Geoelectrical Remote System for Monitoring Shallow Subsurface CO_2 Migration

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Abstract

The implementation of the first CO_2 MMV field lab in Brazil, located in Florianópolis, Santa Catarina state, offered an excellent opportunity for running controlled release experiments in a real open air environment. After three CO_2-controlled release experiments run from 2011 up to 2015, a new site with a more complex geology was selected to implement new experiments. The substrate of the PUCRS campus located in Viamão, state of Rio Grande do Sul is predominantly sandy clay. The purpose of this work is to present the results obtained by the geoelectrical remote time lapse, using 3D electrical imaging technique to monitor CO_2 migration in both saturated and unsaturated clay-rich sediments in Viamão site. The CO_2-controlled release occurred in 2016, covering a subsurface area of approximately 2.925 m^2. The CO_2 was continuously injected through an injection well, at 3 m deep, in a period of 31 consecutive days (24 hours/day), at a rate varying from 5 to 20 kg / day, totalizing 346 kg of injected CO_2. While the CO_2 was injected, 3D electrical images using dipole-dipole array were acquired in a daily base, totalizing 46 consecutive days. 3D (tridimensional) and 4D (time-lapsed) electrical imaging produced images reaching 17 m below the surface. Remote monitoring was used for the continuous characterization of the soil/sediment geoelectric responses, significantly increasing the accuracy of the geoelectric responses, such as changes in the injection rate. Comparison of post-injection electrical imaging results with pre-injection images shows changes in resistivity values consistent with released CO_2 migration pathways. A pronounced increase in resistivity (up to ~ 1,900 ohm.m) with respect to the pre-injection values, was detected at shallow depths (~ 0.50 m) southeast of the injection well. Background values of 75 ohm.m have changed to 2,000 ohm.m, right after injection. On the same day of the resistivity increase CO_2 flux measured using accumulation chambers also increased, reaching values 20 times greater than those observed during baseline measurements (7 mmol/m^2/s). The increased CO_2 concentration in the atmosphere compared to background-measured concentrations using carbon caps, also coincided with the results of the subsurface resistivity survey. Geoelectrical remote monitoring has also shown significant changes in resistivity values occurring in different portions of the area, probably related to the heterogeneous nature of the site lithology.

Introduction

The geological storage of CO_2 in the deep reservoirs represents a viable and attractive solution to mitigate the greenhouse gas emissions. However, the long-term stability of stored gas in the reservoir is poorly understood, mainly with respect to potential risk of leakage to the atmosphere. The monitoring strategies can provide crucial information for verification, accounting and risk assessment at a storage site, representing fundamental to ensure that the effective containment of the gas has actually taken place.

Distinct approaches to long-term monitoring behavior of stored CO_2 within the reservoir were proposed in the last decades and are classified according to their detection principles, i.e. direct or indirect. The indirect monitoring, mediated by geophysical monitoring deploying a variety of surveying methods, such as electrical resistivity tomography, seismic, ground penetrating radar, gravity and electromagnetic assessment (WHITE, 2011; HOVORKA *et al*., 2013; FÖRSTER, 2006; AUKEN *et al*., 2014).

However, these methods require a monitoring well in addition to the injector and have limited areal coverage. In the case of large CO_2 plume, a very large number of monitoring wells is needed that could turn the project uneconomical. Additionally, dissolved CO_2 is difficult to detect in fresh aquifer using ERT (Electrical Resistivity Tomography) as opposed to monitoring supercritical CO_2

in saline aquifers using crosshole ERT (AUKEN *et al*., 2014; CARRIGAN *et al*., 2013; DOETSCH *et al.*, 2010).

While some examples show the potential of geophysical reservoir monitoring, even fewer examples of geophysical leak detection and monitoring of CO_2 in shallow potable aquifers exist. Only very few studies (SCHMIDT-HATTENBERGER *et al*., 2013; DAFFLON *et al.*, 2013; LAMERT *et al.*, 2012; AUKEN *et al*., 2014) have investigated the electrical signature of dissolved CO_2 in shallow aquifers.

