# 3D resistivity model of a lubricant oil waste disposal area in the city of Ribeirão Preto, São Paulo, Brazil.

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## Abstract

The present work presents results of geophysical investigations in a lubricant oil waste area located in the municipality of Ribeirão Preto, São Paulo State, Brazil. In the study area the waste was disposed of in four trenches with a total volume of about 25.000 $m^3$, in an area of sandstone outcroppings of the Botucatu Formation and in basalts of the Serra Geral Formation. The trenches were totally filled with waste over approximately 25 years and no protection liners were used in the bottom or laterals of the trenches. The goal of the study was the acquisition and modeling of 3D data with the electroresistivity method for the environmental characterization of the study area. The acquisition of 3D data, from a series of 2D electrical surveys, was effective in mapping variations of resistivity in three dimensions, showing in the subsurface the behavior of contaminants. The conductive anomalies in the saturated zone and unsaturated zone were related to contamination generated by the biodegradation process. A direct analysis of the soil and groundwater samples confirmed the contamination. In the soil analysis, low concentrations of several polycyclic aromatic hydrocarbons were found, mainly naphthalene and phenanthrene. In the water samples, there was confirmed contamination of the groundwater by lead (Pb). The biodegradation process was confirmed by the presence of microorganisms (bacteria), as evidenced in a biological analysis of soil samples collected at a specific point, where geophysical signatures suggested contamination.

## Introduction

Geophysics has been shown to be effective in identifying areas contaminated by oil products, contributing to the greater efficiency of soundings programs and the installation of monitoring wells. However, this experience, has been limited to the use of conventional procedures in both field studies (electrical sounding and electrical profiling) and in the interpretation of data (1D and 2D models). The waste disposal areas, due to their geometry and the behavior of their contaminants, characterize a three-dimensional environment. The resistivity method of 3D data acquisition has only been recently seen in the literature, while 3D techniques are still in their infancy (Dahlin & Loke, 1997). We can cite the works of Dahlin et al. (2002) and Gandolfo & Gallas (2005). Inside of this context that this work consists in the study of a geophysical methodology of acquisition and modeling of 3D data of electroresistivity applied in the environmental characterization of a lubricant oil waste disposal area in the municipal of Ribeirão Preto-SP.

## Site Description

The study site received waste from the mid-1970's to 1995. The waste was disposed in 4 trenches with approximate dimensions of 41 to 49 m length, 24 to 36 m width and a mean depth of 6m. The pits were not impermeable and were covered with soil after years of deposits.

The area is located close to km 334 of the "Rodovia Alexander Balbo" (SP 328), city of Ribeirão Preto, state of São Paulo (Figure 1).

