3D electrical resistivity tomography geophysical monitoring of the effectiveness of an environmental remediation system by pure oxygen injection

Suivi par méthode géophysique en tomographie électrique 3D de l'efficacité d'un système de dépollution par injection d'oxygène pur

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Abstract. A polluted site with hydrocarbons is being actively treated by an innovative approach consisting of improving the effect of aerobic bacteria to depollute the soil. To do so, pure oxygen is added into the ground by an injection borehole. In order to complement soil, water and gas sampling made directly from adjacent monitoring boreholes, a 3D electrical resistivity tomography (ERT3D) geophysical imaging analysis has been conducted on a monthly basis. The setup consists of 286 electrodes positioned on a 75m x 75m grid centered on the injection borehole. The acquisition is made with more than 45000 apparent resistivity points collected over 4 different array types: Dipole-Dipole, Pole-Dipole, Wenner and Wenner Schlumberger. Over the 5 months survey we have observed that changes in resistivity are mainly located around the injection borehole, especially in the northern and eastern part of the site. The geophysical survey allows a better understanding of the localization, shape and evolution over time of the main pollutants with respect to the injection of O2. This survey demonstrate that 3D electrical resistivity imaging is an efficient tool to quickly map a polluted site and to allow for a better definition of corrective remediation measures.

Résumé. Un site pollué par des hydrocarbures est traité par une méthode innovante de stimulation de la biodégradation aérobie par injection continu d'oxygène pure depuis un forage d'injection. Un suivi géophysique mensuel par tomographie électrique 3D est réalisé afin de compléter le protocole en place d'échantillonnage ponctuelle des gaz, sols et eaux depuis des forages adjacents au forage d'injection. Le dispositif géophysique consiste en 286 électrodes implantées selon un maillage de 75m x 75m centré autour du forage d'injection. L'acquisition consiste en plus de 45000 points de mesures de résistivités apparentes selon différents types de dispositifs : Dipôle-Dipôle, Pole-Dipôle, Wenner et Wenner Schlumberger. Sur la période d'essai de 5 mois nous avons pu observer que les changements de résistivités se situent principalement autour de la zone d'injection ; plus particulièrement vers le nord et l'est. Les résultats géophysique permettent une meilleure définition de la position, de la forme et de l'évolution temporelle des polluants principaux en fonction de l'injection d'O2. Ce projet démontre l'efficacité des méthodes géophysique électrique 3D pour l'étude des sites pollués et leur gestion.

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1 Introduction - Presentation of the project

A pilot site, polluted by hydrocarbons and chlorinated solvents, has been treated since 23/07/2021 by an innovative method of stimulation of aerobic bacterial degradation. This method involves the continuous injection of pure oxygen at different depths of a borehole (Z1). In order to test the evolution of this remediation process three control boreholes (Pz0.5, Pz2 and Pz5) (Fig.1. left) are used to take discrete samples of BTEX, PAHs, HVOCs, C5-C10 and C10-C40 hydrocarbons in water, soil and soil gas (Fig.1. right).