CO_2 migration in the subsurface can occur either as dissolved or as free phases. Some pilot studies showed increase in EC pulse in response to increase in dissolved major and minor ions with concurrent decrease of pH. In this context, the determination of electrical resistivity anomalies by geophysical techniques, using ERT and EI (Electrical Imaging) is quite useful and decreased resistivity would typically be expected (STRAZISAR *et al.*, 2009, AJO-FRANKLIN *et al.*,2013 ; LAMERT *et al.*, 2012; LE ROUX *et al.*, 2013; AUKEN *et al.*, 2014; YANG *et al.*, 2014; KURAS *et al*., 2016). However, the results depend on the injection rate and amount of CO_2 dissolved in water (CAHILL e JAKOBSEN, 2014).

Other pilot studies showed gaseous CO_2 intrusion forming bubble in an aquifer, reducing water saturation with increase of gas content in the soil pore space, leading to increased bulk electrical resistivity of the subsurface (OLIVA *et al.*, 2014). Excess CO_2 not dissolved in deep saline aquifer also results in increased electrical resistivity (GIESE *et al.*, 2009; BYRDINA *et al.*, 2009; WÜRDEMANN *et al.*, 2009).

The main goal of this paper is to evaluate the results of the soil/sediment continuous geoelectric response under continuous CO_2 injection, using a remote system.

A shallow aquifer field site located in the Southernmost state of Brazil was chosen for the CO_2 injection experiment. The release experiment was carried out at the TECNOPUC campus (Pontifical Catholic University of Rio Grande do Sul – PUCRS), Viamão - Rio Grande do Sul state (Figure 1). The experiment site (30° 5'1.47"S latitude; 51° 3'32.75"W longitude; 104 m elevation) occupies a 2,925 m^2 area is covered by low vegetation with a predominance of native grasses.

Figure 1 - *Site location.*

The leakage simulation was performed by injecting gaseous CO_2 directly into the aquifer (saturated zone) through a vertical well.

The maximum injection pressure of CO_2 was set to 5 bar. CO_2 was continuously injected during 31 days (30^{th} September to 30^{th} October - 2016) and in this period consumed 346 kg of CO_2. The mass flux rate was modified as follows: 30^{th} September to 03^{th} October – 5 kg/day; 04^{th} October to 10^{th} October – 8 kg/day; 11^{th} October to 23^{th} October – 10^{th} kg/day and 24^{th} October to 30^{th} October – 20 kg/day.

Method

CO_2 migration in both saturated and unsaturated soil was monitored with Remote System. In a typical monitoring program, geophysical techniques (e.g. seismic) are applied to monitor the quantity and migration of CO_2 within a reservoir and its adjacent formations usually at deeper levels (in the scale of hundred meters to kilometers), thus providing geological characterization and time-lapse imaging information for the CO_2 plume migration. However, because our study focused on measurements in the near subsurface, we used surface-based CO_2 soil gas concentration measurements along with geophysical methods, such as direct current geoelectrics.

Two main processes can be seen as CO_2 migrates through the saturated and vadose zones before degassing into the atmosphere. Firstly, dissolved volatile CO_2 in the pore space has an impact on electrical resistivity due to formation of carbonic acid or mineral dissolution. In this context, the determination of resistivity anomalies is considered to be useful when investigating disturbances caused by variations in lithological parameters and fluid content (BALL *et al.*, 2010; NGUYEN *et al.*, 2007) and decreased resistivities would typically be expected. Secondly, fluid movements through porous media lead to the occurrence of areas that serve as preferential paths for the gas displacement. In saturated porous zones, the gas can move through groundwater partially occupying its space and leading to increased resistivity at the local level.

The monitoring based on time-lapse ERT relies upon multiple and repeated measurements of bulk electrical resistance of the subsurficial soil in the region of interest and are carried out with an array of electrodes that must cover (as a minimum) the perimeter of the volume of ground to be monitored. Through inverse modelling, electrical imaging then transforms these measurements into volumetric images of ground resistivity.

3D electrical imaging was carried out with a Remote System Super Sting R8/IP+28 using dipole-dipole configuration using 112 electrodes.

Remote System control and monitoring of numerous subsurface processes with electrical imaging in 3D and 4D (time-lapse) from a network connection or cloud storage location. The Super Sting Wi-Fi Remote resistivity monitoring system is designed for unattended monitoring of subsurface processes such as environmental remediation progress, groundwater recharge, infiltration tests, injection tests, salt/fresh water interaction, leakage from landfills, tanks and dams, soil moisture changes, under-ground tunneling and temperature changes.

