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Using Electrical Resistivity Tomography (ERT) to Assess the Effectiveness of Capping in Old Unlined Landfills

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Abstract—Engineered capping systems are efficient tools for the safety concept for landfills and contaminated land, consisting of multilayer barriers installed at the top of the deposited waste, even years after its closure. The efficiency of such systems is closely associated with avoiding rainwater infiltration into the waste body, a process that can be assessed and monitored with geophysical methods, such as Electrical Resistivity Tomography (ERT). A surface geomembrane capping of approximately 900 m^2 was installed over an abandoned unlined landfill in southeastern Brazil and ERT surveys were adopted to assay the effectiveness of the intervention measure. It was possible to verify significantly more resistive regions below the geomembrane and an increase in conductivity values only at approximately 6 m, at the groundwater level of the area. Thus, the reduction of rainwater input possibly, even in the short term, reduces the moisture content and prevents the formation of leachate sheets in unlined landfills, leading the deposit to be more isolated from the surroundings. Lateral flow affected distances as far as 2.5 m from the capping borders, showing that about 70% of the capped area was effectively isolated from the rainfall infiltration. Therefore, capping contributed to reducing leachate production and can be considered an effective method for mitigating impacts from old unlined landfills.

Keywords: Landfill covers, geophysics, non-sanitary landfills, contaminants migration.

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1. Introduction

Despite the fact that Brazilian law, in line with international regulations, prohibits uncontrolled landfills and dumpsites (2020a; Brasil, 2010), a significant number of them can still be found in Brazil, in operation or decommissioned, without proper monitoring of soil and water contamination (Brasil, 2020b). Such dumps are unlined, increasing the risks of environmental contamination by the migration of contaminant plumes off-site and causing environmental impacts to persist (Lavagnolo, 2018).

In order to avoid contamination migration from uncontrolled landfills, source removal (Calderón Márquez et al., 2019; Dubey et al., 2016) or source control (Bjerg et al., 2013) have been adopted worldwide. Even though the former would be more effective for environmental control, the last is more cost-effective for developing countries. It commonly consists of the implementation of a final surface cover that acts in controlling medium and long-term emissions, minimizing water infiltration into the system and the consequent production of leachate (Cossu & Garbo, 2018).

These multilayer barrier systems can be made of several materials, but are commonly composed of soil and geosynthetic layers (Cortellazzo et al., 2022). Their adoption and construction require continuous monitoring and maintenance (Cossu & Garbo, 2018), especially considering unlined landfills where lateral flow could permit water entrance into the waste body.

In this regard, geophysical techniques, especially Electrical Resistivity Tomography (ERT), are non-invasive procedures that have been widely applied in investigations of waste deposits (Guinea et al., 2022;

Helene et al., 2020; Maurya et al., 2017; Morita et al., 2020a; Shao et al., 2022). Some applications include defining the geometry of the deposit (Ibraheem et al., 2021), analyzing the interior of capped landfills (Audebert et al, 2016; Deidda et al., 2022; Genelle et al., 2014), characterizing the moisture content in landfills (Audebert et al., 2016; Dumont et al., 2016, 2018), and evaluating shifts in contaminants migration according to different hydrological events (Gasperikova et al., 2012; Park et al., 2016).

The present study aimed to investigate the effectiveness of capping adoption in an old unlined landfill using ERT surveys. The purpose was to answer whether capping reduces leachate production in unlined landfills, or if lateral flow could make its adoption ineffective.

2. Methodology

2.1. Study Area

The study area is an old unlined landfill located in southeastern Brazil, in the city of São Carlos (Fig. 1), in an outcrop zone of the Guarani Aquifer, which is mainly formed by sandstones and sandy soils. The local climatic conditions are classified as humid subtropical climate (Cfa by Koppen and Geiger), with annual precipitation of about 1440 mm and the average temperature of 19.7 °C.

The landfill was installed inside a gully and received mixed waste, including domestic, industrial, healthcare, and demolition waste, for approximately 16 years (1980–1996) with no engineering structure for long-term collection and treatment of gas and leachate. Hence, the contamination was confirmed both considering its spread to the surroundings (Morita et al., 2020a) and its persistence after 20 years (Morita et al., 2020b), and the site was included in the list of contaminated areas with confirmed risk controlled by the Environmental Agency of the state of São Paulo, Brazil (CETESB, 2021).

