Introduction

Surface electrical resistivity tomography (ERT) is a widely used tool to map the subsurface. One of its limitations is the decrease in resolution as the depth increases. Another limitation is that the electrodes planted on the surface can be heavily influenced by temperature, weather, and water saturation changes over time. Consequently, the data can be easily contaminated by noise and thus unreliable for long term monitoring. Borehole DC electrical surveying allows to extend the anomaly detection capability beyond the limits of surface electric surveying. Even more, with two wells, the cross-hole DC electrical surveying provides detailed information on the variation of electrical resistivity between boreholes, but just in a very limited zone near them (Picotti et al. 2013). However, the implementation of borehole to surface electrical resistivity tomography allows to reduce this limitation (He 2018), (Bongiovanni et al. 2015). It is expected that such an arrangement provides an increase in detection capability in the area in-between boreholes and surface. This type of arrangement can be used for geological, geotechnical and environmental investigations (LaBrecque et al. 1996), (Bevc and Morrison 1991), (Kiessling et al. 2010), among others. Furthermore, surface downhole configuration is applied to increase the investigation depth of the geoelectrical measurements.

Only limited application of such a measuring configuration has been reported in literature describing surface-to-borehole application for very deep targets (Daniels 1983), (Bergmann et al. 2012). In (Grünhut et al. 2018) we have studied the feasibility of surface-downhole ERT measurements in order to detect and estimate the dimensions of a contamination plume in a deep aquifer that lies above an oil reservoir. Before doing field measurements, we carried out a synthetic study taking into account that is the first step; if such a feasibility study fails to detect a contamination, then it might be considered not worthwhile to carry out the field measurements, thus preventing wastage of time and money. In that work, the synthetic results obtained showed that detection and monitoring of contaminated deep aquifers is possible with a surface-downhole ERT. The aim of the present work is to study the feasibility of detection performing the analogue physical model at laboratory scale.

Technical characteristics of the experiment

We considered two numerical models, simulating a conductive and a resistive anomaly. The target was buried in a glass container filled with soil, of horizontal dimensions 0.8 m x 1.08 m and 0.6 m height. The target is of 14 cm x 26 cm and 3 cm thickness, located at 13 cm from the upper surface. It was placed in the central part of the box to eliminate boundary contributions. The scheme of the model can be seen in Fig. 1a. The resistive target was a piece of expanded polystyrene, and afterwards, the same piece was wrapped with an aluminium film in order to study the conductive case. We performed 3 lines parallel to x axis and 5 lines parallel to y axis as can be seen in Fig. 1b, where the locations of the wells named P0 and P1 are also indicated.

