Geoelectrical analysis from Electrical Resistivity and Induced Polarization data applied in an old waste disposal area in São Carlos/SP

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Abstract

Industrial and urban wastes generation have increased over the years. In consequence, their disposal in landfills and open dumps has amounted to environmental impacts such as soil contamination and greenhouse effect. Geoelectrical methods can help to identify subsurface leachate contamination and to estimate the waste trench depth, thus providing a tool to restore areas of unduly waste disposal. In this work we apply electrical resistivity and induced polarization analyses to characterize an old open dump in São Carlos city, which has been built in particularly unlawful circumstances. Through Electrical Resistivity Imaging (ERI) technique and dipole-dipole array, we may infer leachate subsurface contamination. The corresponding resistivity profile contains values lower than 27ohm.m, below 10 meters of depth. Chargeability profiles have shown larger values nearby the waste. With this data, we could estimate waste trench depth, resulting in values up to 8 meters along the line 4.

Introduction

The increasingly urbanization rate has equally raised the production of industrial and urban wastes of various types. In Brazil, these residues are mostly disposed in landfills and open dumps. Solid residues can impact the environment and, consequently, the population's health. Liquids with contaminants, e.g. leachate, may leach to the soil and degrade the groundwaters (Shinzato, 2014; Velozo, 2006). Improper disposal of the wastes favors the dissemination of insect vectors and can be a risk factor for respiratory symptoms (Corrêa et al., 2011; Dias; Leal; Marques, 2020). In addition, solid waste belongs to the main sectors that contribute to the greenhouse effect, in that it impacts the emission of gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). In particular, it ranks third as the major sector emitting methane (Kweku et al., 2017; Lohmann, 2020).

In landfills, the anaerobic decomposition of organic matter produces the biogas, which is composed mainly of methane and carbon dioxide, among others. Such a product can be used to generate electricity through methane combustion, thereby reducing polluting potential. From this combustion, a significant reduction in terms of carbon dioxide equivalent emissions is obtained (Abrelpe; Lohmann, 2020). The leachate also results from the decomposition of organic matter. It is captured through pre-installed drains and sent to differentiated channels of treatments in wastewater treatment plants or alternative systems. The Brazilian standards NBR 8.419 (1992) and NBR 13.894 (1997) present guidelines with respect to the criteria, implementation and monitoring of landfills.

In inadequate systems of waste disposal, where the minimum normative criteria are not obeyed, e.g., in open wastes, capturing these compounds becomes impracticable. Procedures for the environmental restoration of dumpsites can be applied. They include: covering the waste pile, installing a surface drainage system to collect percolates, installing drains to collect gas in the waste mass, or even removing the waste and transporting it to another location. The feasibility of waste incineration from open dump can be studied. Such a practice would promote the reduction of waste volume and produce energy from the burning of these residues. To this end, factors such as operation costs, logistics, transport and estimated volume of waste present in the trenchs should be taken into account. (Beli et al., 2005; Carvalho; Pfeiffer, 2004; Lanza, 2009; Lins et al., 2021).

To determine the best procedure to the environmental restoration of open dumps, it is important to perform a preliminary assessment of the area. In this sense, geophysics can be a great ally, through the two-dimensional evaluation of the subsurface, that is unfeasible by means of direct engineering methods (Braga, 2016). If geoelectric methods can be used to estimate the depth of the waste pile, often unknown in dumpsites, then the volume of this waste could also be estimated. In addition, these methods are also applied in identifying soil and groundwater contamination, contributing to the evaluation of the environmental impacts. Brahmi et al. (2021) applied the electrical resistivity (ER) and induced polarization (IP) methods at a landfill in Algeria, where they were able to determine leachate infiltration zones and distinguish the boundaries between the waste and the leachate-contaminated region. Leroux and Dahlin (2007) also developed a study in a landfill with the ER and IP methods, in which they demonstrate the applicability of these methods for the spatial delimitation between cover and waste materials.

The objective of this work was to investigate the viability of the ER and IP methods to characterize solid waste disposal areas which can be either disactivated or under operation. We sought to show that these methods can aid environmental restoration of open dumps as well as to monitor existing contaminants therein.