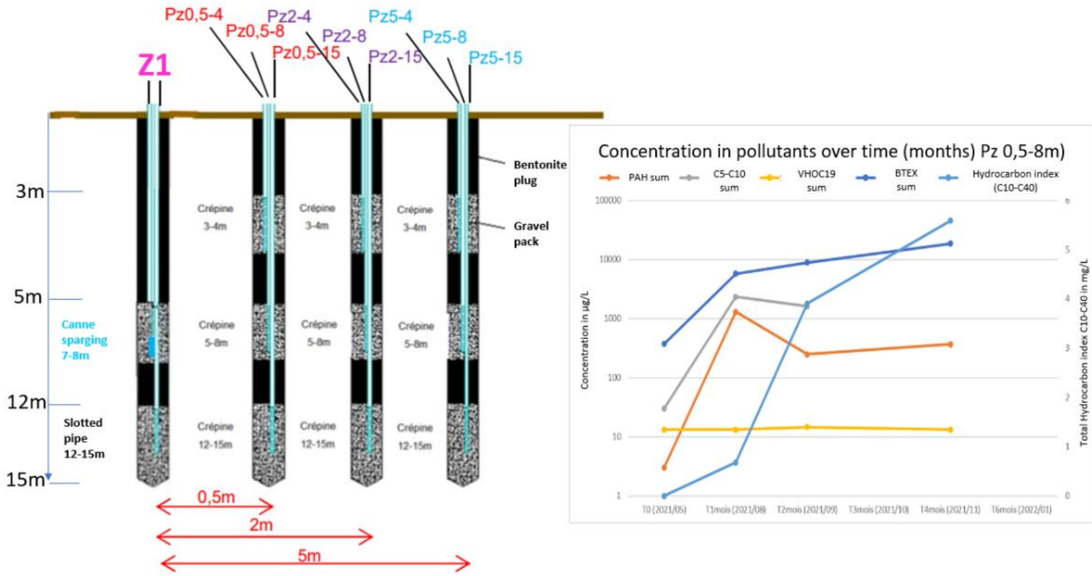

Fig. 1. Pure oxygen injection borehole (Z1) and three control boreholes for soil, gas and water sampling (schematic on the left) and an example of measurements of water pollution from the piezometer located 0.5m away from the oxygen injection borehole. Samples were taken at a 8m depth (graphs on the right).

In order to provide information on the effectiveness of the remediation system within a larger volume around the injection borehole, it was decided to conduct a 3D geophysical survey by electrical tomography measurements (ERT3D). This monitoring has been carried out monthly over a five-months period. Initial measurements were recorded in May 2021, at a time before the beginning of oxygen injection. Geophysical monitoring phases followed in September, October, November, and December of 2021 with the aim of measuring the temporal and spatial variations in soil resistivity, and therefore provide a more detailed vision of the evolution of the subsoil pollution during the remediation process.

2 Methodology

The ERT3D surface geophysical monitoring system is located on a target area of 75m x 75m centred around the injection borehole and its three control boreholes. The survey is conducted with a Syscal Pro SW96 (from Iris Instruments) with a setup consisting of 256 electrodes positioned on a 5m x 5m square grid. A similar but tighter 2.5m x 2.5m grid, made of 66 electrodes, is set up more closely around the oxygen injection borehole (zone ~15 m x 15m) to increase the resolution toward the center of the site. System has a total of 286 electrodes that are left on the site throughout the project, which allows for a rapid re-installation of the measurement system at the beginning of each new monitoring phase. The

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measurement protocol is established in 4 blocks: block A, B and C which consists of 96 electrodes, and block D consisting of 66 electrodes (Fig.2.). For each of these blocks, 4 types of acquisitions are conducted: Dipole-Dipole, Pole-Dipole (note: sequence effective since the 2nd measurement in September), Wenner and reciprocal Wenner-Schlumberger, adding up to approximately 5000 points of apparent resistivity measurements for each monthly monitoring. All points are collected over one and a half days of fieldwork.

