Introduction

Electrical resistivity tomography (ERT) is one of the most common geophysical techniques used to reconstruct reliable two (2D), three (3D) and four (4D) dimensional models of the subsurface resistivity. Data acquisition, processing and interpretation methodologies are widely described in the literature (Coscia et al. 2012; Doetsch et al. 2012; Johnson et al. 2012; Majken et al. 2008). The collected apparent resistivity data are inverted to produce true resistivity images of the subsurface (Candansayar 2008; Loke and Barker 1996). ERT electrodes can be deployed either as surface or borehole, or as a combination of the aforementioned arrays. Moreover, in the time-lapse mode, ERT provides spatial or volumetric subsurface information on resistivity changes in time (Karaoulis et al. 2011; Kim et al. 2009). The concept of field or laboratory scale crosshole electrical imaging as a method of investigating transport mechanisms in heterogeneous media is quite simple since the final model is constructed as the difference between an image during tracer injection and an image prior to tracer injection. Repeated imaging over time allows the identification of temporal changes in transport processes.

The main purpose of this work is to monitor a saline tracer in a laboratory tank experiment. This is part of a larger research project which aims to the study of the transfer mechanisms of the olive-oil mill wastes (OOMW) which are a severe source of contamination in Mediterranean countries as typically they are being disposed to open ponds. OOMW are conductive and fully dissolved in groundwater so we can simulate them with a conductive tracer of similar physical properties and monitor its movement using ERT. In the first place, some preliminary tests have taken place in a smaller scale tank (almost 2D) that formed the basis to design and execute a full 3D time-lapse ERT experiment in a larger scale using a bigger tank.

2D tank experiment

Initial experiments were conducted in a small tank, where a coloured saline tracer was released (fig. 1a). A three step permeable medium made of sand was constructed at the centre of the 2D tank. The permeable materials were surrounded with fine, well compacted and almost impermeable sand. During the compaction, the fine sand was saturated in order to achieve proper compaction and avoid any leakage of the saline tracer. After the saturation of all the layers, the injection of saline tracer initiated by supplying 50ml per injection with a rate of 1.5 ml/min. The tracer was released at the upper step of the permeable model and totally 400ml of tracer were used for the experiment. The experiment was successfully completed when all permeable staircase model was fully saturated by the tracer. The monitoring of the tracer was accomplished by simple photo shoots during the progress of the experiment. The above experiment produced an estimate of the spatio-temporal changes occurred helping us to decide the amount of tracer injection and the ERT monitoring setup for the larger scale full 3D experiment.

3D tank experiment

A larger experimental tank with dimensions 1m x 1m x 1m made of plexiglas was used in order to perform the medium scale controlled laboratory experiment. Six vertical electrode lines, simulating boreholes were placed within the tank. Each borehole was made of a plastic pipe with eight electrodes installed in each borehole; the spacing between them was 4cm. Thus, the crosshole electrical resistivity tomography setup incorporated 48 electrodes in total. The distance between the boreholes pair was 23 cm, the distance between the three boreholes in the same line was 16 cm and the boreholes were located 34 cm away from the sides of the tank to minimize the tank boundary effects. Additionally, a surface to horizontal borehole experiment between the centre of the boreholes pairs was also considered using 32 electrodes (16 electrodes in each line) with electrodes being spaced 4 cm apart. The surface to horizontal borehole lines where located 4cm both sided of the staircase formation. In total, 80 electrodes were used for the 3D experiment.

Figure (1b) shows the setup of the vertical boreholes (green pipes) along with the surface horizontal borehole (grey pipe). At the beginning of the experiment, a calibration model prior the injection was acquired and then 100ml of saline tracer was injected with a rate of 1.5 ml per minute. After the injection, a full 3D dataset combining all the boreholes (measuring protocol involved a combination of pole-tripole, bipole-bipole and gradient electrode arrays) was collected consisting of 3296 quadripoles. The whole time lapse ERT monitoring procedure was repeated 19 times after injecting each time (between the ERT measurements) 100 ml of saline tracer and lasted for 74 hours. A total of 21 ERT data sets were collected including the two reference data prior and after the completion of the experiment. The verification of the geophysical monitoring results at the end of this experiment, was made though excavating the material of the tank.

