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ASSESSING THE ENVIRONMENTAL IMPACT OF OIL SPILLS IN BEACH ENVIRONMENTS: A CASE STUDY USING THE CAPACITIVE RESISTIVITY METHOD

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ABSTRACT. The accident involving oil spill that occurred on the Brazilian coast in 2019 reached 2,880 km in extension, and more than 200 tons of oily material was removed from coastal environments in the northeast of the country in about five months. In the impact on beach environment there may still be non-visible residues and its by-products in subsurface, so that geophysical prospecting can be the suitable to evaluate the presence of remaining material. The evolution of environmental studies has required new research technologies. Geophysical methods have shown to be efficient in environmental studies, with the use of relatively new methods in Brazil that provide results with excellent coverage in the area and quickly. Among these methods stands out the Capacitive Resistivity Method. Environmental research work with this method has been reported with good results, but it is necessary to take into account the operational physical bases of the method so that the data are reliable. This work presents the results of tests carried out in a beach environment that was affected by oil. This environment is characterized by a medium of high conductivity, where data acquisition with equipment configured with smaller dipolar cables results in extremely noisy data. On the other hand, the configuration with larger dipolar cables allowed the transmission of higher electrical current to the ground resulting in the acquisition of good quality data. The results showed that there are no more indications of oil residues on the beach studied.

Keywords: oil spill; environmental impact: beach environment; Capacitive Resistivity method; pollutant removal.

INTRODUCTION

The 2019 environmental disaster that occurred on the Brazilian coast, is an example of recurrent events involving oil spillage with great impact on the environmental and the socioeconomic sector (Oliveira et al., 2020). The 2019 oil spill disaster extension reached 2,880 km and more than 200 tons of oily material was removed from coastal environments in about five months. According to the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA, 2019) this episode is considered the largest extension of contaminated coastline in the world recorded over the last 30 years.

Although the large amount of oil is no longer visible in the environment, the sense and weathered oil persisted in the environment (Disner and Torres, 2020). Because the oil density is similar to that of seawater, the oil can sink and mix with sand and other materials, solubilizing some of its compounds, which, even at low concentrations, can be toxic to aquatic organisms. In the beach environment, non-visible oil waste and its by-products may still be present and detectable with geophysical prospecting methods, which may be used as the sensor to evaluate the presence of remaining material in the environment.

The development of environmental investigations demands new research technologies. Environmental diagnostic studies have increasingly required research methods that provide large amount of data, surveying large areas at low costs of price and time. The investigation sites often demand a continuous spatial survey to locate the contamination source, nonviable to direct investigation methods. This ability can be achieved using geophysical methods, capable of scanning the contaminated site and providing high density datasets.

The presence of petroleum derivatives, which are typically electrically resistive, produces a typical geophysical signature in spills, characterized by high resistivity features at the locations affected by the contaminant. Heenan et al. (2015) demonstrated the feasibility of long-term resistivity monitoring as a noninvasive technology for monitoring oil spills in coastal environments. The authors monitored the electrical resistivity of a beach impacted by oil released from the Deepwater Horizon platform accident in the Gulf of Mexico in 2010. Kimak et al. (2019) used the Induced Polarization method on a laboratory scale to monitor the natural degradation of sediments collected from one of the beached impacted by the same accident.

This work is based on the hypothesis that the oil spill that reached the beaches of northeastern Brazil in 2019 will produce typical geophysical signatures. Specifically, resistive anomalies must have been initially produced by contrasting the natural environment (sand and saline water) and the impacted medium (sand, saline water and oil).

The Capacitive Resistivity Method has been increasingly used in environmental investigations, because it does not require electrical contact via grounded electrodes, thus becoming a very practical moving system through capacitive coupling. Because it is a relatively new method, in some field situations the acquisition parameters need to be evaluated and adapted to obtain the desired answers. A situation that requires attention is in research in environments with high conductivities, where the relationships between the size of the conductor cables and non-conductive rope will define the possibilities of use as well as the quality of the data. This type of situation is found in a coastal environment, and in this work the results obtained in beach survey for different system configurations are presented and analyzed.

This work presents the results of Capacitive Resistivity tests to evaluate the presence of remaining material from the oil spill that occurred on the coast of northeastern Brazil in the second half of 2019.

Study area

This work presents the geophysical investigation conducted on beaches located on the southern coast of Pernambuco State in Brazil. Bomtempo Filho et al. (2022) evaluated the temporal evaluation of the remaining contaminants on some beaches by sediment analyses (grain size, calcium carbonate, and total organic matter content). Results showed intense weathering of the remaining residues due to the high energy environment. No oil residues were found in shallow subsurface sediments, and only oil balls reworked by seasonal erosion. These punctual analyses were obtained from sediment samples collected at locations where the oil presence has been reported. In this context, geophysical methods were suggested to extend the investigation as research strategy capable of fast and continuously scanning the beach subsurface environment for the occurrence of oil residue.