The study was conducted in the region of an open dump, in the city of São Carlos/SP. This deactivated dump was used by the city's government for domestic waste disposal for 16 years. Wastes were disposed in a region of an old "voçoroca" area (natural depression zone produced by intense erosion). The waste area is approximately 600 m long and 100 m wide and received industrial, domestic and hospital wastes. It does not have drainage structures for collecting leachate or gases, nor base waterproofing, although being highly exposed to contamination of surface and groundwater. The dump is located in the eastern part of the Paraná Basin, on the Botucatu Formation (Figure 1). It is inserted in the Feijão basin, Tietê-Jacaré Macro basin, which is responsible for 40% of the municipal water supply and is a recharge area of the Guarani Aquifer (Velozo, 2006). In the region one can find sandstones with few fines of high permeability. The soil is mostly sandy and has a high potential for erosion. Monitoring wells point to the presence of silty fine sand and yellow fine/medium sand.

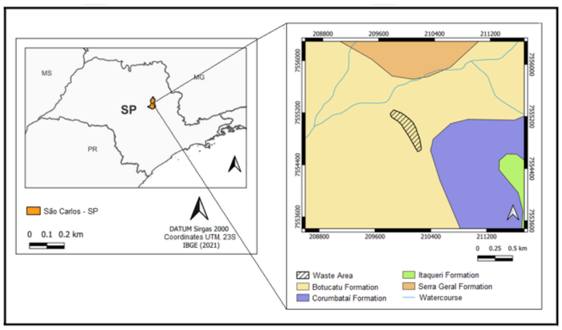

***Figure 1** – Location and geological maps of the area where the dump was installed.*

Method

Electrical resistivity

Electrical resistivity is a geophysical method currently used in the identification and monitoring of contaminants in groundwater and soils, groundwater exploration, mapping the extent of remnants of buried foundations of old buildings, among others (Reynolds, 2011). It is characterized by the investigation of the resistivity, whose concept relates to the measure of how well the material slows the flow of electric current (Braga, 2016; Herman, 2001). The propagation of electric current in rocks often occurs through ionic or electrolytic conduction, in which there is a displacement of ions present in the pore fluids of soils and rocks.

The resistivity method employs investigation techniques from sets of electrodes, usually two, where one pair (AB current electrodes) provides electric current (I) and the other (MN potential electrodes) measures the potential difference (ΔV). The apparent resistivity measurement, expressed in ohm.m, can be obtained by expression 1. The true resistivity is obtained from inversion methods.

$$\rho = \frac{K\Delta V}{I} \quad (1)$$

where K is the geometric coefficient, of length dimensions, which varies according to the geometry of the arrangement of the four electrodes on the surface.

The resistivity of the medium varies from properties such as moisture content, porosity, mineralogical composition, degree of saturation, particle size and shape, among others (Braga, 2016; Kearey; Brooks; Hill, 2009). The presence of water plays an important role in the medium's conductivity. For unsaturated sediments the range of resistivities is high and inconclusive. Igneous and metamorphic rocks usually present high values of resistivities.

Induced Polarization

The induced polarization method is especially applied in mineral and groundwater prospecting, geothermal exploration, and the identification of hard-to-detect organic contaminants (Reynolds, 2011). It is characterized by the investigation of the physical property chargeability, when measured in the time domain.

The phenomenon occurs when electric current is injected into the ground, through the AB electrodes, in direct current mode. When the current is switched off, an instantaneous decay of part of the initial voltage (ΔV_P) is observed, followed by a gradual decay of the residual voltage (ΔV_{IP}), between the MN electrodes, which produces a discharge curve of the voltage as a function of time (t). The chargeability is calculated from the integration of this discharge curve, over the interval $\Delta t = t_1 - t_2$, given by:

$$M = \frac{1}{\Delta V_P} \int_{t1}^{t2} \Delta V_{IP}\,(t)dt \quad (2)$$

The energy stored in the material, commonly rocks and soils, is due to variations of the ion's mobility in the fluid along the rock, called membrane polarization. In the simplified form, this phenomenon generates an increase in the concentration of positive ions in a certain region, which prevents the movement of ions along the fluid, hence creating a potential difference. When current is switched off, the gradual return of these ions to their initial configurations in a finite time represents the IP response (Telford; Geldart; Sheriff, 1990).

Data Acquisition

In both ER and IP methods, data were obtained through the Electrical Resistivity Imaging technique, which allows a two-dimensional investigation of the subsurface and construction of 2D profiles. It was employed a dipole-dipole arrangement with 10-meter electrode spacing and a theoretical depth of 30 meters. Equipment used comprise resistivity-meter developed by IRIS Instruments, through the Iris Syscal R2 equipment, pairs of metallic electrodes, non-polarizable electrodes, and other auxiliary instruments. In gathering induced polarization data, the same standard resistivity arrangement and equipment is normally used, capable of acquiring measurements of resistivity and chargeability simultaneously.