In this study, remote monitoring has been used for continuous characterization of soil/sediment geoelectric responses before, during and after CO_2 injection, substantially increasing the number of data acquired, without the operator actually being in the field. Parameters such as measurement time, injected current, maximum voltage, accuracy, cycle repetition were monitored in real time, reducing the uncertainties inherent to geophysical methods and substantially improving the geological model, which delimited the preferred paths of CO_2. (Figure 2).

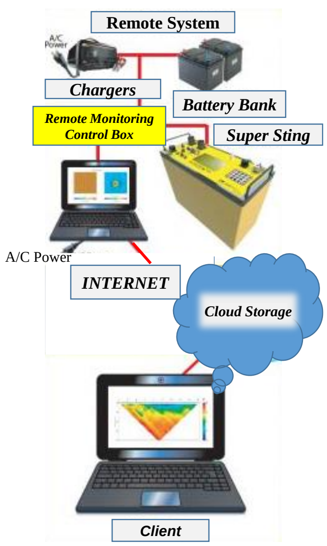

Figure 2 - *Remote system configuration.*

The spacing between the electrodes was 5.0 m, reaching depth of 17.4 m and covered an area of 2,925 m^2 (Figure 3). A background survey was performed during 4 days, prior to the CO_2 injection as to supply a resistivity site-based experimental model. During the release experiment, the measurements were carried out 24 hour per day, using remote monitoring system. Post injection survey was also performed during twelve days and a stable reading was observed, consistent with those of background levels.

Prior to inversion of the acquired time-lapse electrical imaging data, it was preprocessed for quality control, outlier detection, and noise estimation purposes. The large amount of data allows for a detailed time-series analysis, but requires automatic processing and outlier detection.

To identify the degradation of the surface electrodes that were installed in the field throughout the campaign, resistance checks were carried out before and during the CO_2 injection. These checks measure the resistances between adjacent electrodes and use them simultaneously for currents and voltages.

Therefore, these checks are more sensitive to the contact resistances than to reservoir resistivity and serve here as an indicator of the condition of the electrodes and materials in close contact. Resistance checks were initially performed on a daily basis shortly before the start of the CO_2 injection, and continued with about one measurement per day, until the end of the campaigns.

The filtering, analysis functions, and their parameters were therefore carefully chosen and tested on subsets of the data set. Initially, the data was statistically analyzed to evaluate the data quality based on the data removal thresholds set.

Inversion parameters have been determined successively by running inversions for which single parameters were varied. The inversion method chosen was smoothness constrained inversion method (DE GROOT-HEDLIN e CONSTABLE, 1990), provided by the software package Earth Imager 3D.

Figure 3 - *3D electrical imaging area with electrode distribution.*

Results

The CO_2 injection started on September 30th of 2016 14:00 h local time. As described above the mass flux ranged from 5 kg/day to 20 kg/day of CO_2 and injection pressure level was kept at 5 bar.

Investigations employing 3D electrical imaging were carried out with a Super Sting R8/IP+28 using dipole-dipole array configuration.

A base line survey was performed prior to the CO_2 injection as to supply a resistivity site-based experimental model, for 4 days. During the release experiment the measurements were carried out 24 hours per day for 30 days. Twelve post injection surveys were also performed.

First of all, in 29th September, prior to the start of the injection, a slice was made in the 3D electric imaging, on the Y axis to correlate local lithology, obtained through the detailed description of samples recovered during the drilling by direct push technology (DPT), with resistivity values. The resistivity values below 180 ohm.m were correlated to clayey silt sediment and/or sandy clay. Values above 180 ohm.m were correlated to sandy sediment and/or granite rock alteration. Below 13 m depth, the resistivity values exceed 1,000 ohm.m, which indicates these values are related to granite rock.

To obtain a base line prior to the initiation of CO_2 injection experiment, we carried out the ERT investigation and inversion of the acquired data. Figure 4 shows the percentage change of resistivity, and as expected the changes were minimal, probably caused by external interferences and at the limit of the survey.