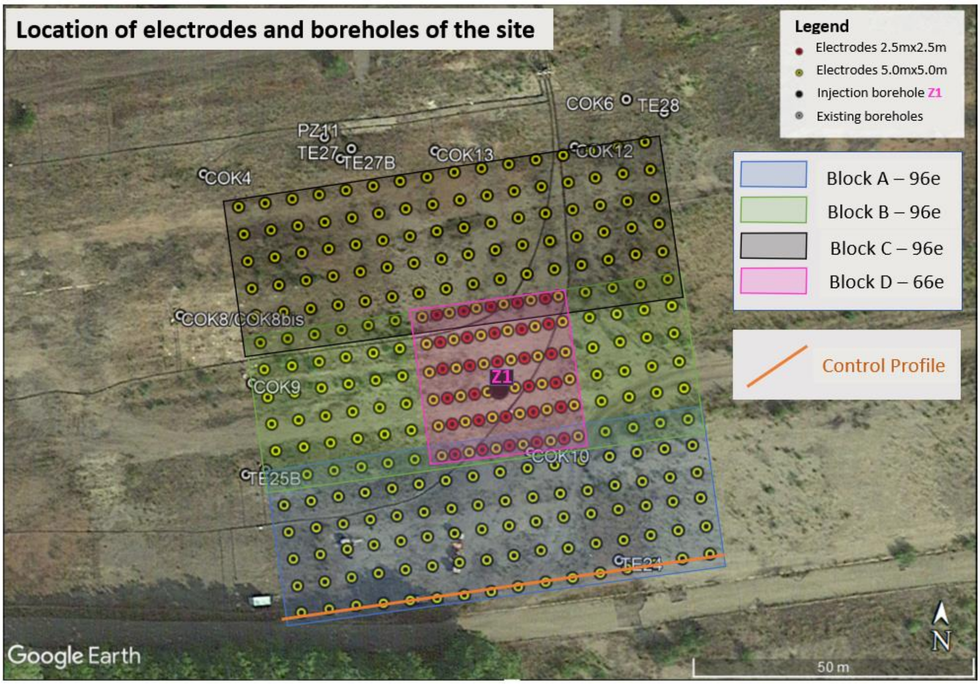

Fig. 2. Location of ERT3D measurement electrodes, existing boreholes, control profile, oxygen injection borehole (Z1) and indication of measurement methodology made by blocks of 96 electrodes (blocks A, B and C) and 66 electrodes (block D) - Z1 is the oxygen injection borehole

3 Data processing and interpretation

The processing and inversion of the data, followed by their interpretation, reveal a site with strong heterogeneities, with the development of resistivity anomalies that are both conductive (resistivity < 20 ohm.m) and resistive (> 500 ohm.m). Although these variations are abrupt (rapid change from resistive to conductive), the inversion of the data is still possible and exploitable (robust inversion calculated with Geostudi Astier's ERTLab software).

3.1 Anomalous resistivity zones in 3D views

The interpretation of the results shows a good reproducibility of the measurement protocol with a recurrence of most of the main resistivity anomalies (which we associate with pollution phenomena) identified on the different monthly measurement phases. The 3D visualization of the isosurfaces of both low and high resistivities shows that the position and general shape of the main anomalies remain comparable over time. Efficacity of the remediation process is visible as a decrease in volume/isosurface of the main anomalies (Fig.3.)

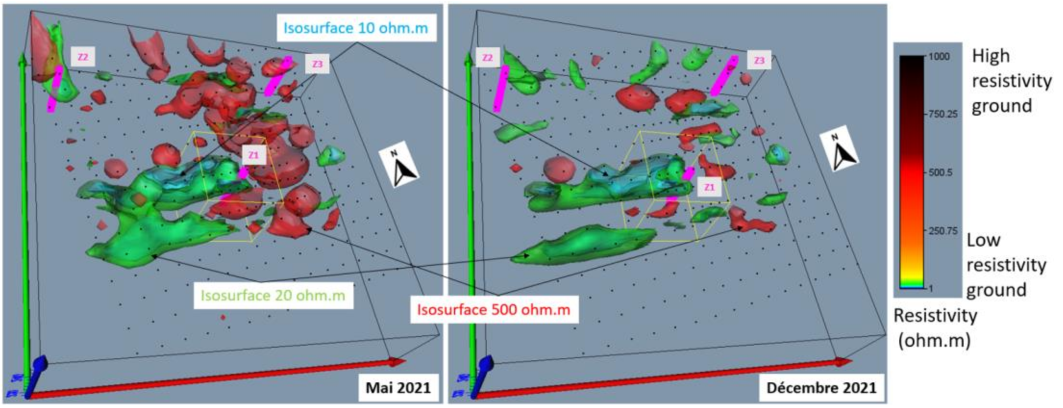

Fig. 3. 3D visualization of the 10 ohm.m, 20 ohm.m and 500 ohm.m isosurfaces of the electrical tomography model - on the left measurements of May 2021 and on the right measurements of December 2021 - Z1 is the oxygen injection borehole

3.1 Statistical study - Histograms of resistivity distributions

The histograms of the resistivity distribution calculated over the entire volume (volume 75 m x 75 m x 18 m) of the resulting 3D electrical tomography inversion model show an increase/push in the 50-70 ohm.m resistivity range whereas other resistivities have remained roughly equivalent throughout the project (Fig.4.).