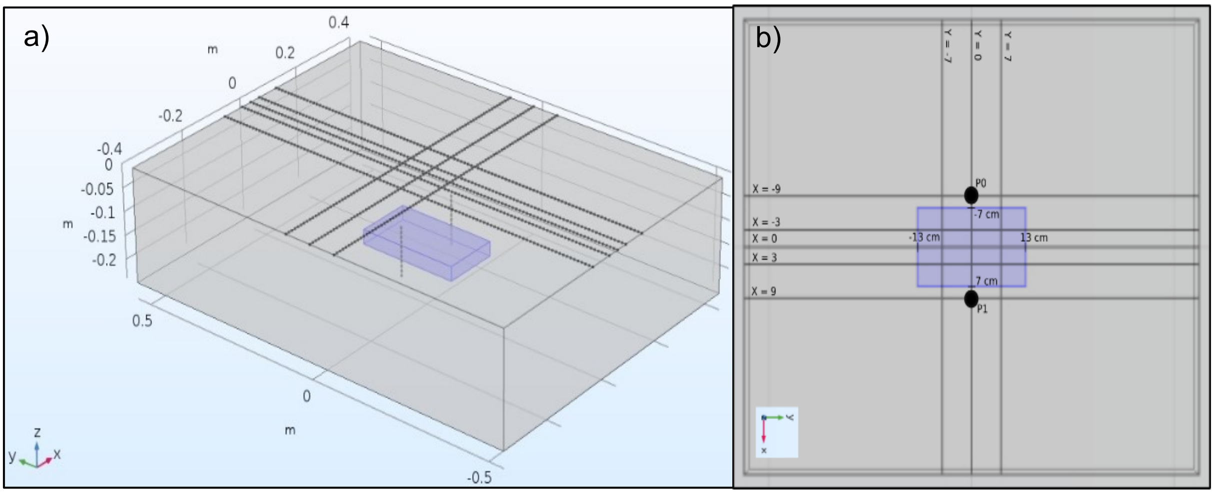

Figure 1 Scheme of the experiment. a) 3D view and b) cut view at z = 0 including the location of the anomaly with the lines and the wells performed.

We used 59 electrodes along each *x* axis and 69 electrodes along each *y* axis. The electrode separation was of 0.01 m. Conical wooden sticks of diameter, approximately, 1 cm and 13 cm length were made for the boreholes, while copper wire rings around them acted as electrodes. There are 11 electrodes separated 1 cm.

Data were collected using the resistivimeter made in our laboratory (de la Vega el al. 2019). To invert the data, we used the RES3DINV inversion code developed by Loke 1996. It can be seen in Fig. 2: a) a photo of the general experimental setup, b) the conductive target buried, and c) the conical wooden stick.

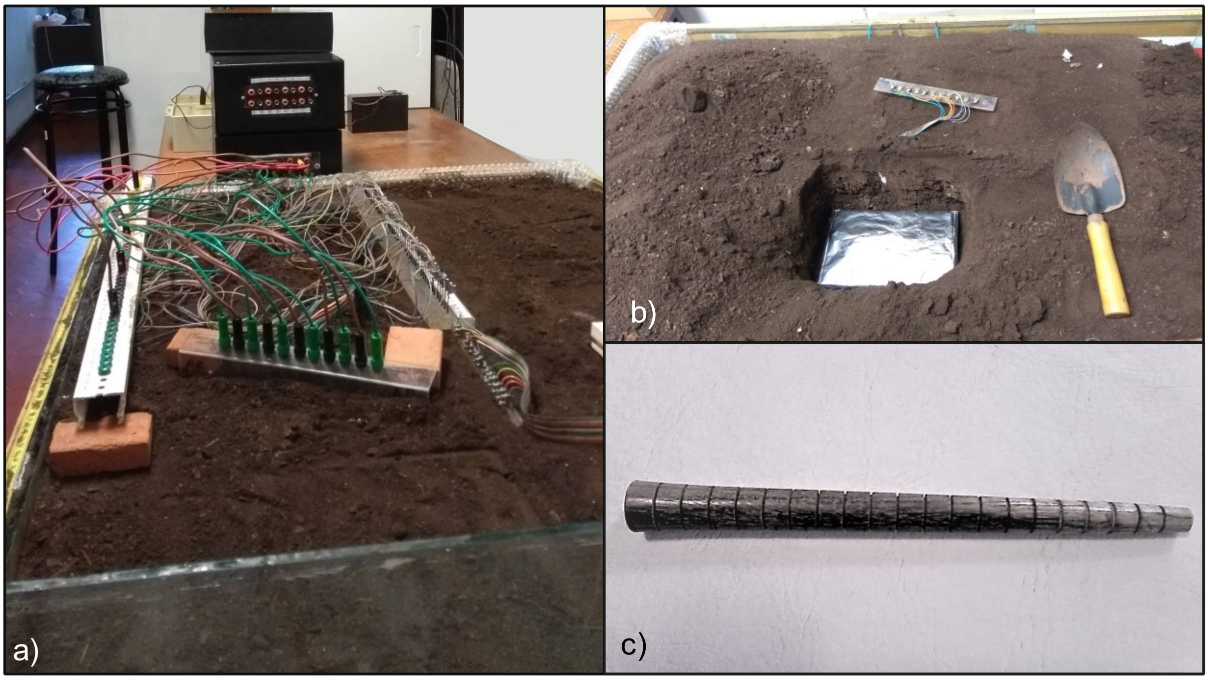

***Figure 2**: a) Experimental setup. b) Conductive target buried. c) Conical wooden stick.*

Methodology and Results

We started considering only surface measurements in order to verify that these anomalies could not be detected from surface. We used dipole-dipole, gamma and wenner configurations along the lines schematized in Fig. 1. Effectively, no anomaly about 14 cm depth was detected (see Fig. 3), suggesting the benefit of locating potential electrodes at depth in order to have a successful detection of the anomaly.