It is important to note that a previous study identified waste disposal at portions as deep as 7 m (Pelinson et al., 2020) and that the groundwater level in the area varies from 5 to 7 m. Thus, it can be assumed that some portions of the waste body get in

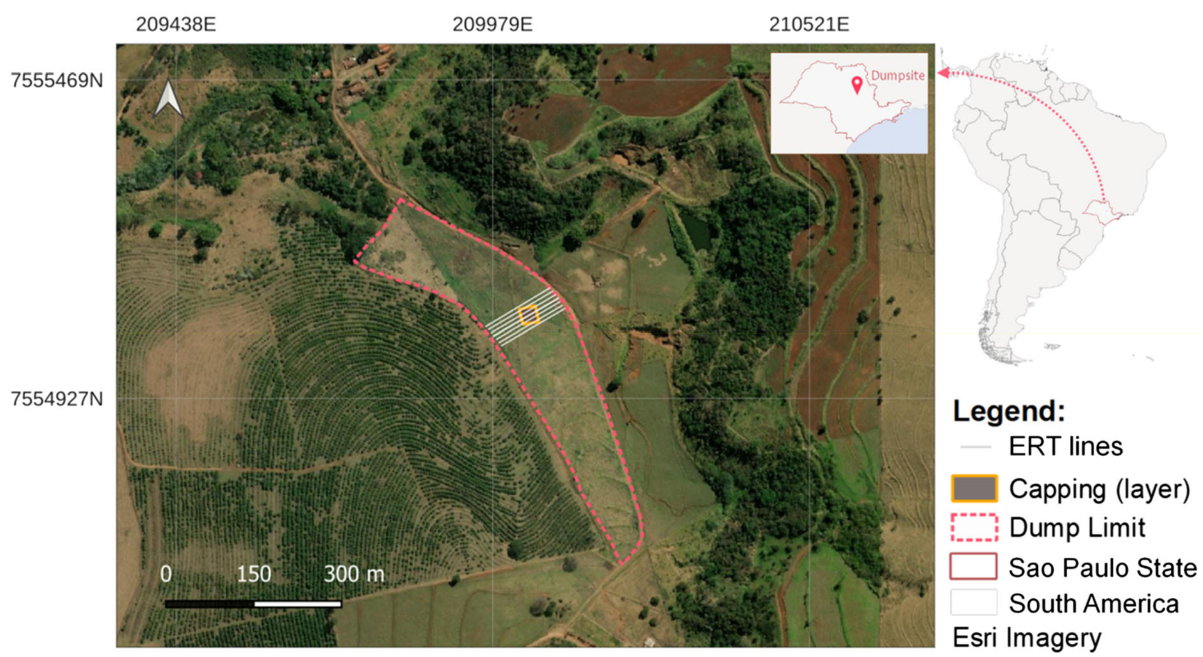

Figure 1
Location of the studied landfill, the capping construction, and the ERT lines

direct contact with the groundwater, which affects water lateral flow and the consequent leachate production and may impair the effectiveness of capping as a mitigation technique.

2.2. Construction of Capping Layers

A square area of about 900 m^2 (30 m edge) in the center of the studied landfill received a capping system with three layers: the first layer was composed of a 20 cm-thick soil layer to level the terrain; the second layer consisted of a PVC geomembrane coupled to a geotextile (80 mm thick in total); and the third layer was another 20 cm-thick regularization soil layer, adopted to protect the geomembrane (see *Supplementary Material*). Capping construction was performed in October 2018.

2.3. Electrical Resistivity Tomography (ERT)

A total of seven profiles of about 115 m long were surveyed (Fig. 1), five inside the capped area (lines 2–6) and two outside it (lines 1 and 7). Line 4 crosses a leachate monitoring station (LMS), where water/leachate levels inside the waste body could be monitored. Such levels correspond to accumulated leachate in the waste body, which does not necessarily match the local groundwater levels. Dipole–dipole arrays and a 2.5 m electrode spacing were adopted, resulting in an estimated depth of investigation of 25 m, in the central portion of the profiles.

The ERT surveys were conducted at two different moments: before capping construction, during the dry season (July 2018) and after capping construction, during the wet season (February 2020). Such surveys permitted to observe the landfill's water content in dry and wet seasons, and also enabled to identify the effects of capping, by means of the comparison of internal (2–5) with external lines (1 and 7). It is important to highlight that the electrodes totally perforated the geomembrane during the second survey (February 2020), so that its electrical resistivity did not influence the resistivity profiles.