This observation can be explained by "zooming" in a closer area near the injection borehole. To do so we decided to extract from the resulting inverted model the resistivities in a 20 m x 20 m x 18 m cube where the variations in resistivity over time are more clearly visible. A noticeable change in the distribution of resistivities over time is observed, with a possible rebalancing from resistivity values in the range of 30-50 ohm.m toward the 60-70 ohm.m range (Fig.5.).

According to the statistical results on the original measurements of apparent resistivities of the site before injection (made in May 2021) and the successive interpretation (September, October, November, and December 2021) of the results on block A (considered to be far less impacted by the pollution) this range (60-70 ohm.m) is interpreted as representing the surrounding soil that is not, or only slightly, polluted. Therefore, any change in resistivities towards this range can be interpreted as an effect of the remediation system.

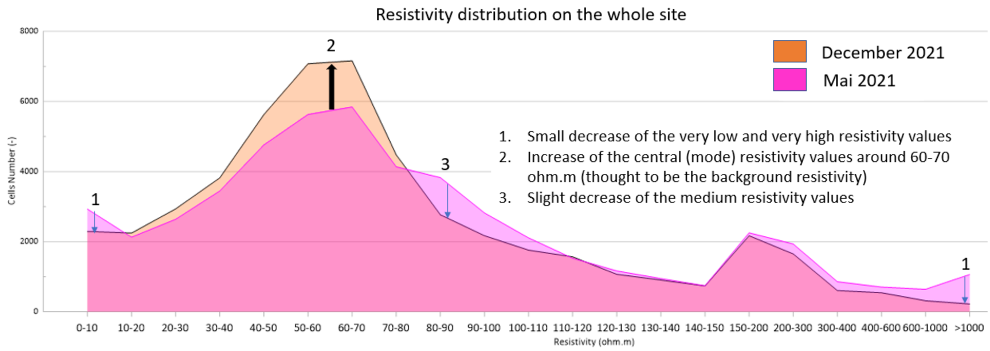

Fig. 4. Resistivity distribution histograms of the model obtained after 3D tomographic inversion on the whole site

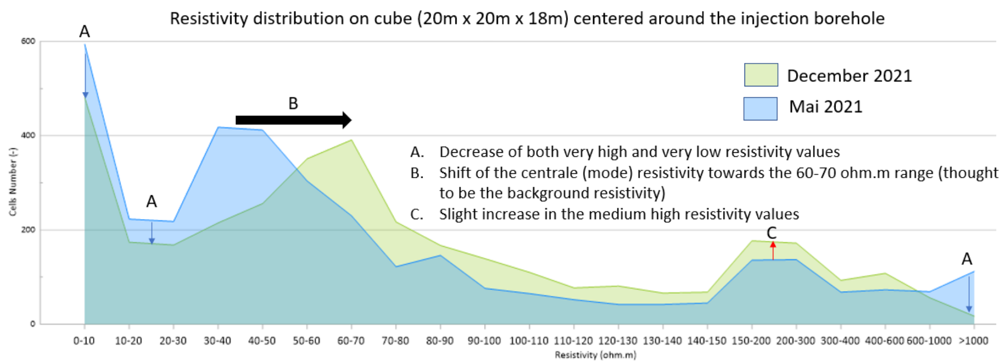

Fig. 5. Histograms of resistivity distribution of the model obtained after 3D tomographic inversion on a zone closer to the injection hole (20m x 20m x 18m)

3.1 Study of planimetric XY resistivity slices

The effectiveness of the system is clarified by studying the resistivity XY (planimetric) maps taken just above the intermediate water table of the site, in the capillary fringe, which appears to be one of the areas of the site the most impacted by the remediation system (Fig.6.).

