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2D Electrical Resistivity Tomography surveys optimisation of solutes transports in porous media.

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The purpose of this study is to quantify experimentally the evolution of dissolved species in porous media from 2D resistivity models. Transport experiments are carried out at the laboratory scale by performing flow in a model porous medium obtained by filling a transparent container with mono disperse glass beads. A tracer made by mixing a dissolved of blue dye and a known NaCl concentration is injected with a constant flow rate through the porous medium already saturated by a transparent fluid. ERT measurements are acquired during the fluid flow. The measurement conditions and the inversion parameters are estimated so that the relation between spatial and temporal resolutions is optimised. A video follow-up is also carried out during the upward tracer propagation. The comparison of the temporal evolution of the NaCl concentration distribution estimated from ERT models with Video analysis shows remarkable agreement.

Introduction

Subsurface electrical imaging has been previously developed to follow the main directions and groundwater flow velocity (White, 1988), but it can be also used in cross-borehole field experiments to monitoring of conductive solutes transport (Barker, 1998) in saturated media using the resistivity contrasts between the fluids saturating initially the pores spaces and the moving fluids (Bevc & Morrison, 1991; Slater & al, 1996; Kemna, 2002; Oldenborger & al, 2007). Archie's law (1942) relates the measured bulk apparent conductivities to the fluids conductivity in the poral network via a priori information about the porosity and the particles cementation state. Even on laboratory experiments (Binley & al, 1996; Chambers & al, 2004), variability of hydrodynamic parameters remains difficult to be estimated. Porosity is not perfectly homogeneous into the entire soils/rocks core samples, particles shape and their orientations may create some variations on the cementation factor (Jackson & al, 1978) and main electrical anisotropic directions (Rey & Jongmans, 2007) which can not easily evaluated. Moreover the electrical resistivity distribution is obtained through data inversion, thus the non-unicity of the solution can leads to misinterpretations of the geological and hydrodynamic reality. Archie's law (1942) relates the measured bulk apparent conductivities to the fluids resistivity in the poral network via a priori information about the porosity and the particles cementation state. As previously shown by Slater & al 2000, it is possible to use this method to express the spatial distribution of the tracer in solute concentrations. In this study, model's reliability is tested from laboratory experiments in porous media where the hydrodynamic parameters can be easily estimated. We optimise the protocols of measurements and inversions according to the medium's geometry for the tracer's follow-up. The built models are then expressed in terms of tracer concentration distribution on several time-steps and compared to the estimated concentrations by a parallel video follow-up.

Experiment protocol

Experiments are carried out in transparent container plexiglas (of volume V=HxLxE=233.75 cm^3) filled with glass beads of 166 microns diameter. Porosity is $\Phi = 0.365$, close to the theoretical value (Gondret, 1994): the porous medium may be considered homogeneous and isotropic. Hydrodynamic parameters are supposed constant, and the edge effects on the porosity are neglected since the pores diameter is small in comparison to the walls dimensions (Gondret, 1994). A permeable nylon fabric of 100 μm mesh covers the lower opening of the container. This part is in contact with a tank which contains the tracer, whereas three injectors are set on the upper cover in order to ensure a constant flow rate (figure 1a). Two lines of twenty one electrodes of 1.5 mm diameter, spaced every of 1 cm are installed along the edges of the cell (figure

1b). This configuration reproduces the measurements conditions used in borehole. The first and the last electrode of each line are located respectively at 3.5 cm of the lower and upper opening of the container.
Four experimental conditions must be respected in order to optimise the ERT follow-up of the tracer propagation (Slater & al, 2000):
1/ all the pores space is saturated.
2/ the matrix conductivity is low in comparison to the tracer conductivity.
3/ the temporal variations of the electric conductivity are only due to conductivity changes of the interstitial fluids.
4/ the electrical conductivity is linearly related to the tracer concentration.

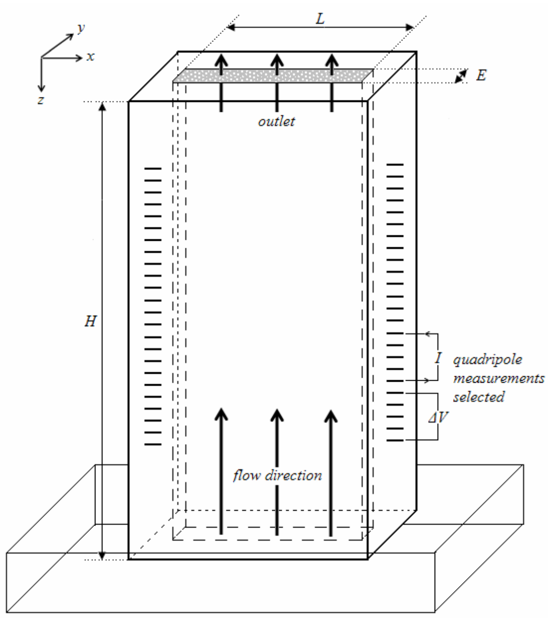

Figure 1a. Shematic of the experimental Plexiglas container filled with spherical glass beads of 166 μm diameter. *H*=27.5 cm, *L*=8.5cm, *E*=1cm.