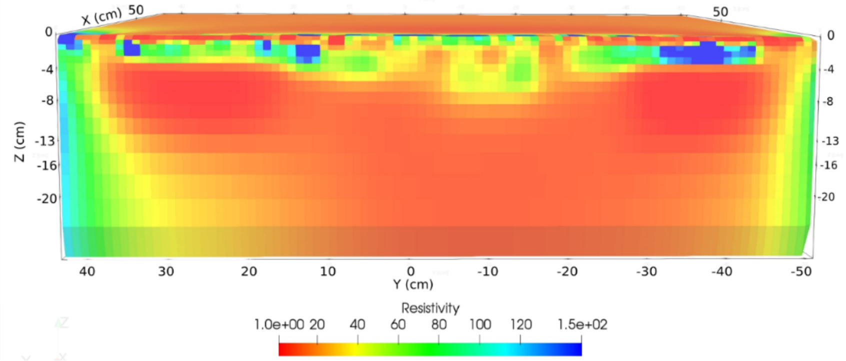

***Figure 3** 3D resistivity image obtained from the surface configuration. Cut view at x = 0 cm for the resistive case.*

Afterwards, we performed two boreholes, located at 2 cm from the anomaly, i.e., along *y* = 0, at *x* = -9 cm (P0) and *x* = 9 cm (P1). We used the dipole–dipole array in the experiments. The current electrodes were the ones on surface and the voltage electrode the ones in the boreholes. Firstly, we study the possibility to detect the inhomogeneity using only one well, trying with P0. Both in the resistive and the conductive case, the anomalies were difficult to detect. In all the figures we plotted the location of the target with dotted lines. In Fig. 4, the ERT of the conductive case with only P0 can be seen. Although it can distinguish a conductive anomaly about $x = 0$ in-between a more resistive zone, the resolution is minimal. The resistive case with only P0 (see Fig. 5) shows evidences of a the conductive anomaly near $x = 0$ and from $z = -13$ cm to $z = -16$ cm, but neither the location nor the resolution is good. Measurements from a single well are not justified, due to the low resolution obtained.

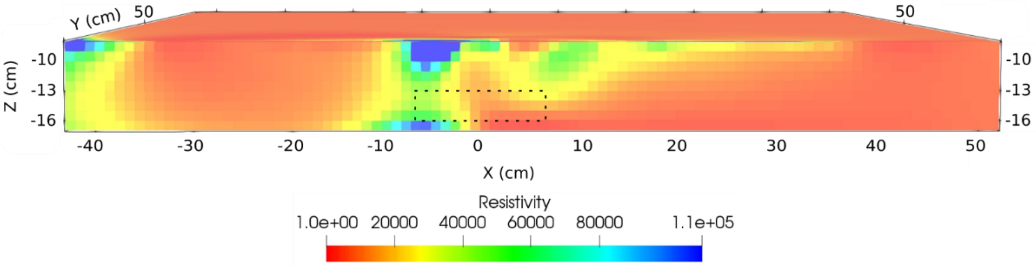

Figure 4 *3D inversion of the conductive case using only the well P0, cut view at y = 0 cm.*