Difference maps, made by subtracting the XY resistivity map of successive monthly surveys, confirm the preferential impact of the remediation system mainly in in the capillary fringe, closer to the center of the site around the oxygen injection borehole, with a more prominent effect along the north/northeast/east directions (Fig. 7.).

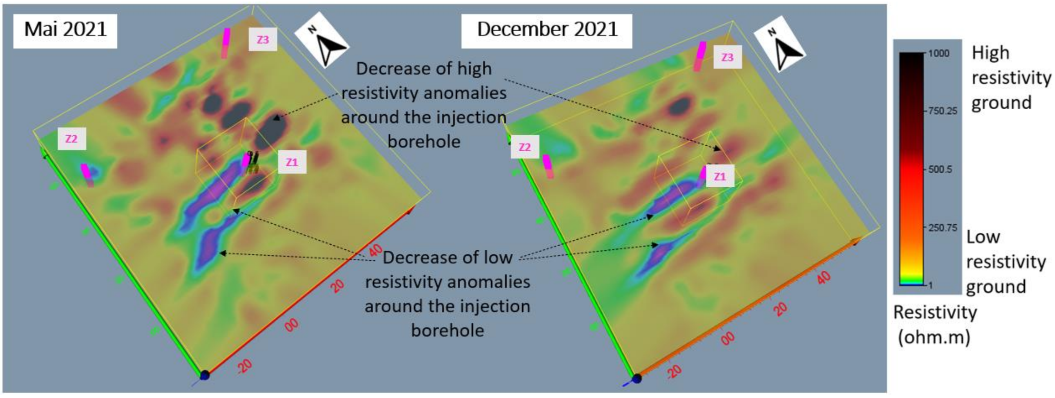

Fig. 6. XY resistivity map - Comparison between May 2021 (before injection) and December 2021 (after 144 days of injection) - Maps extracted at a depth just above the intermediate water table in the capillary fringe - Z1 is the oxygen injection borehole

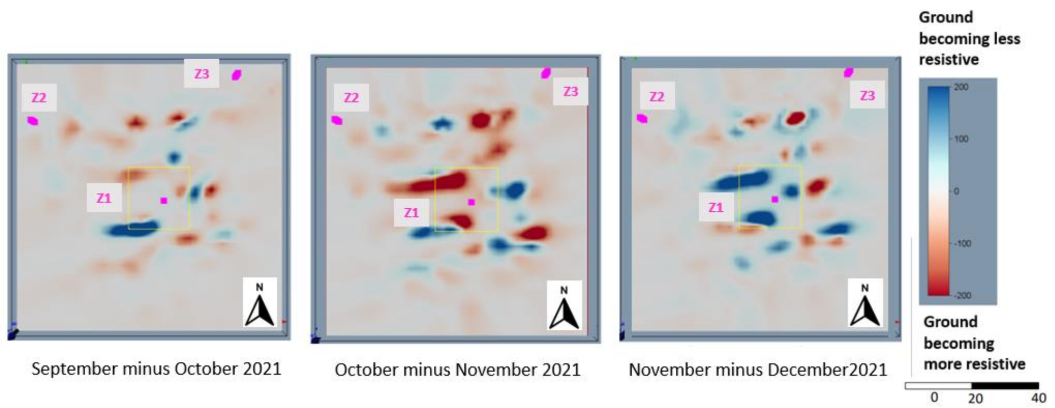

Fig. 7. XY map of resistivity differences calculated over the monitoring phases (calculation = t-(t+1month)) - Maps extracted at a depth just above the intermediate water table in the capillary fringe - Z1 is the oxygen injection borehole

4 Discussion

Last figure (Fig.7.) shows that the resistivity variations are not linear and can even oscillate (increase then decrease in resistivity values) with time. This illustrates the complex nature of the biological process monitored by the geophysical imaging system in place on this pilot site.