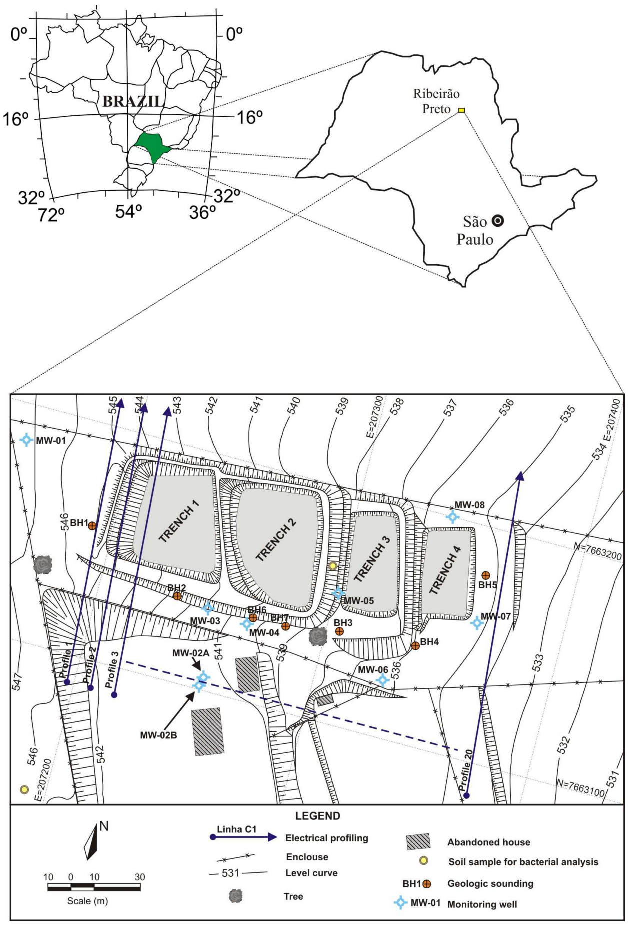


**Figure 1** – Study area and geophysical surveys locations.

### 3D Resistivity Survey

The geophysical surveys in the study area were conducted by analysis of the residues and from these, in adjacent areas, a study of the relations between the residues, the natural environment, and the generated contamination plume. For the 3D dipole-dipole survey the area was picketed of 10 in 10 meters, each picket serving as point for an electrode. In many cases, a 3D data set for the dipole-dipole array was constructed from a number of parallel 2D survey lines (Figure 2), which diminishes the acquisition time and becomes a viable methodology. Therefore, the data acquisition system used this methodology in the study area.

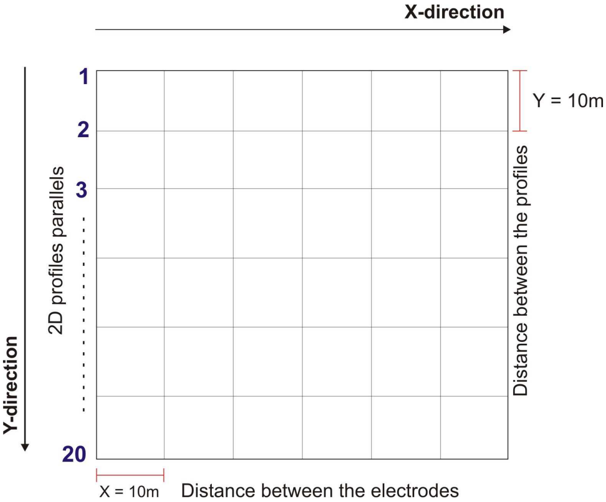


Figure 2- Mesh of acquisition 3D dipole-dipole array.

A great problem of the 3D acquisition method is the time necessary to make the measurements. In accordance with Loke & Barker (1996), in a 3D resistivity survey the electrodes are generally arranged in a square mesh, with the same spacing between electrodes in X and Y directions. The pole-pole electrode configuration is commonly used for 3D surveys. In the complete data set survey, current electrode will be used for measures in each potential electrode. This requires an immense number of measures and, therefore, a great time of acquisition. Another possibility is called the cross-diagonal survey, in which the potential measurements are only made at the electrodes along the x-direction, the y-direction and the 45 degrees diagonal lines passing through the current electrode. This procedure diminishes the time of acquisition without causing significant loss of resolution, according to author cited above.

However, the pole-pole array has two main disadvantages. First, it has a much poorer resolution compared to other arrays, where subsurface structures tend to be obscured in the final inversion model. A second disadvantage, particularly for large electrode spacings, is that the second current and potential electrodes must be placed at a sufficiently large distance from the survey grid.

The data processing used Res3dinv software (Geotomo, 2001). This program uses the smoothness-constrained least-squares inversion technique to produce a 3D model of the subsurface from the apparent resistivity data.

### Presentation of results and discussion

Resistivity data interpretation

Figure 3 shows the 3D resistivity model obtained from the inversion of the data set. The RMS (Root Mean Square) error achieved was 61.8% after three interactions. The model is shown in the form of horizontal slices corresponding to the six levels of depth investigated.