Shortly after the oil spill, due to the impacts on the Brazilian beaches, IBAMA technicians and the local communities gathered to work on the removal of oil from water, sand and rocks, in addition to promptly serving the affected fauna (IBAMA, 2019). This community effort was highly efficient in removing oil from the beaches and nowadays the residues are not visible.

The first tests were carried out at Pontal do Cupe Beach, in the Porto de Galinhas region, Ipojuca-PE (Figure 1). Sparse oil stains arrived on this beach in October 2019, which were quickly collected. Some oil marks can still be visualized on residence walls.

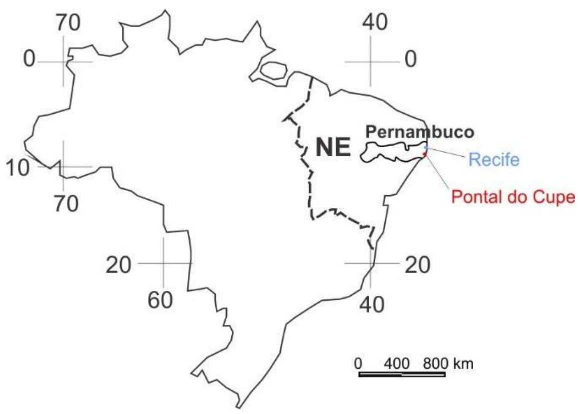


Figure 1: Location of Pontal do Cupe Beach (Ipojuca-PE), where the geophysical survey was conducted.

The geophysical survey was chosen for its data acquisition capability to scan the terrain as well as the surveying speed, as the data need to be acquired quickly during low tide period.

MATERIALS AND METHODS

The geophysical Electrical Resistivity (ER) method is based on the transmission of a direct current (DC) to the surface of the ground through two electrodes and the resulting electrical potential being measured through two additional electrodes. Even though the DC resistivity method is traditionally and widely used in environmental studies, the imaging resolution is limited by the number and position of the electrodes placed on the survey, which also adds time costs to data acquisition. The Capacitive Resistivity (CR) method attends on this demand for high resolution technologies and high acquisition speed. The CR has been developed to be interpreted in the same way as the traditional ER, but with no need to make galvanic contact between the electrode and the terrain. Additionally, the CR method allows continuous data acquisition, enabling surveying of large areas with rapid field operation (Kuras et al., 2002, 2006; Loke et al. 2013; Pan et al., 2014).

In the CR method, the coupling between the terrain and the instrument is capacitive, guaranteed by the components inside the instruments, such as metallic plates to establish a capacitance with the ground and by the operation settings, such as the alternating current frequency. Apart from the electrode coupling with the ground, the operation of a CR survey is quite similar to that od DC resistivity, requiring a pair of transmitter and receiver "electrodes". The coupling, in this case, is by electrical capacitance, as diagramming in Figure 2.

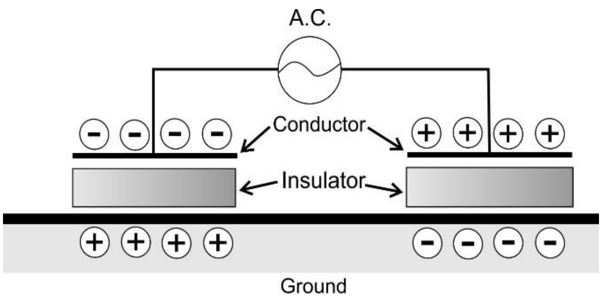


Figure 2: Conceptual model of capacitive coupling of the CR method (modified by Yamashita et al., 2004). Its fundamental difference with respect to the DC resistivity system is that there is no galvanic coupling of electrodes with the soil. The coupling, in this case, is granted by electrical capacitance.

For the CR method, the dipole-dipole array has the most favorable geometry for data acquisition. The coupling mechanism between the sensor and the surface is predominantly capacitive and the inductive effect is negligible. Under quasi-static conditions, the voltage measurements are essentially equivalent to DC resistivity.

In this work we used the OhmMapper system, Geometrics Inc. The acquisition systems for CR are formed (in a basic configuration) by a transmitter, a set of receivers and the data recorder. The receivers are connected to each other via dipolar cables, and the transmitter is connected to the receiving system by means of a non-conductive rope. The whole set is easily dragged onto the surface of the ground by an operator (Figure 3).

One important aspect of the data acquisition is signal attenuation. Considering that the arrangement is analogous to that of conventional resistivity, the separation between the transmitter and the receiver will influence signal attenuation. According to Kuras (2002) the electrical resistivity of the terrain also influences the attenuation of the signal and the depth of investigation of the Capacitive Resistivity method, with a difference in the penetration of the electric current emitted in more resistive or more conductive terrains. In more resistive places the voltage in the receivers tends to be higher, favoring measurements and allowing a greater depth of penetration. In the case of very high conductivity locations, the voltage will be low, making it difficult to read for longer transmitter-receiver distances.