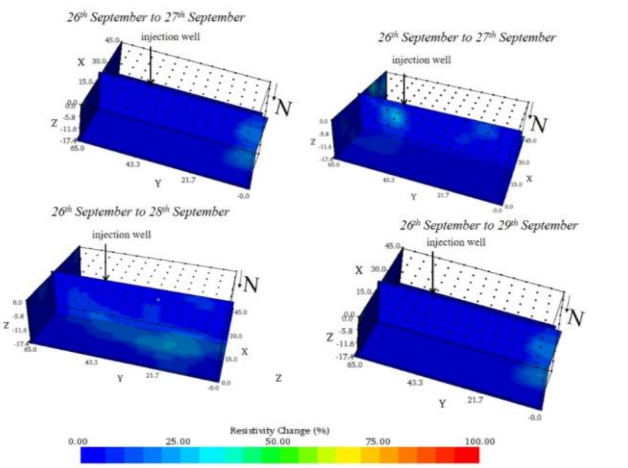

Figure 4 - *Resistivity change (%) section obtained by 3D electrical imaging slicing showing the resistivity percentage change before CO_2 injection.*

Comparison of pre-and post-injection electrical imaging shows changes in resistivity values consistent with migration pathways of the CO_2 injected.

Considering the base line obtained in 29th September, figures 5a, 5b, 5c and 5d show the maximum increase in percent change of resistivity occurred in the period that mass flux was 5 kg/day, 8 kg/day, 10kg/day and 20 kg/day, respectively.

The largest geoelectrical anomaly as expressed in percentage change was detected in the SE area reaching 9,500 % in 29th September (Figure 5d). A pronounced increase in resistivity (up to ~ 1,900 ohm.m) with respect to the pre-injection values, was detected in the same day. Background values of 75 ohm.m have changed to 2,000 ohm.m (Figure 6).

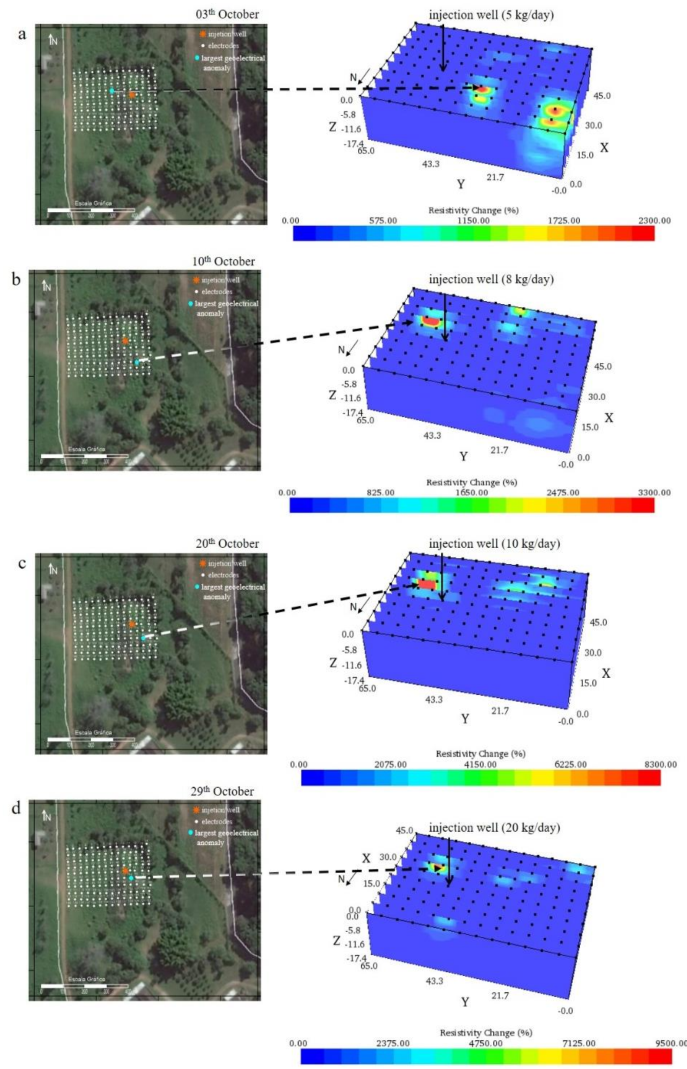

Figure 5 - *The maximum increase in percent change of resistivity occurred in the period that mass flux was 5 kg/day, 8 kg/day, 10kg/day and 20 kg/day, considering. the base line obtained in 29th September.*