Data acquisition was made by *Syscal Pro* de250W, and data treatment and inversion with the software *Prosys II* and *Res2dinv 3.4.,* respectively.

3. Results and Discussion

The resistivity profiles obtained for lines 1, 2, 3, and 4, considering dry (July 2018) and wet (February 2020) seasons, can be observed in Figs. 2, 3, 4, and 5, respectively.

During the dry season (July 2018) a clear differentiation of the surroundings can be observed, being the highest resistivity values associated with the walls of the gully in which the waste was disposed of (sandy material). Additionally, an in-depth contaminant migration could be identified, justifying the migration of the contaminants observed elsewhere (Morita et al., 2020a).

Differently, during the wet season (February 2020) a strong influence of rainfall could be observed, leading to a decrease in resistivity values. Even though it is still possible to identify the waste mass using ERT (until about 6 m deep, mainly in the center portion between 20 and 60 m of horizontal distance), the resistivity values are considerably low ($\sim$ 20–40 Ω m) showing greater water content. Considering that the water/leachate level measured in the LMS was located at 2.5 m in the wet season, it can be assumed that intense rainfall propitiates the formation of leachate sheets that feasibly get in contact and mix with local groundwater ($\sim$ 6 m deep).

Figures 2 and 3 shows the resistivity profiles for lines 1 and 2, in the dry and wet seasons. These lines are located in the borders of the constructed cover, suffering more lateral influence of rainfall infiltration. Thus, no clear influence of the capping can be observed (February 2020).

Figure 4 shows the resistivity profiles for line 3, in the dry and wet seasons. Line 3 is located inside the constructed cover, having suffered a clear influence from it. Thus, regions with higher resistivity values could be observed just below the cover (between 40 and 70 m, see Fig. 4, below), and more conductive values were only observed at about 6 m deep, where the groundwater level is located. Therefore, the reduction in rainwater infiltration reduced humidity values in the waste body, avoiding the formation of leachate sheets in the region and contributing to the landfill isolation from the surroundings.

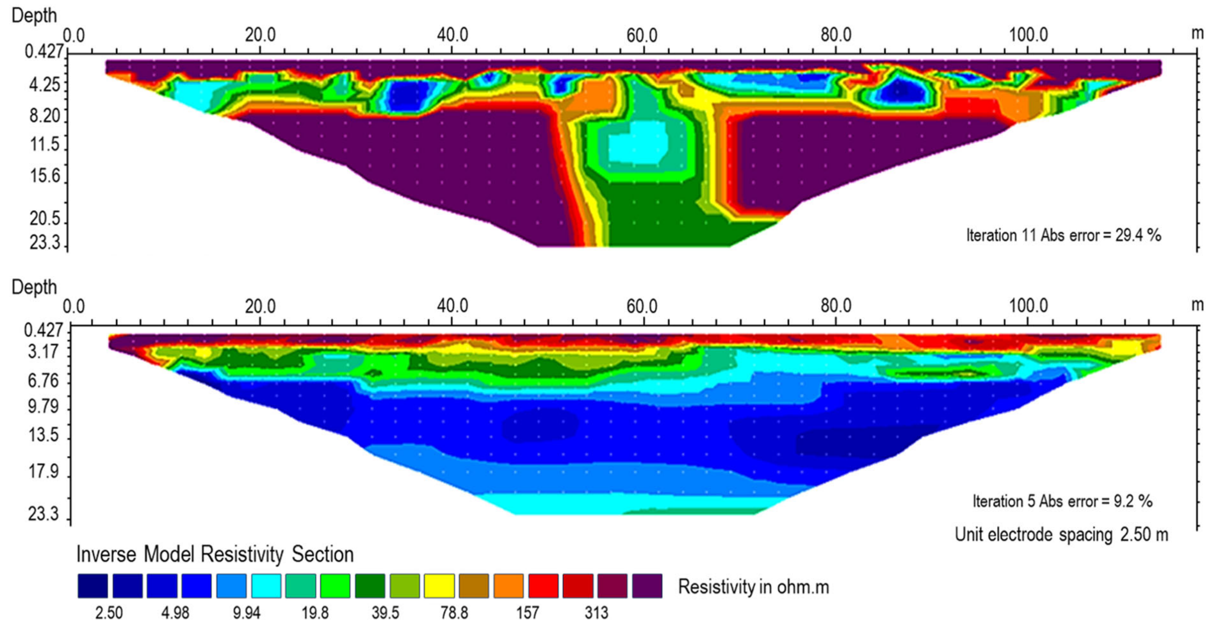

Figure 2
Resistivity profiles for line 1, in July 2018 (above) and February 2020 (below)