Another relevant condition for the applicability of the method in question refers to the fact that the separation between the transmitter set and the receiver must be influenced by the effects of the parameter called skin depth (d), which is related to the depth of penetration and is associated with the attenuation of the electric field. The skin depth relates to the depth at which the signal strength is attenuated by 37% of its original value and according to Timofeev et al. (1994) is calculated by:

$$d = 15.9\sqrt{\frac{\rho}{f}} \qquad (1)$$

where ρ is the electrical resistivity of the medium in ohm.m and f is the frequency of the signal emitted in kHz.

Equation (1) shows that the lower the resistivity of the site, the lower the signal penetration. This implies that the method will work only for small transmitter-receiver openings. OhmMapper works

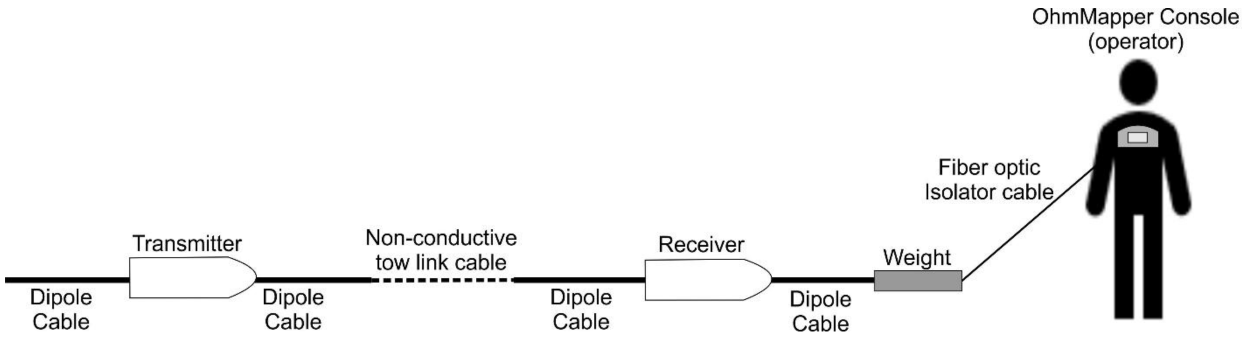


Figure 3: Schematic setup of OhmMapper System. The system can be configured to record data in a discrete or continuous setting, as the operator moves along the survey.

with a fixed frequency of 16.5 kHz, thus it is possible to estimate *the skin depth* for a certain resistivity value, to be the largest transmitter-receiver spacing allowed for the method to provide reliable data.

On very conductive terrains, such as beaches, this condition may limit or even derail the functioning of the method. As capacitance varies directly with the length of the cable, a longer cable can be used to have greater capacitance and thus transmit more current to the ground (Halihan et al., 2009).

RESULTS AND DISCUSSIONS

Three parallel lines 150 meters long were made, as shown in Figure 4. All profiles were acquired from south to north. As the beach environment is extremely conductive, the acquisition parameters defined at first presented limitations. These parameters were dipolar cables of 5 meters and distances between transmitter and receiver of 1.25, 2.5 and 5.0 meters, thought to be sufficient to investigate the sediments up to a maximum depth of 2.8 meters. Figure 5 shows the equipment with 5 meters dipolar cables working on the beach. This investigation depth was believed to all the detection of the oil residue within the thickness of sediment reworked by the tides, estimated around 1 meter deep.

During the acquisition, it was possible to establish transmitter-receiver coupling. However, the readings indicated the need to increase signal gain. Figure 6 shows the raw data (apparent resistivity) as a quality filter for the data from line 1, using the 5 m dipole cable. This analysis was conducted using the raw data visualization tool, with the inversion software RES2Dinv (Geotomo Software, 2007) and it reveals extremely noisy data. Nevertheless, the data inversion results (Figure 7) show significant variation of resistivity within the section, spanning from almost zero to as high as 300 ohm.m. The features of high resistivity (above 300 ohm.m) could be erroneously interpreted as possible occurrences of oil residues, showing the importance of data analysis before the inversion process.

In a second attempt, line 1 was surveyed using cables of 10 meters and transmitter-receiver distances of 1.25, 2.5 and 5.0 meters. The new length enabled the dipolar cables to transmit more electrical current into the ground, thus allowing adequate capacitive coupling. Figure 8 shows less noise within the signals recorded under this new configuration.

The inversion results (Figure 9) show a resistivity model that is consistent with the geological setting of the site, observed as a highly conductive medium, expected for beach environment. In the most superficial depths, there is a layer of resistivity above 10 ohm.m, which characterizes the wet but not saturated sandy sediment. Below these sediments, it is possible to observe the transition to a much more conductive medium, below 2 ohm.m. This zone characterizes the sandy sediment saturated by salt water. Seawater, which has resistivity of 0.2 ohm.m, causes resistivity to decrease in this way.

As can be seen in Figure 9, resistivity in general is very low at the site, not being indicative of the presence of oil. Several authors state that oil spills such as those that reached northeastern Brazil have high resistivity. For instance, crude oil, not degraded by bacteria, present resistivity values typically above 500 ohm.m (Bauman, 2005). Win et al. (2011) registered values between 500 and 2500 ohm.m that were related to unsaturated sandy layers with the presence of oil. Manual probing holes provided values always above 200 ohm.m for the oil layer (range from 200 to 1000 ohm.m). Andrade (2019) found resistivity values between 400 and 1500 ohm.m for oil layers, with an average of 800 ohm.m.