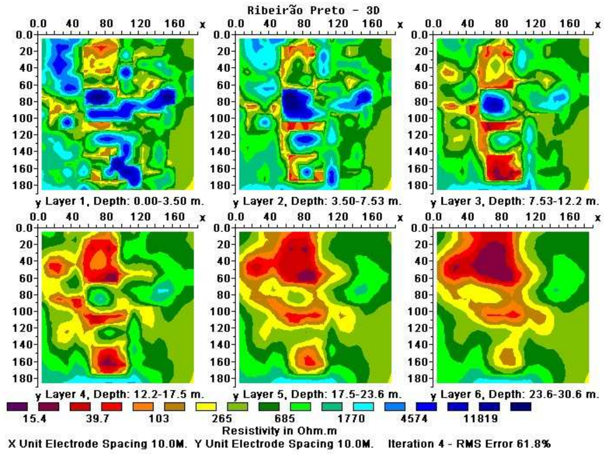


Figure 3- 3D resistivity model of the study area.

The first level (depth: 0-3.50 meters) and the second level (depth: 3.50-7.53 meters) show variations in the distribution of the resistivities. These variations correspond to the basalt and sandstone residual ground, in accordance with the information from the soundings and monitoring wells present. The zones with values of higher electrical resistivity, located in the positions between 52 - 100 meters (X-direction) and 65 - 105 meters (Y-direction), 62 - 98 meters (X-direction) and 118 - 135 meters (Y-direction) and 75 - 90 meters (X-direction) and 150 - 172 meters (Y-direction) characterize trenches 2, 3 and 4, which are filled with residues. We believe that the increase of resistivity must be explained by the fact that the residue is more plastic in these trenches. However, while the residue is resistive, in the zones of bigger aeration (limits of the trench), the environment starts to be less resistive.

A zone with inferior resistivity values less than 260 Ω.m was observed between the distances 50 - 100 meters (X-direction) and 18 - 50 meters (Y-direction), which characterizes trench 1 filled with residues. Trench 1(less resistive) was the first place to receive residues in the area (Penner, 2005). It is suggested that the older trench 1 is liberating or liberated bigger amount of solute. According to Sauck (2000), the greater the exposition time of the residue, the greater the bacteriological attack and concomitantly bigger the production of acid and reduction of the electrical resistivity of environment.

There were also observed more conductive zones in relation to the environments located between the trenches, suggesting that processes of contamination from the migration of materials coming from trenches are occurring. From inquiry level 3 (depth from 7.53 meters), the values of electric resistivity tend to diminish with the depth, which would be characteristic of the presence of a saturated zone and/or the presence of contamination, and the deeper measurements present a trend of increasing size of the area of lesser resistivity from the center to the left side. Taking into consideration that the study area is constituted of two systems of aquifer (suspended and deep), and of the knowledge of the depth of the water table obtained by information from the soundings and monitoring wells, we can make the following interpretations:

1- Levels 3 and 4 (depth: 7.53-17.5 meters) show a conductive zone in the positions between the distances 60 and 101 meters (X-direction) and 145 and 178 meters (Y-direction) characterizing a contaminant inside of the non-saturated zone;

2- Levels 4, 5 and 6 (depth: 12.2-30.6 meters) characterize the materials below the saturated zone until approximately 110 meters in Y-direction;

3- For the same levels, there was a zone of greater conductivity (resistivity values smaller than 150 Ω.m) with descending and lateral movements of leachate (center to left) characterizing the presence of the contaminant inside the saturated zone and developing a contamination plume in the same direction as the underground flow.