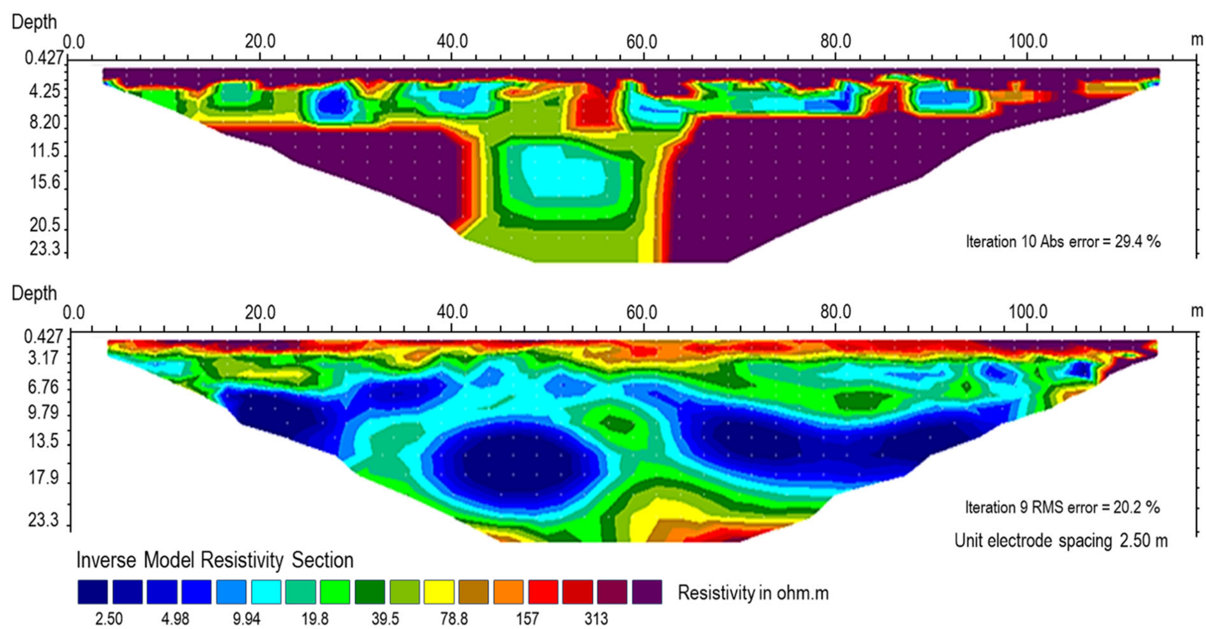

Figure 3
Resistivity profiles for line 2, in July 2018 (above) and February 2020 (below)

Finally, Fig. 5 shows the resistivity profiles for line 4, in the dry and wet seasons. Line 4 is located in the central portion of the constructed cover, clearly influenced by it, as observed in line 3. Thus, regions with higher resistivity values could be observed just below the cover (40–70 m, see Fig. 5, below).