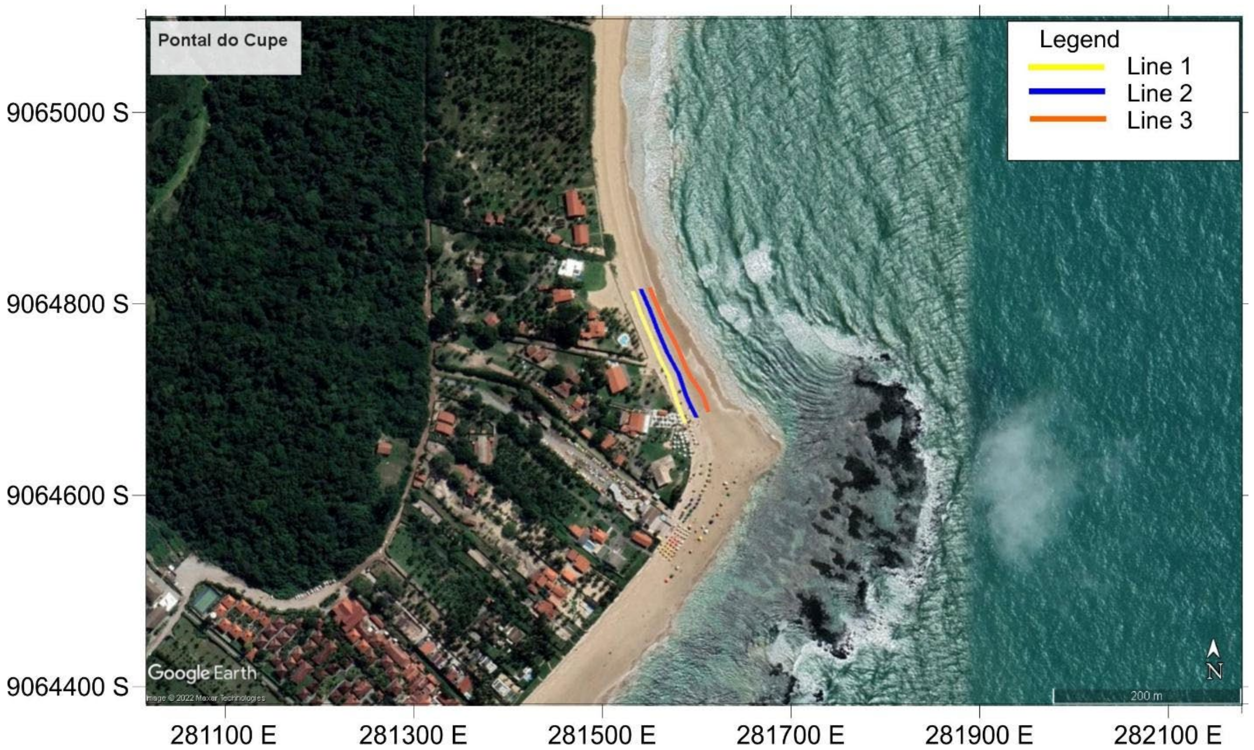


Figure 4: Survey lines at Pontal do Cupe Beach.

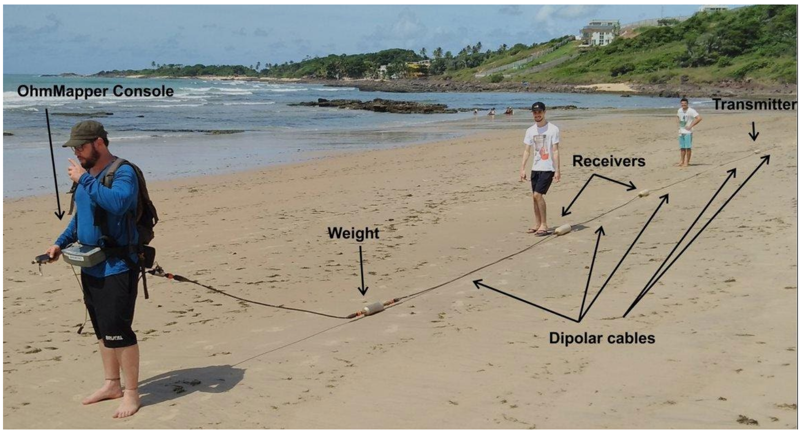


Figure 5: OhmMapper System working with the 5 meters dipolar cable.