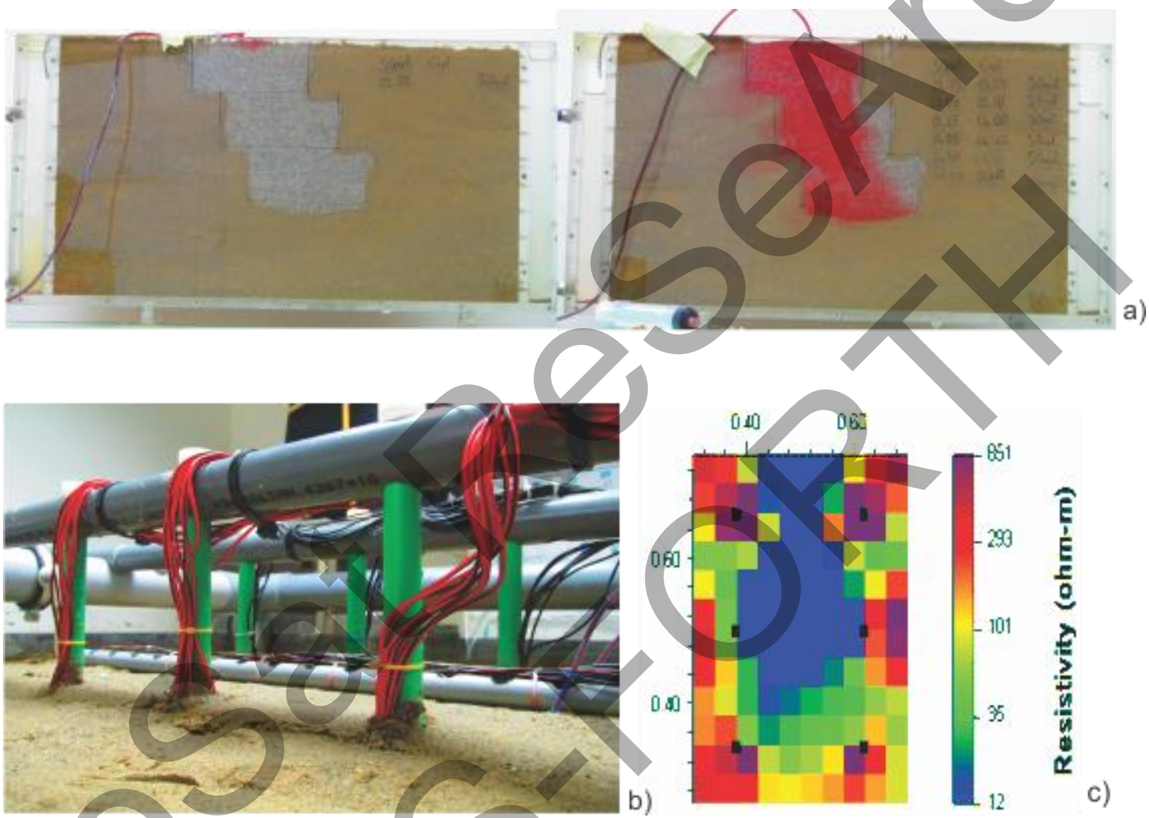

***Figure 1**. (a) 2D tank experiment before and during the injection of the saline tracer into the permeable staircase model, (b) layout of the 3D experiment where the 6 boreholes and the surface array are shown (c) Depth slice resulted image of a 3D inversion, after the 9th injection at the depth of 20cm.*

Data processing

At the end of the experiment, the data was processed with the DC3DPRO inversion software (Kim, 2013). The average of RMS error for the individual 3D data sets was 2% to 5%. Figure (1c.) depicts a horizontal depth slice of xy axis with z equal to 20 cm from the surface of the tank that has been extracted from the full 3D inversion model. Boreholes are illustrated with black squares. This slice corresponds to the ninth injection when 900ml of saline trace had been injected, after 14hours of experiment. Between the boreholes a low resistive zone appears corresponding to the conductive tracer into the middle and the deepest step.

Figure 2 shows time-lapse (ratio) images of the central section of the inversion model after preforming full 4D inversion. The injection of the saline tracer started from the upper part of the staircase formation. In ratio images blue indicates a decrease in resistivity and its change corresponds to the movement of the tracer which is clearly depicted. I1 is the reference image prior to injection so the I1/I2 ratio image (Fig.2) was obtained after the injection of 200ml of tracer and shows the initial movement of the tracer, with direction from the second step to the third step. Subsequent ratio images illustrate the tracer reaching the bottom of the third step. Ratio I1/I4 is obtained after the fifth injection of 500ml and indicates that the tracer flushes the last step. Further some possible artefacts (increase in resistivity) are now more pronounced. Ratio image I1/I5 (Fig.2) suggests that the third step is completely saturated with the saline tracer. In last ratio image I1/I6 the bulk of the saline tracer is 900ml. A small portion of the tracer moves outside the permeable formation. This movement is explained by the fact that the tank formations were fully saturated so after some time (i.e. several hours of experiment) the tracer started infiltrating the surrounding less permeable formations.

After the termination of the experiment, the ERT time lapse results were verified by in situ excavation. Figure 3 shows the last stair which is full saturated of the coloured saline tracer.