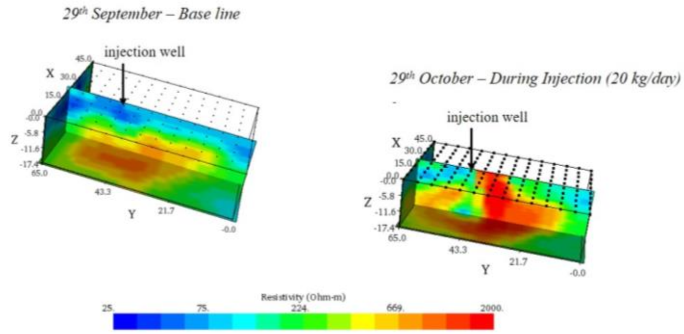

Figure 6 - *Resistivity (ohm.m) sections obtained by 3D electrical imaging slicing showing the pronounced increase in resistivity (up to ~ 1,900 ohm.m) with respect to the pre-injection values.*

The percent change of resistivity is related to the base line resistivity values established for the area. For example, portions that have low resistivity values, taking into account the range of resistivity values of the area, may present a significant percentage change in resistivity values when compared to portions with higher resistivity values. This is because CO_2 shows an insulating feature, since it is a gas, and when it occupies the pores of portions composed of fine sand and/or silt, with lower values of resistivity, they may present a higher percentage change of resistivity. Therefore, high changes in the percentage resistivity did not necessary mean higher concentrations of CO_2, but rather a shift to these portions.

Comparing the base line result obtained in 29th September with the other days (Figures 5a, 5b, 5c and 5d), it can be seen that the most significant percent changes of resistivity occurred in different portions of the area. This is because the lithology of the area is very heterogeneous and without a well-defined underground water flow. If we consider a perched aquifer, which is not present in every area investigated, the gas will have a tendency to flow into the unsaturated zone of the area, since it is easier to displace air than water.

Eleven days after the injection stopped, the resistivity change dropped without reaching the base line (Figure 7).

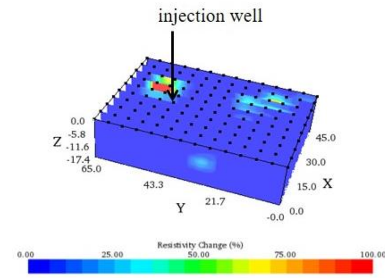

Figure 7 - *Percent change of resistivity eleven days after the injection stopped.*

Figure 8 portrays a mixed plot illustrating soil flux and resistivity change (%) at shallow level (0.5 m depth) during the release campaign. The integration of these two data sets shows correlation between techniques. In the same day the CO_2 concentration measured in the atmosphere were also at the highest and reached 7,585.16 ppm in 29th October nearby the injection well.

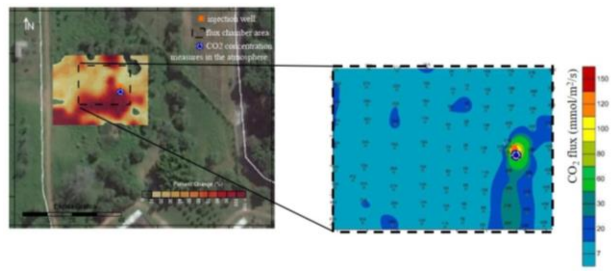

Figure 8 - *Integrated maps showing percentage resistivity changes, CO_2 flux measurements and the point with the highest CO_2 atmosphere measurement in 29th October.*

The CO_2 concentration measurements obtained with the carbon caps increased after their repositioning, following the anomaly detected in the geophysical acquisitions (Figure 9).

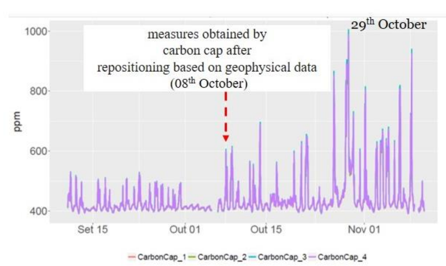

Figure 9 - *CO_2 concentration obtained by carbon cap.*

Conclusions

The results presented confirm that 3D/4D electrical geophysical remote monitoring technique is very useful and efficient to determine preferential CO_2 flow paths. The remote electric imaging permitted identify the geoelectric anomalies related to gas migration before, during and after the injection experiment.

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