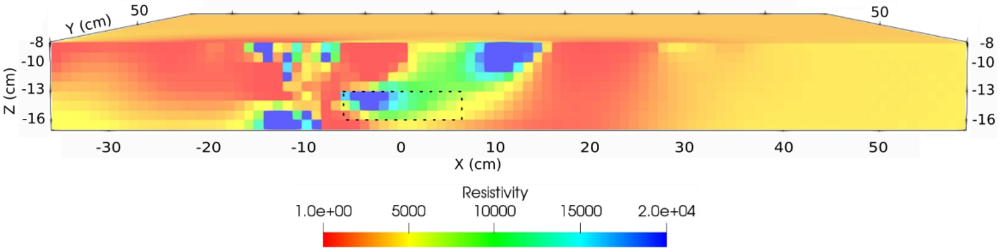

Figure 5 *3D inversion of the resistive case using only the well P0, cut view at y = 0 cm.*

In order to improve the detection, we invert jointly the data from the two wells. In Fig. 6 we show the inversion result for the conductive case, a cut view at $y = 0$. A conductive anomaly between $x = -6$ cm and $x = 2$ cm, at 13 cm depth approximately can be seen. The anomaly could be localized, although its exact delimitation could not be achieved.

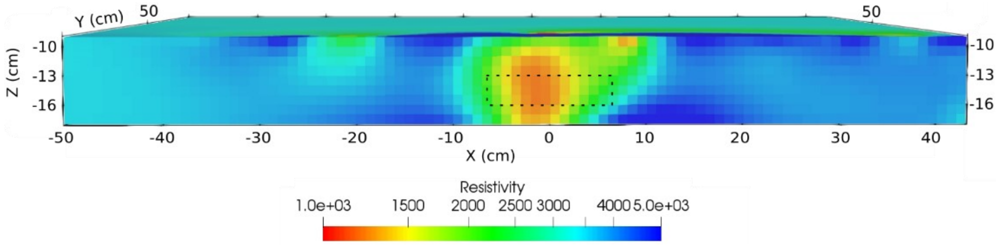

Figure 6 *3D inversion of the conductive case using both P0 and P1, cut view at y = 0 cm.*

In Fig. 7 we show the inversion result for the resistive case, a cut view at $y = 0$. A resistive anomaly between $x = -7$ cm and $x = 7$ cm and between $z = -13$ cm and $z = -16$ cm approximately can be seen. In this case, both the localization and the delimitation of the anomaly could be achieved.

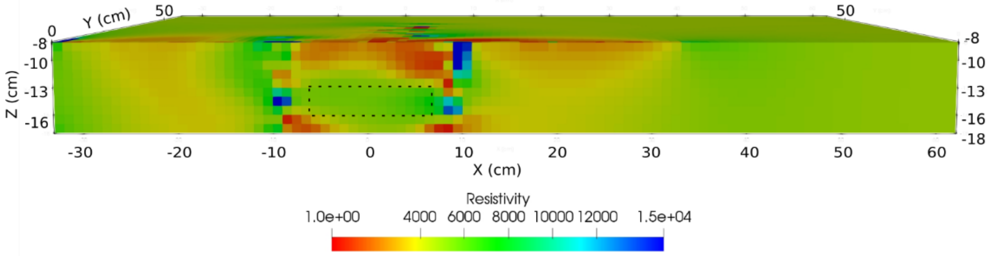

Figure 7 *3D inversion of the resistive case using both P0 and P1, cut view at y = 0 cm.*

Conclusions

In previous works, we have studied the feasibility of surface-downhole ERT measurements in order to detect and estimate the dimensions of a contamination plume in a deep aquifer. Through performing several numerical simulations including surface and surface-downhole configuration of ERT, we came to the conclusion that detecting a deep anomaly can only be achieved with surface-downhole measurements. In the present work, we made a laboratory scale experiment in order to reproduce the numerical results, considering the resistive and conductive contaminations at depth in scale of the previous work. Firstly, we performed the experiment with only one well and afterwards with two wells. The results obtained show that it was not possible to detect the contaminated plume with only one well, but although the plume could not be completely characterized due to the limitation in the lateral resolution of the borehole configuration, the detection and consequently the monitoring of contaminated deep aquifers with two wells using surface-downhole ERT is possible.

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