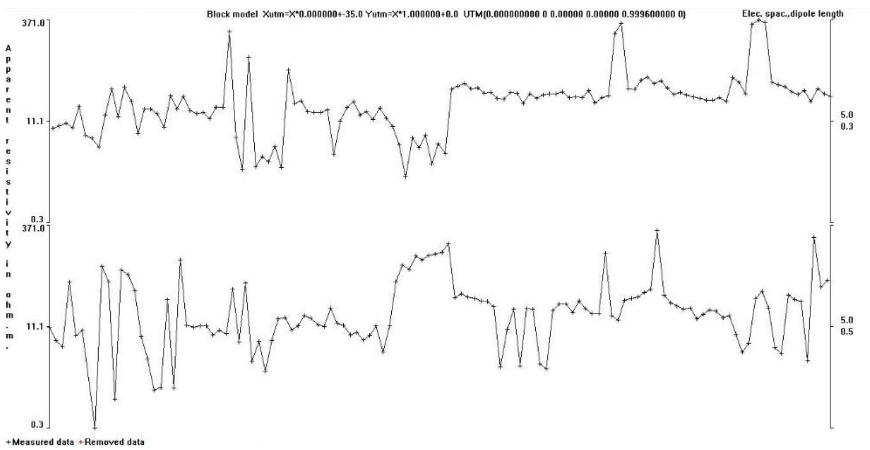


Figure 6: Raw data of apparent resistivity of Line 1 with 5-meter cables. RES2Dinv (Geotomo Software, 2007) raw data visualization tool, in which it is possible to visualize noisy data and delete it.

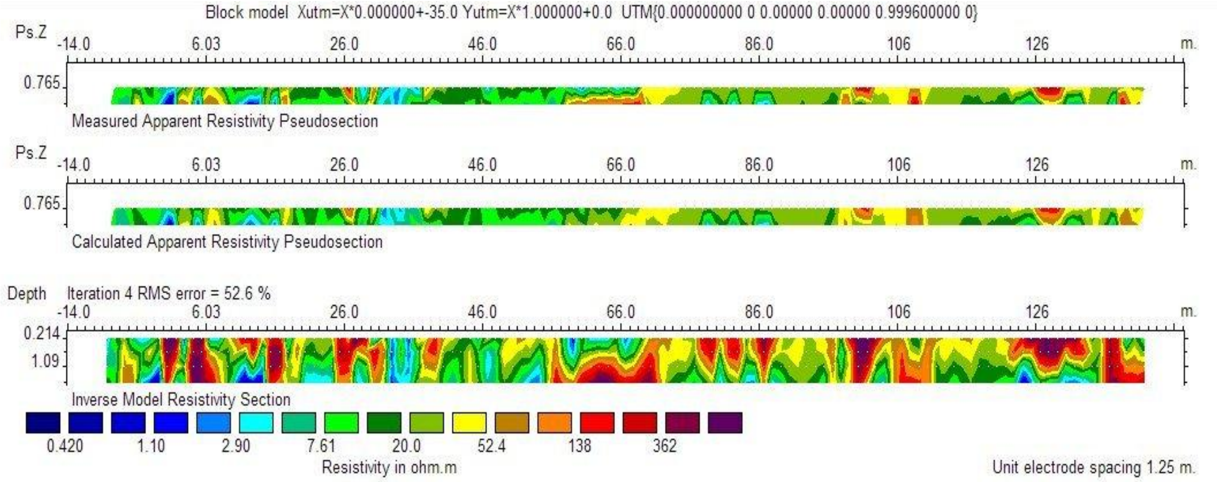


Figure 7: Inversion result of Line 1 with 5-meter cables: resistivity model (bottom), apparent resistivity values calculated from the resistivity model (middle) and measured apparent resistivity values (top).

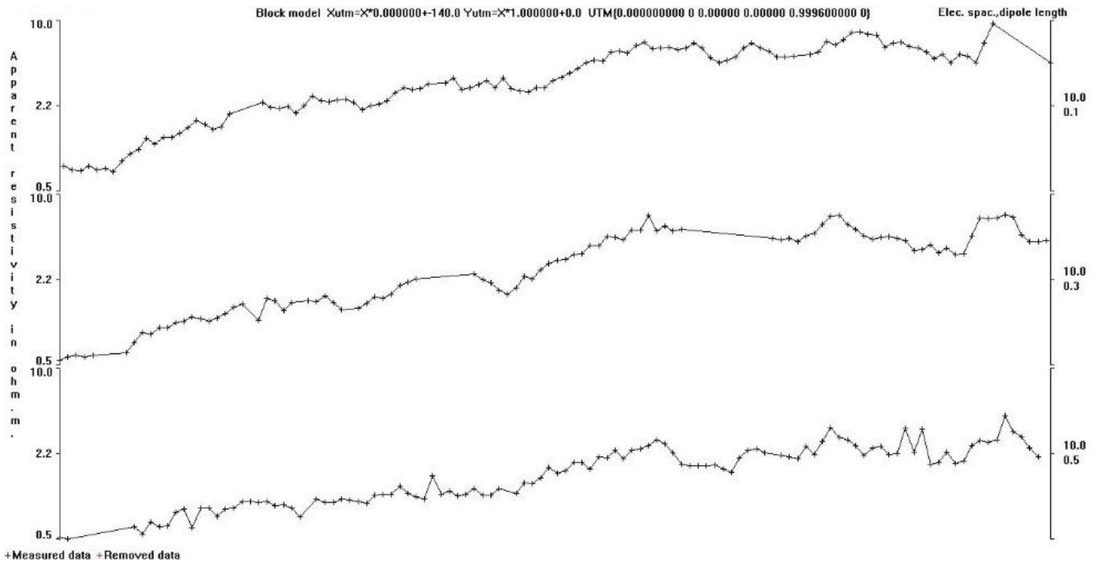


Figure 8: Raw data of apparent resistivity of Line 1 with cables of 10 meters.