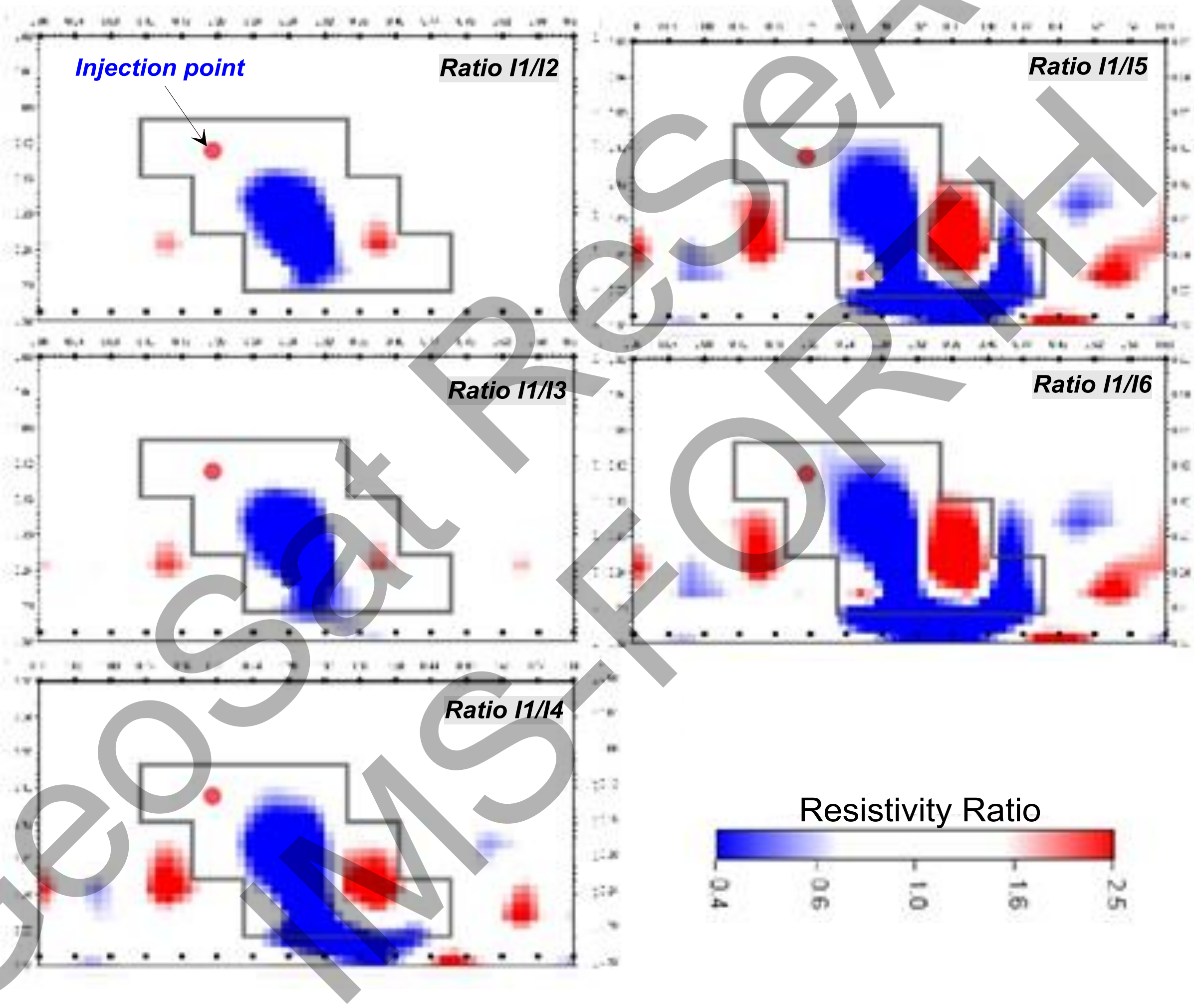

***Figure 2**. 4D time lapse images of the central section of the experiment.*

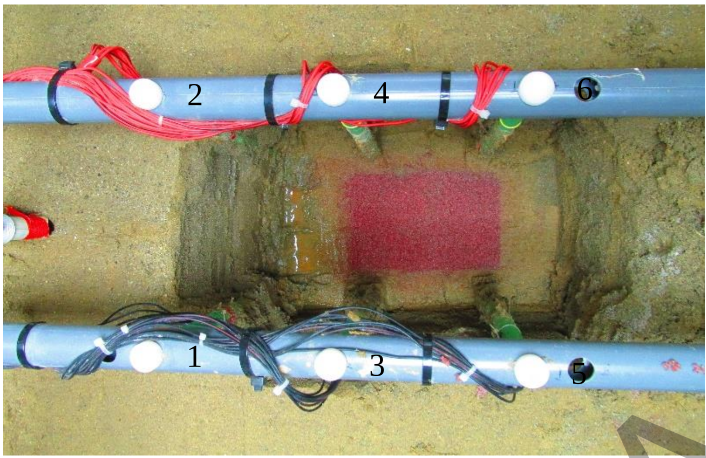

Figure 3. *View of the third stair of the three staircase formation, that is full saturated with the red coloured saline tracer. The numbers 1 to 6 indicate the position of the vertical boreholes.*

Conclusions

In this work 3D ERT was evaluated for the monitoring of a conductive saline tracer in a controlled experimental environment. The aim was to simulate real conditions of a tracer in different permeability environments and record its resistivity footprint. As it shown from the time lapse model the movement of the saline tracer is described in a very clear way through 4D time-lapse inversion images. Current work involves further processing of the geophysical data to extract hydrogeological parameters and create a model of the saline tracer flow and evaluate the applicability of ERT monitoring in this context.

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