Profile lines were positioned on the NE-SW direction, passing by previously installed monitoring wells (Figure 2). Data obtained were processed with the software RES2DINV, which performs the inversion process by means of the Gauss-Newton least squares method, with nonlinear smoothing (Aarhus Geosoftware, 2022).

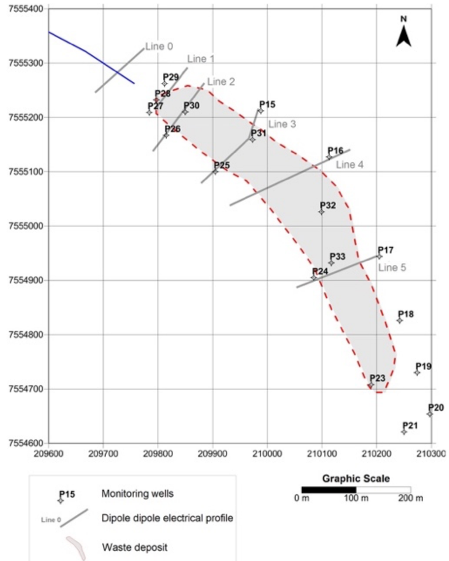

***Figure 2** - Location of the* Electrical Resistivity Imaging *technique lines at the landfill, and additional information.*

Results

The obtained results from the geoelectric surveys were contrasted with information from monitoring wells, previously installed in the region. The saturated zone varied according to the section investigated, from 1.97 meters to 8.7 meters. The predominantly sandy soil present in the area, in the saturated zone, frequently presents resistivities higher than 60 ohm.m. The presence of contaminants reduces the resistivity values, as well as it can reduce or increase the chargeability values, depending on the concentration of percolate.

Line 2

In the resistivity profile along the line 2 (figure 3) there predominates low resistivity values (< 11.2 ohm.m) between 80 and 120 meters horizontally, and values below 156 ohm.m spreading laterally and at depth. These low resistivity values are concentrated in the same region where the waste trench is bounded. These results indicate the presence of waste and leachate. According to the information from the monitoring well P-30, the waste is concentrated in the first 7 meters of depth, with contaminants reaching at least the first 10 meters.

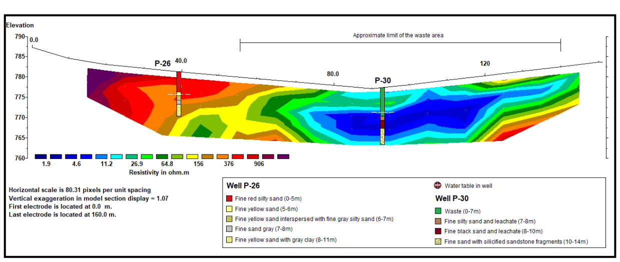

***Figure 3** - Section for resistivity, line 2, ERI with 10-meter electrode spacing.*

Figure 4 shows chargeability profile. Higher chargeability values are also observed at the approximate boundary of the waste trench. These high values are certainly related to the presence of leachate and polarizable materials in the waste. The high values below the waste trench may be related to the existence of silicified sandstone fragments. Another hypothesis explaining this increased IP response is the decrease in leachate concentration with increasing depth. Regions of lower resistivity can be observed at the lower limit of the waste trench. A likely explanation is the existence of preferential path of percolate flow with increasing salt concentration.

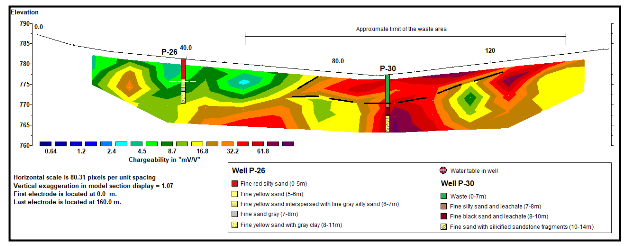

***Figure 4** - Chargeability, line 2, ERI with electrode spacing of 10 meters.*

Also, from the chargeability section, it is possible to estimate the limit of the waste trench (black dashed line in figure 4), through the contrast of the physical property values. The depths obtained are estimated values but serve as a basis for future investigations or strategies.

Line 4

The resistivity profile along the line 4 (figure 5) is also characterized by low resistivity values in the region of the waste trench boundary. Between positions 70 and 170 meters horizontally, values less than 26.9 ohm.m are observed.