Sampling with the piezometers confirms that there are local redistributions of pollutants that are rapid, variable with time and with depth. These redistributions influence the resistivities (measured by the geophysical survey) by several orders of magnitude (from a few ohm.m to a few hundred ohm.m) as can be observed when a correlation is established (Fig.8.)

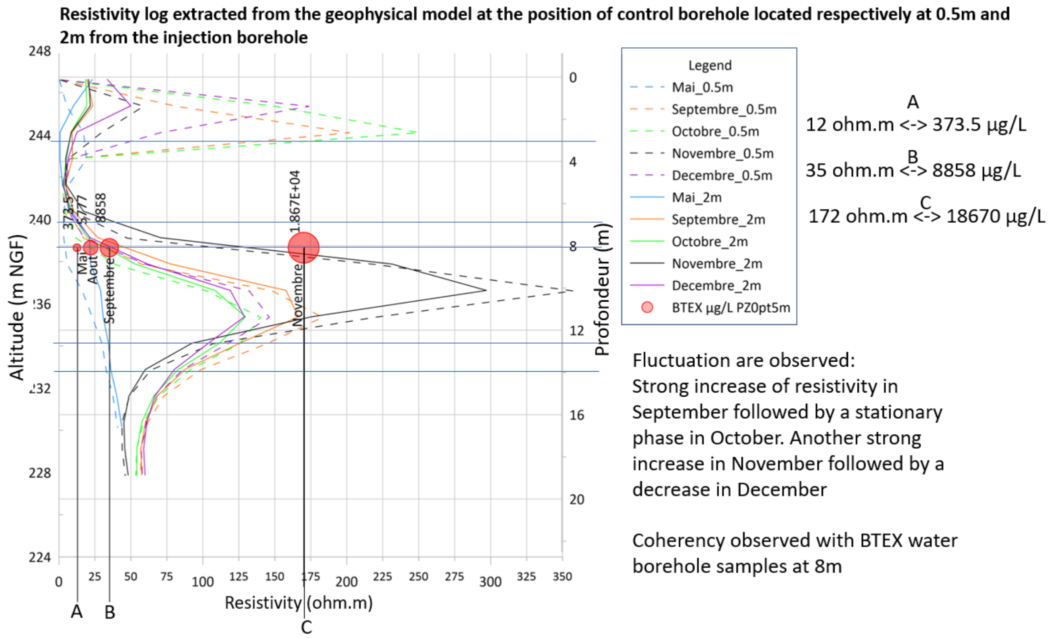

Fig. 8. Example of comparison between point measurements of pollution in soil water in the piezometer at 0.5m and 2m from the oxygen injection borehole (samples taken at 8m depth) and the evolution of resistivity extracted from the geophysical monitoring

Indeed, other interactions, not related to the bacterial activity, remain possible and can induce noise in our measurements. Such effects include (1) natural variations of water content of the soils (pluviometry and seasonality), (2) variations of temperatures (seasonality), and finally (3) the possible self-potential currents (natural electrical potential) that we suspect by the observation of corrosion affecting some of our stainless-steel electrodes (Fig.9. right).

Interactions (1) and (2) mentioned above are weighted by the study of a control profile located in a stable zone in the south of the site (Fig.1.) that have been measured since November 2021 and which shows very little variation (Fig.9. left). Corrosion effects (3) are more difficult to weight because they are very heterogenous by nature and affect only very specific parts of the site. It should also be noted that this effect can also be a consequence of the remediation system itself: aerobic bacterial degradation of a chlorinated pollutant liberating chloride ions in solution, causing the observed corrosion by electrokinetic processes.