## Investigation methods

In an environmental characterization program it is essential to collect and analyze the soil and/or water samples to identify the contaminants and their concentrations. The waste, soil, and water from 8 monitoring wells in the study area were sampled. Chemical analysis of material removed from inside the trenches showed that the inorganic fraction of the residue has high percentages of sulfur (20.56%) and calcium (23.35%), as well as high percentages of siliceous, and not neglible amounts of titanium and lead. In soil analysis of the area in general, low concentrations of several polycyclic aromatic hydrocarbons (PAHs) were found, mainly naphthalene in BH-01 (0.004 ppm, without comparison pattern) and phenanthrene in MW-08 (0.004 ppm, below the CETESB intervention level of 0.2 ppm). In water collected from monitoring wells in the area, an analysis verified contamination of the groundwater by lead (Pb). In general, because of the measured concentrations (17.5 µg/l in MW-08, 23.4 µg/l in MW-05, 30.5 µg/l in MW-07) the area can be considered contaminated (the CETESB intervention level is10.0 µg/l).

The source of contamination at this site (trenches with re-refined lubricating oil waste) is different from the conductive anomalies in zones contaminated for LNAPL's from leaking underground storage tanks as shown in the literature (Atekwana et al., 2004; Werkema Jr et al., 2003 and 2004). However, the results obtained by the physical-chemical parameters of the soil and underground water show alterations compatible with those observed by the authors. This model of conductive anomaly, confirmed in the literature, correlates the geophysical anomaly with the subproducts of the oxi-reduction reactions and of the hydrocarbon biodegradation. At this site, the main contaminants are PHAs degraded by bacteriological action. Bioremediation is considered the more efficient method for the recovery of areas contaminated for PHAs (Eriksson et al., 2000).

The ph values and potential Redox measurements in samples of the soil from the unsaturated zone, and the ph values, redox, conductivity and dissolved oxygen in the underground water show a relationship with the geophysical anomalies compatible with the expected alterations. Table 1 shows a summary of the values of the parameters obtained from the soils from boreholes 1 to 5.

Table 1- Results of soil analysis.

| Borehole | Depth (m) | pH | Eh (mV) | Conductivity (mS/cm) |
|---|---|---|---|---|
| BH-01 | 3.0 | 5.41 | 553 | 265.0 |
| BH-01 | 16.2 | 6.59 | 512 | 39.0 |
| BH-02 | 3.3 | 6.17 | 503 | 24.6 |
| BH-02 | 15.0 | 6.42 | 513 | 25.5 |
| BH-03 | 3.0 | 5.79 | 545 | 27.3 |
| BH-03 | 12.1 | 5.75 | 558 | 23.8 |
| BH-04 | 3.5 | 6.0 | 560 | 21.8 |
| BH-04 | 11.0 | 5.7 | 546 | 20.5 |
| BH-05 | 3.5 | 4.45 | 616 | 865.0 |
| BH-05 | 10.7 | 5.89 | 556 | 25.2 |

**NOTES:** (1) The red color detaches the soundings that present anomalous values for the parameters ph and conductivity. (2) The yellow color detaches the anomalous values of the parameters ph and conductivity.

The results obtained from the samples of soil show anomalous values of pH and conductivity for BH-01 (depth 3.0 m) and BH-05 (depth 3.5 m). Generally, all the soil samples show an acid or slightly acid pH. However, the lower pH values associated with the high conductivity values could be indicative of the existence of organic and carbonic acids, subproducts of the bacterial action on the hydrocarbons.

Anomalous pH values, conductivity and concentration of dissolved oxygen were observed in samples of water from some of the monitoring wells (Table 2).

High values of conductivity (more than 400 mS/cm) were observed in the reference wells MW-05, MW-06 and MW-07. Low values (in relation to the reference well) of the concentration of dissolved oxygen were observed in the MW-03, MW-04 and MW-06. Water samples of MW-05 and MW-06 show an acid pH (close to 4.0). All the wells are close to the trenches, in the area where the conductive anomalies of resistivity and GPR can be observed, except the MW-08. Since the direction of the underground flow is from NW to SE (as identified by Penner, 2005), this could be explained by the fact that this well is upstream the area of the trenches.