The low resistivity anomaly can be observed extending to elevations near 778 meters. These low values suggest contamination by leachate, along with the fine sand characteristic of the region. Externally to the approximate boundary of the waste trench, the resistivity values are higher, characterizing an uncontaminated zone. There are no monitoring wells installed in the waste trench, in this specific section.

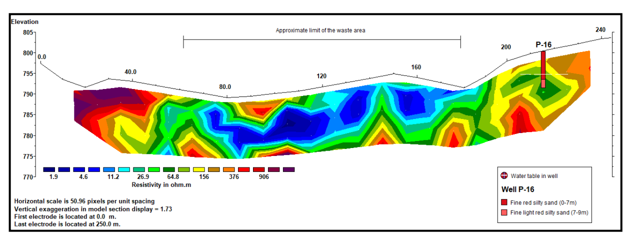

***Figure 5** - Resistivity profile, line 4, ERI with 10-meter electrode spacing.*

Chargeability profile of line 4 (figure 6) is marked by high and low chargeability values. The composition of the waste is varied and therefore the chargeability values are not homogeneous. The work done by Shinzato in 2014 at this open dump showed that in certain regions inside the waste, considerable amounts of immobile leachate, i.e., stagnant liquid with high concentrations of pollutants, were found on the plastic residues. This means that the concentration of leachate also varies in the waste trench, which consequently alters the IP responses.

The estimated boundary between waste trench and percolate-contaminated sand can be observed following the black dashed line. The observed higher chargeability values may be related to the lower leachate concentration.

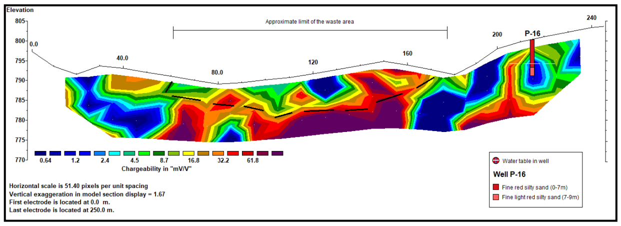

Figure 6 *- Chargeability profile, line 4, ERI with 10-meter electrode spacing.*

The low resistivity values found in both lines are behaviors already observed by other authors. Brahmi et al. (2021) states that the composition of the waste, i.e., highly rich in ions and metallic materials, increases the conductivity of the medium and often increase the IP response. However, the presence of contaminated soil will not always show the same pattern. Ustra (2008) and Gallas et al. (2011) noted that the low values of chargeability are usually related to high concentration of the ionic content, but a drop in the salinity of the fluid can produce higher values.

From the chargeability sections it was possible to estimate the depth of the waste trench, through the contrast observed between the IP responses. For Line 2, this estimate could be confirmed by the existing information from the monitoring well, which points to a depth of 7 meters. Line 4, on the other hand, does not pass through any monitoring wells. However, from the information from wells P-31 and P-32, the waste depths vary between 6.5 m and 7.5 m. Estimated depths are close to 8 meters at the center of the trench and decrease at the edges. If this waste is sought to be removed in the future, geophysics could assist evaluating the volume of the waste.

Considering the characteristics related to the dumpsite studied, with water levels at low depths and evident contamination of the highly permeable soil, removal and controlled incineration of the solid waste may be a relevant alternative for the reduction of environmental impacts and consequent energy production. This alternative is performed, virtually, in all countries of the European Union, in which 26.3% of all waste generated is sent to incineration plants (Eurostat, 2022). Among the main advantages are the reduction in the volume of waste sent to final disposal and the production of energy from combustion. In addition, the recovery and valorization of metals through the treatment of slag and bottom ash by means of incineration can reduce indirect greenhouse gases emissions. This promotes energy savings from the mining process and natural resource processing. The major disadvantage is the possibility of generating pollutant gases and residues with potential contamination (Zuberi; Ali, 2015).

Conclusions

The obtained results attest the efficiency of the resistivity and induced polarization methods to the investigations related to the contamination in waste disposal areas. A standard behavior is observed in the investigated sections: low resistivity values in the region of the waste trench, which is justified by the presence of trash and leachate percolation into the existing soil; and high chargeability values in the same region, due to the existence of polarizable materials and leachate. Moreover, the chargeability profiles presented a contrast between the waste trench and the percolate-contaminated soil. This suggests the applicability of the IP method to estimate the solid waste depth. Restoration of open dumps is an alternative to mitigate environmental impacts; however, each area must be assessed separately, considering the most important aspects and the cost-benefit. Geophysics can be applied to identify environmental impacts and quantify the volume of waste.

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