysical monitoring and soil sampling (Fig. 1).

2.2. Sampling and laboratory analysis

Eight soil cores down to a depth of approximately 2 m were extracted along the experimental transect before the water injection test. The locations of soil cores were shown in Fig. 1. These cores were sectioned into 0.2 m lengths and prepared for laboratory analysis of soil physical properties namely particle density, bulk density, texture and also gravimetric water content. Standard set of sieves were used to divide sand into classes, and to separate sand fractions from silt and clay fractions in the soil. The particle size distribution analysis along transect indicated a sand texture class with less than five percent clay and silt, on average. The observed average particle density and bulk density were 2.65 and 1.66 respectively and the porosity value was equal to 37%. As the soil texture and bulk density exhibited a low degree of variation along the field site, the site was considered homogeneous and the porosity was fixed at 37%.

2.3. Water injection test and ERT monitoring

An artificial water injection test was carried out at a rate of 8.96 cm/h over a 12.6 by 2.1 m^2 area of the field site, using drippers spaced every 30 cm over the surface (344 drippers) for about 3 h. Therefore, about 0.71 m^3 of water was injected during the experiment. Pressure compensating drippers with drip rate of 8 l per hour were used for all drippers in this experiment to guarantee uniform water distribution along the entire lines. The water supplied from a nearby groundwater access was used in this test in order to inject water with the same electrical conductivity of the in-situ water. The water was supplied to a water tank and was distributed to the drippers by using pump to ensure constant flow during the experiment. A water flow meter was connected to the system to verify a constant flow rate of water and also measured the final amount of injected water. In addition, 14 soil temperature sensors were installed in 2 boreholes at depths of 0.1 m, 0.3 m, 0.5 m, 0.7 m, 0.9, 1.1 and 1.3 m. The sensors monitored temperature changes minutely during the experiment.

The evolution of the injected water was monitored by the ground surface time-lapse ERT survey using 4POINTLIGHT_10W device. Geotest software was used for remote controlling of 4POINTLIGHT_10W in combination with active boxes for geoelectric tomography using multi-electrodes. ERT surveys were performed using Schlumberger electrode configuration with the maximum current electrode (AB/2) expansion of 6 m and electrode spacing of 0.30 m respectively. 40 electrodes were used in this experiment and a total of 361 data were collected for each image. The required time for each acquisition was about 22 min and 8 data sets were obtained during the water injection.

3. Material and methods

The saturated hydraulic conductivity estimation from time-lapse ERT data consists of four main elements (outlined in Fig. 2); 1) Inverting the time-lapse ERT data, 2) Establishing an in-situ approach to convert time-lapse ERT model to water content images, 3) Simulating unsaturated flow, 4) Using moment analysis to evaluate mass balance and estimate the saturated hydraulic conductivity. These elements will be separately discussed in the following sections.

3.1. Time-lapse ERT inversion

We inverted the time-lapse ERT data using three different approaches: independent data inversions, difference inversion (LaBrecque and Yang, 2001) and simultaneous space–time inversion (Kim et al., 2009). In independent inversion, independent data inversions are carried out separately and changes in ERT models with time are obtained by subtraction of pixel-by-pixel values from a background image (Deiana et al., 2007). The difference inversion method minimizes the misfit between the difference in two datasets and the difference between two model responses and smoothness is imposed directly on the time-lapse model change. This method is widely used for inverting time-lapse ERT data as suggested by several published works (e.g., Kemna et al., 2002; Deiana et al., 2007). In simultaneous space–time algorithm, subsurface structure and the entire monitoring data are defined in the space–time domain to obtain a simultaneous space–time model using just one inversion process. The method introduces the regularizations not only in the space domain but also in time to reduce inversion artifacts and improve stability of the inverse solution (Kim et al., 2009). A description and comprehensive comparison of these methods were presented in Hayley et al. (2011).

In order to map water content variation inferred from time-lapse ERT inversion, the temperature fluctuations that affect the unsaturated zone during water injection test must be taken into account (Hayley et al., 2009). It is common practice in electrical geophysics to assume a linear variation in resistivity with temperature over the typical range of temperatures encountered in shallow surveys (Musgrave and