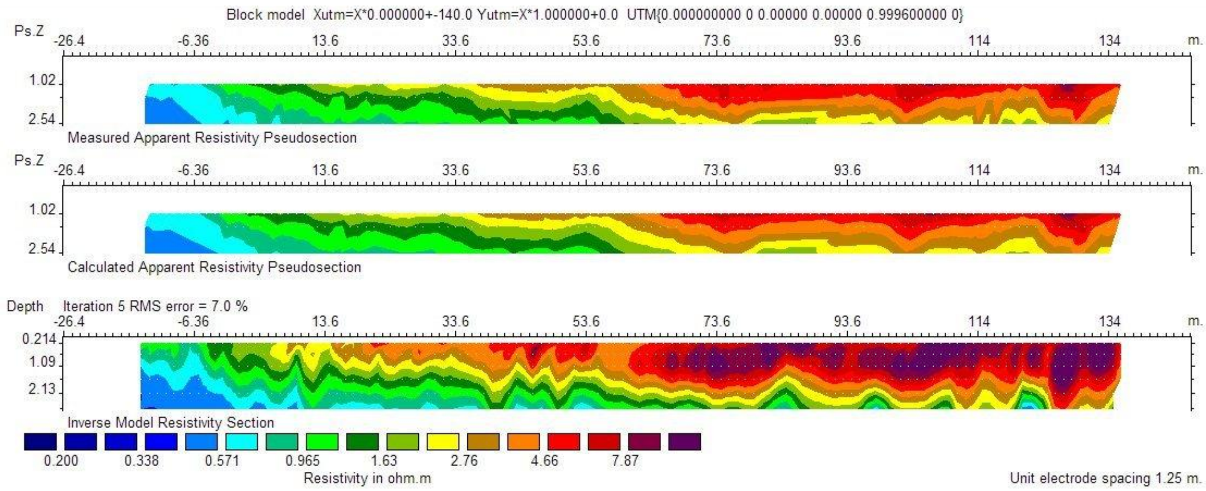


Figure 9: Inversion result of Line 1 with cables of 10 meters: resistivity model (bottom), apparent resistivity values calculated from the resistivity model (middle) and measured apparent resistivity values (top).

To understand how the response would be in terms of geoelectrical imaging of the presence of oil in a beach environment, numerical simulations were conducted to obtain 2D resistivity models. ResIPy software (Blanchy et al., 2020) was used in this process. The model was elaborated by observing the geoelectric stratification of the environment, with a value of 50 ohm.m for the unsaturated sandy sediment and 2 ohm.m for the sediment saturated with salt water. These values were based on laboratory tests with sediments collected in the area. A 10 cm thick oil layer and 2 meters wide was inserted just above the salt water, where it would be the thickness of sand reworked by the tides, which according to Bomtempo et al. (2022), takes place up to the thickness of 1 meter. The estimated resistivity value for oil was 500 ohm.m, based on the range of values found in the literature (Bauman, 2005; Win et al., 2011).

The model is presented in Figure 10, where the 3 geoelectric units are identified. The layer of unsaturated sand to the depth of 1.2 meters, followed by the saturated layer with salt water. The oil is represented by the blue body positioned 40 centimeters above the salt water. The synthetic model was used to calculate a set of synthetic data of apparent resistivity for a specific array and electrode spacing. The numerical simulation considered the dipole-dipole array, with 1 m of electrode spacing and 8 investigation levels. The calculated apparent resistivity data were interpreted using least square inversion routine to obtain the correspondent geoelectrical section. The inversion results were presented in Figure 11. A zone of high resistivity (> 80 ohm.m) that characterizes the oil can be observed. The surface sand layer has a resistivity ranging between 40 and 70 ohm.m and the area saturated by salt water is conductive (< 30 ohm.m). That way this would be an image of a place with an oil stain buried by the tide.

For comparison, the oil stain was excluded from the model and the synthetic data obtained were submitted to the same inversion routine. The geoelectric model obtained is presented in Figure 12, where it is possible to observe the unsaturated sand layer with resistivities between 40 and 60 ohm.m and the sand saturated with salt water, with resistivities lower than 30 ohm.m. With these results, it is possible to evaluate the results obtained in the field regarding the presence or not of oil.