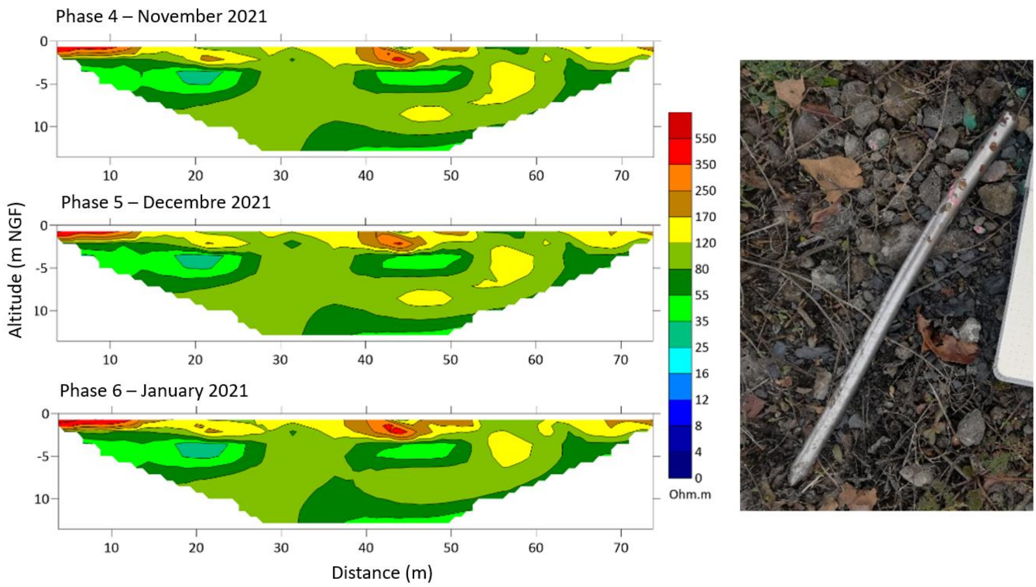

Fig. 9. Control profile used to weight the natural variations of soil resistivities (left) and example of a corroded electrode (right)

5 Conclusion

This study shows the possible contributions of electrical tomography to the study of polluted soils. These polluted zones can be well-characterized by electrical geophysics imaging with either anomalously high or anomalously low resistivities within a more intermediate resistivity surrounding soil. The study shows that, on this specific pilot site, hydrocarbon and/or chlorinated solvent pollutants are mainly 3D in shape, forming plumes or lenses. These forms are better resolved by the use of 3D geophysical methods. The study also confirms that associated borehole sampling is a necessary tool for a better understanding of the intricate process of bacterial remediation.

Finally, this measurement method allows for relatively rapid data collection, which in turn allows for effective monitoring of the depollution process. In this sense, this project is a new example of the usefulness of geophysical 3D electrical resistivity tomography as a modern tool, complementary to the monitoring methods currently used, for informed decision-making about soil (de)pollution issues.

6 References

1. B. Biosca, L. Arevalo-Lomas, F. Barrio-Parra, J. Diaz-Curiel, *Application and limitations if time domain induced polarization tomography for the detection of hydrocarbon pollutants in soils with electro-metallic components: a case study*, in Environmental Monitoring Assessment 192 (2), February 2020

2. B. Biosca, L. Arevalo-Lomas, M. Izquierdo-Diaz, J. Diaz-Curiel, *Detection of chlorinated contaminants coming from the manufacture of lindane in a surface*

detritic aquifer by electrical resistivity tomography, in Journal of Applied Geophysics (191), August 2021

3. E. Cardarelli, G. Di Filippo, *Electrical resistivity, and induced polarization tomography in identifying the plume of chlorinated hydrocarbons in sedimentary formation: A case study in Rho (Milan-Italy)*, in Waste Management & Research (27), Mai 2009

4. Y. Jiang, Y. Li, G. Yang, X. Zhou, *The application of high-density resistivity method in organic pollution survey of groundwater and soil*, in Procedia Earth and Planetary Science, December 2013

5. M. Naldi, A. Godio, *Two-dimensional electric imaging for detection of hydrocarbon contaminants*, in Near Surface Geophysics (1:131-137), August 2003