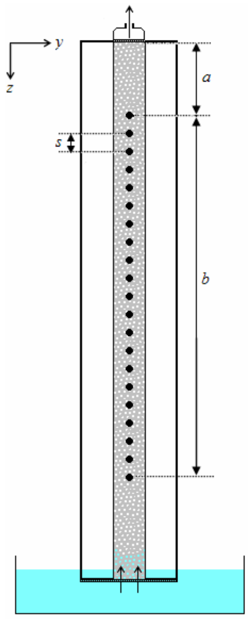

Figure 1b. Side view of the experimental device. s=1cm, a=3.5 cm, b=21 cm.

The container in contact with the lower opening is filled by a transparent fluid, which is pumped upward by the injectors until total saturation of the medium. This fluid is produced by dissolution of a small amount of NaCl in degassed and demineralised water. The pumping rate (1.5 ml/min) is sufficiently low to obtain a perfect saturation of the medium. The tracer is obtained by the dissolution of 0.1 g/L blue dye mixed with 1.0 g/L NaCl in demineralised water. The two fluids are miscible, have the same viscosity and their different NaCl concentrations create a stable density contrast. During the experiments a mixing zone appeared between the two fluids: its characteristics depend upon the densities contrasts, pore size and flow rate.
The geometry evolution of this zone is observed, at the same time, by two independent techniques: the video follow-up which links the transmitted light intensity through the cell measured on each pixel of the camera to the dye concentration, and the electrical measurements which reveal the NaCl dispersion during the transport.

Electrical measurement protocol optimisation

A sensitivity analysis (Furman & al, 2007) is necessary to characterise the sequence of quadripoles which would gives the most reliable description of the dispersion, while minimizing the acquisition time. At first, a set of experiments were performed by stopping the flow when the half of the porous medium is saturated by the tracer. In these conditions gravity stabilizes the front and its position is fixed. We have tested several standard protocols measurements (Wenner-Schlumberger, gradient, dipole-dipole,…). First results show that the measurements are strongly perturbed by the resistive edges of the plexiglas tank. In order to remove theses effects, data are normalised (Daily & al, 1995; Nimmer & al, 2008) and the inversion parameters are optimised to produce reliable models of conductivity distribution. Archie’s law and a linear relationship between conductivity and concentration (figure 2) allow relating the bulk conductivity of each model to NaCl concentration. Vertical variations of dye concentrations estimated by video (red curve) and NaCl estimated by ERT (black curve) are compared. For all experiments, the two concentration curves are shifted: the mean position of the NaCl mixing front appears to be in advance in comparison to the dye. This shift is probably owing to dye trapping in dead end pore zones and adsorption on particles surfaces.

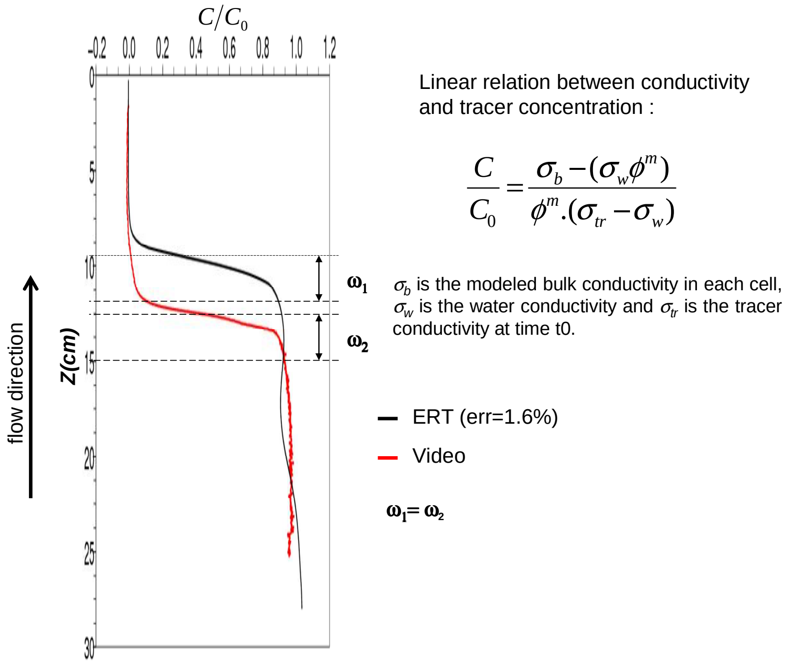

Figure 2. Vertical variations concentrations of NaCl (C/C_0) and dye obtained by ERT (black curve) and video analysis (red curve).