Table 2- Results of the parameters obtained from the water from the monitoring wells.

| Well | T ($^{o}$C) | E. C. (mS/cm) | DO (mg/l) | pH | Eh (mV) |
|---|---|---|---|---|---|
| Ref. well | 27.1 | 49.0 | 4.4 | 5.8 | 122.5 |
| MW-01 | 26.2 | 60.0 | 4.9 | 6.3 | 105.7 |
| MW-02A | 26.4 | 55.0 | 5.6 | 6.2 | 90.7 |
| MW-02B | 26.7 | 138.0 | 4.5 | 6.4 | 86.2 |
| MW-03 | 26.3 | 37.0 | 3.9 | 5.9 | 127.8 |
| MW-04 | 26.7 | 44.0 | 3.0 | 5.8 | 123.4 |
| MW-05 | 27.2 | 816.0 | 4.8 | 3.9 | 217.5 |
| MW-06 | 27.7 | 504.0 | 3.0 | 4.2 | 192.6 |
| MW-07 | 26.9 | 484.0 | 4.6 | 5.8 | 136.9 |
| MW-08 | 26.5 | 5.2 | 5.7 | 6.0 | 113.7 |

**NOTES:** (1) The red color detaches the monitoring wells that present anomalous values for the parameters electrical conductivity (E.C.), dissolved oxygen concentration (DO) and pH. (2) The yellow color detaches the anomalous values of the conductivity, DO and pH.

These anomalous values associated with the geophysical anomalies indicate a possible degradation of the hydrocarbons by bacterial action. The geophysical anomalies as well as the physical-chemical parameters from the water samples indicate contamination and bacterial action in the two aquifers identified at this locale. An analysis of the most marked anomalies also shows a relation to the age of the trenches, since the most marked anomalies are in the region of the most recent trenches (3 and 4). This could be because the bacterial activity was greater in the area of trenches 1 and 2 which resulted in a greater attenuation of the contamination.

For the closing of the discussion on the contamination of the area is needed the evidence of the existence of bacteria. Therefore, soil samplings had been made in a specific point of the study area (until the depth of 4 meters), where geophysical investigations suggest contamination and, also, a sampling of reference was made. The Table 3 shows the result obtained for the biological analysis (bacterial counting) in soil samples. The presence of bacteria in the zone of the geophysical anomaly exists, with up to $4.20.10^{5}$ UFC/g and, therefore, is occurring a process of natural bioattenuation in the study area. The sample of reference shows absence of bacteria.

Table 3- Results of biological from the soil.

| Sample | Depth (m) | Bacteria (UFC/g) |
|---|---|---|
| AM-R* | 1.5 | 0 |
| AM-1 | 1 | $0.94.10^{5}$ |
| AM-2 | 2 | $1.73.\ 10^{5}$ |
| AM-3 | 2.5 | $2.15.10^{5}$ |
| AM-4 | 3 | $4.20.10^{5}$ |
| AM-5 | 3.5 | $2.71.10^{5}$ |
| AM-6 | 4 | $3.45.10^{5}$ |

**NOTE:** (1) * Sample of reference.

## Conclusions

The results obtained show the great potential for application of the 3D dipole-dipole resistivity survey to image the contamination plume originated by the lubricant oil waste disposal, revealing an important tool for environmental studies. The 3D resistivity model allows a better analysis of the study area both in terms of the characteristics of the environment and in terms of the relationship between the residues and the disposal place.

The variations of resistivity in three dimensions allow better visualization of the geometry of the trenches and also the behavior of the contamination plume if developing in the same direction as the underground flow, characterized by the conductive anomaly from level 4.

The trenches filled with residues presented high resistivity values, with the exception of trench 1 (older chronologically). Probably trench 1 is liberating or liberated bigger amount of solute. According to Sauck (2000), the greater the exposition time of the residue, the greater the bacteriological attack and concomitantly bigger the production of acid and reduction of the electrical resistivity of environment.

The direct analysis confirms the existence of contamination and suggests the existence of bacteriological activity in the soil samples and water from the monitoring wells. The biological analysis in soil samples shows the presence of bacteria in the zone of the geophysical anomaly.

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