The results of the profiles performed on the beach are presented in Figure 13. The three sections are shown with the same color scale for easy comparison. Resistivity ranged from 0.2 to 18 ohm.m. The unsaturated sand layer can be easily visualized, with resistivity above 5 ohm.m. The saturated sand layer has high conductivity, below 2 ohm.m. No zones of resistivity values are observed that indicate the presence of oil.

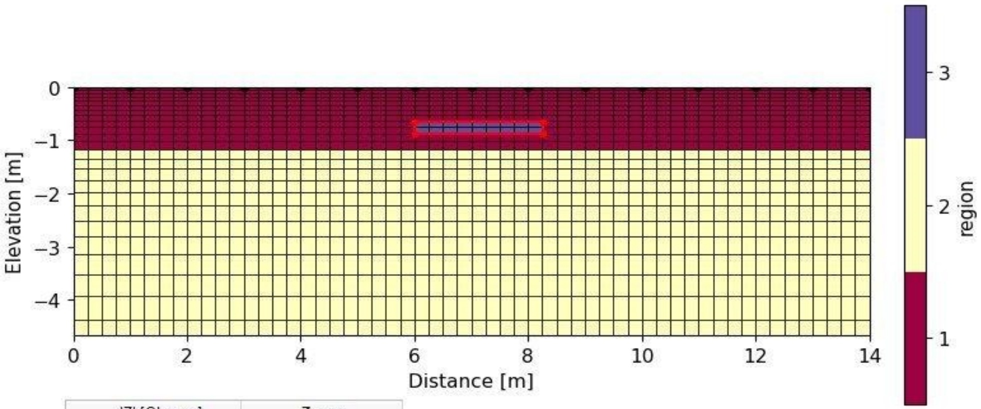
The results obtained from the inversions resulting from the different acquisition parameters show that the acquisition with 5-meter dipolar cables presented a very poor signal-to-noise ratio compared to the acquisition with dipolar cables of 10 meter. The RMS error obtained from inversion with 5-meter dipolar cables was greater than 50%. In the case of acquisitions with dipolar cables of 10 meters, the errors were smaller, of a maximum of 7%. This is another factor that shows that only the second form of acquisition resulted in reliable data.

CONCLUSIONS

The RC Method showed to be very suitable for environmental tests where it is necessary to scan the ground to search for sources of contamination. As it is a method with high area coverage and rapid data acquisition, it is especially suitable for coastal environments where sea level variations caused by tides can limit the use of conventional methods.

The physical characteristics of the method's operation need to be considered to provide reliable results. This work shows that in very conductive environments the effects of skin depth limit the use of the arrangement with dipolar cables of 5 meters, often resulting in extremely noisy data. On the other hand, the use of dipolar cables larger, 10 meters, allows the increase of the current transmitted to the ground and allows the equipment to operate with good results, even in this condition of terrain.

To evaluate the geoelectric signature, synthetic models and respective geoelectric models obtained by inversion were used. These models indicate that an oil spot would be identifiable in profiles with high resistivity. In the tests carried out on the beaches it was not possible to visualize any feature of high resistivity that indicates the presence of oil



	|Z| [Ohm.m]	Zones
1	2	1
2	50	2
3	500	3

Figure 10: Conceptual model of layers of sand, sand saturated with salt water and oil spot. The high resistivity zones simulate the oil presence (zone 3), within the reworked beach sediments (zone 2) above the seawater saturated sands (zone 1).

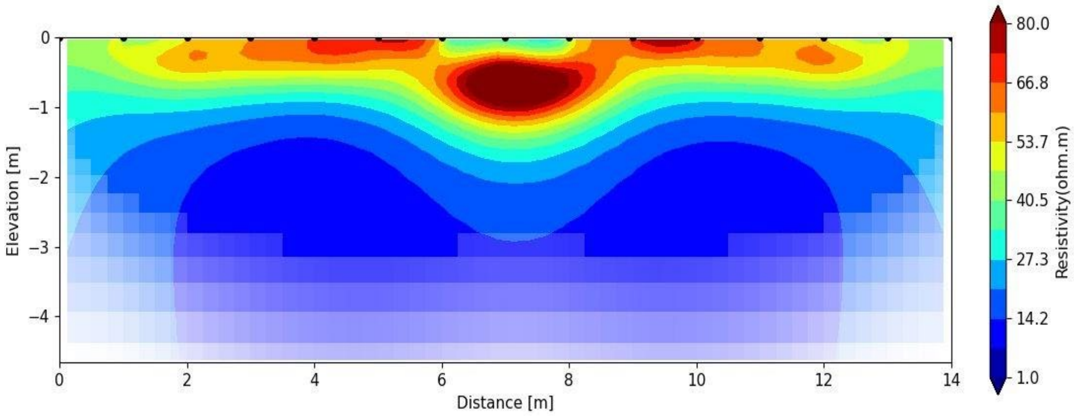


Figure 11: Geoelectrical model obtained by inversion of synthetic data generated from the model of Figure 9. The high resistivity feature suggests the oil presence (> 80 ohm.m) would be detectable by the simulated survey.