Dynamic monitoring of the mixing front

Results obtained from a static position of the mixing front allow to evaluate the efficiency of each measurement protocol to describe the fluid interface. We found that a transversal dipole-dipole configuration with 190 quadripoles is the most adapted to the geometry of our medium. The temporal resolution is also optimised: each time step is performed in 5 minutes while 30 minutes were needed for the measurements in static conditions. Yet, the continuous tracer propagation causes a temporal shift between the first and the last measurements of each time step. This drawback is corrected assuming a linear conductivity variation with time. Data analyse and inversion parameters are similar as in the case of static fluids (figure 3), vertical variations of concentrations estimated by both methods present the same trend. The thickness and the average front position on first time-steps are similar (figure 3), but the tracer propagation creates a temporal drift of the front position which increases with the upward tracer propagation.

Conclusions

• Optimisation of the electrical measurements protocol provides an acceptable compromise between spatial and temporal resolutions.

• ERT monitoring gives a reliable estimation of position and thickness of the mixing front.

• The shift observed between video and ERT is caused by adsorption and dye trapping, which may be quantifying by our method.

In the future it will be necessary to check on the repetitiveness of the results with several densities differences and flow rates. The system will be also complexified while adding permeability heterogeneities and a 2D vertical fracture.

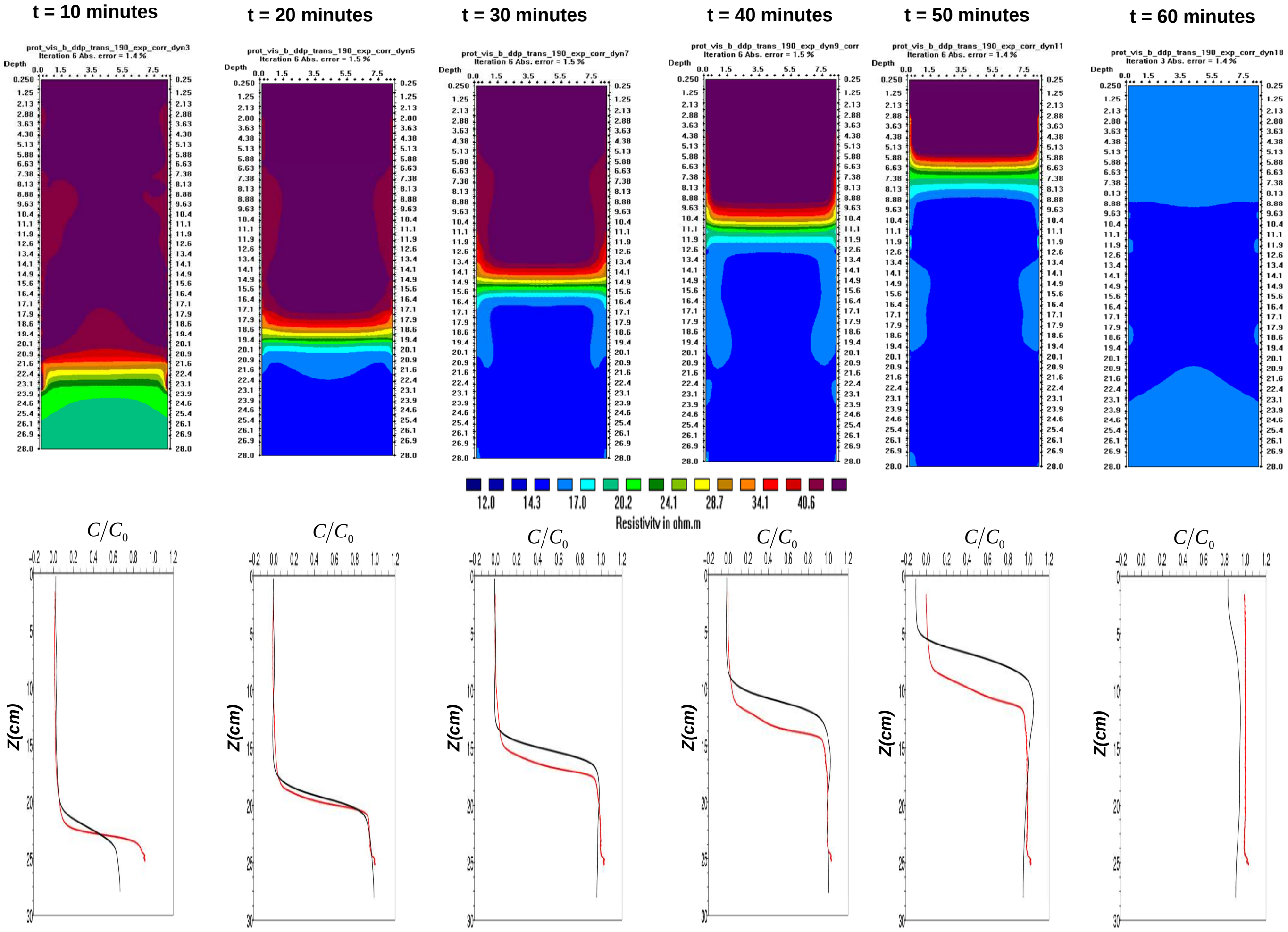

Figure 3. 2D ERT tracer monitoring and comparison with the vertical variation of relative concentrations estimated on each time-step in the middle of the porous medium.

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