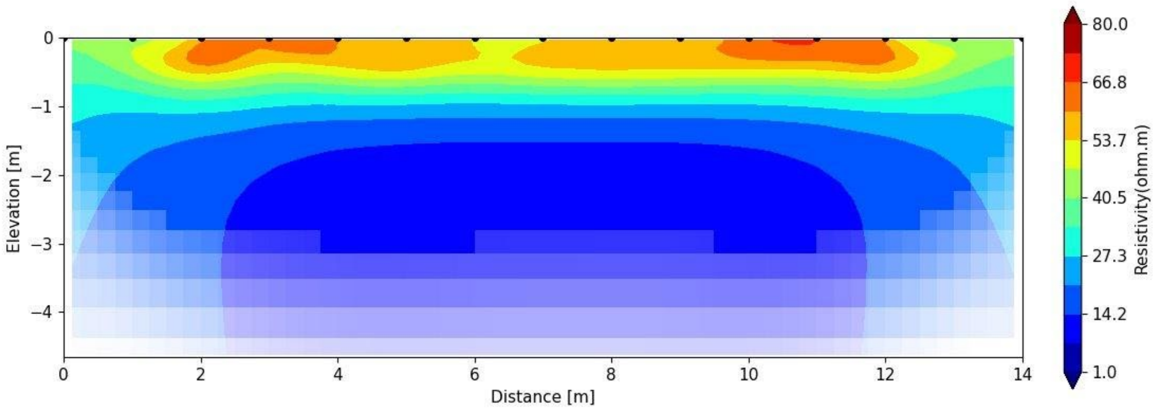


Figure 12: Geoelectrical model obtained from model without the oil spot.

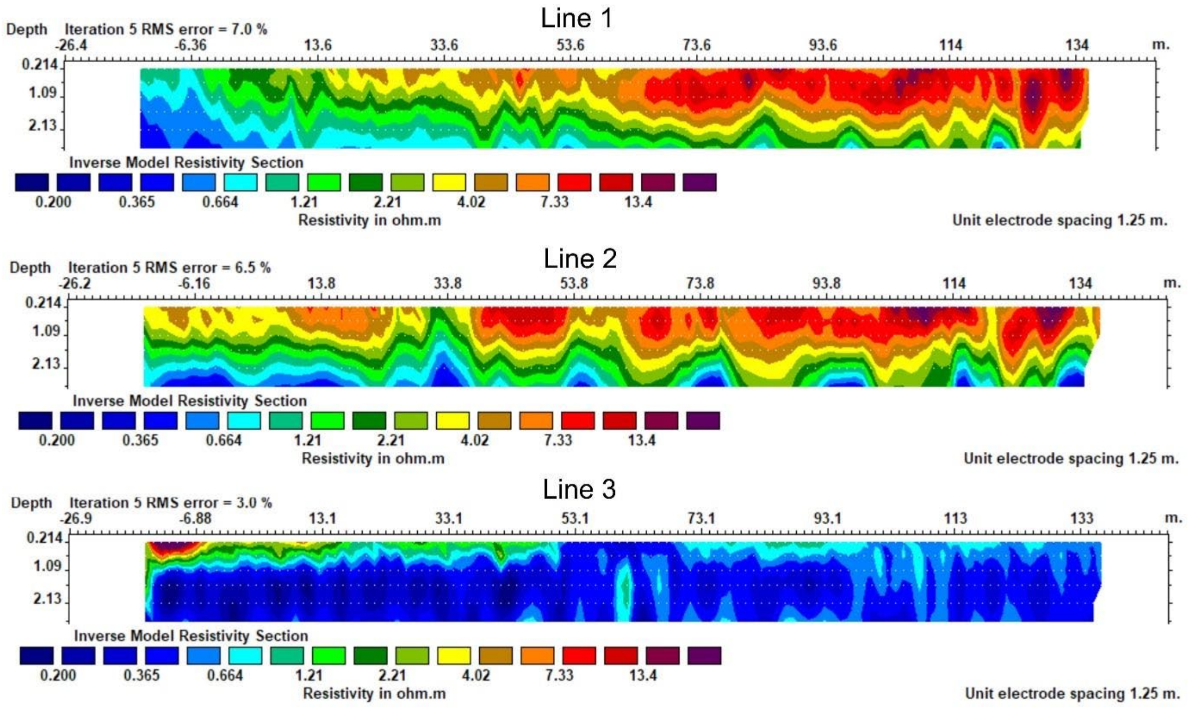


Figure 13: Inverse resistivity sections of Cupe Beach.

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Elis, V.R., A.T. Ustra, M.C. Stangar, H.L. Giacheti: these researchers were responsible for collecting, processing and interpretation of geophysical data; **Barros, M.S.F., C.A. Mendonça:** these researchers were responsible for 2D resistivity modeling and integration with geophysical interpretation of field data; **Santos, P.J.P., B.M. Bezerra, A.M. Barbosa:** these researchers have been working on assessing the effects of the accident on the coastal environment. In this study case, they worked in the acquisition of geophysical data and integrating the history of contamination in the area to the geophysical study.

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