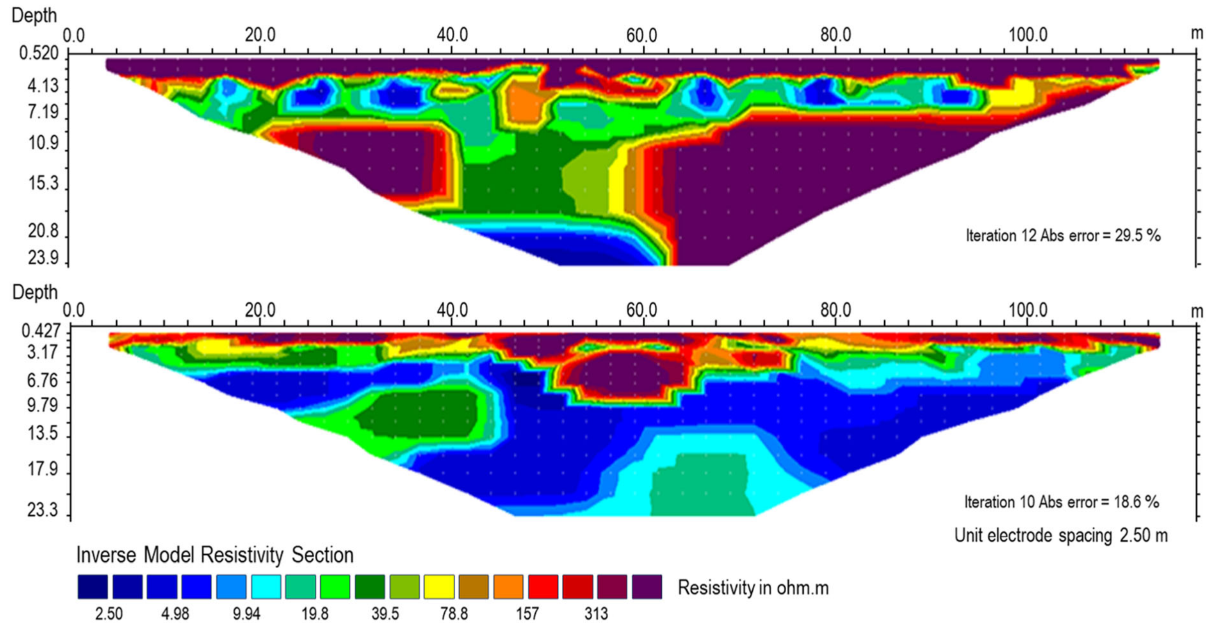

Figure 4
Resistivity profiles for line 3, in July 2018 (above) and February 2020 (below)

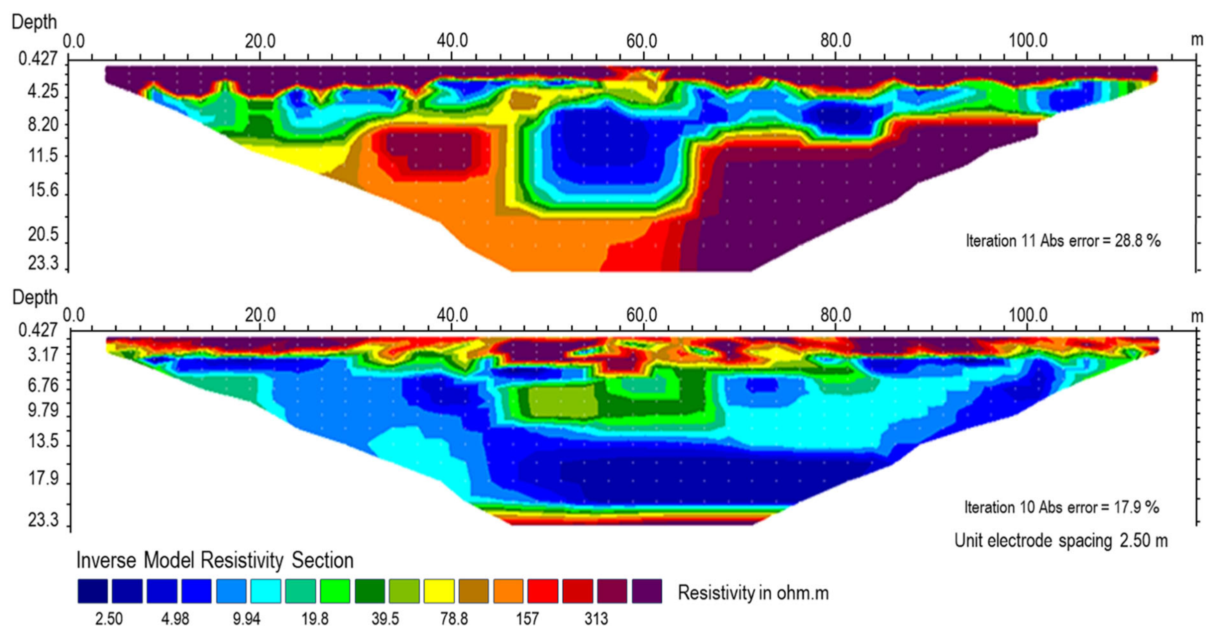

Figure 5
Resistivity profiles for line 4, in July 2018 (above) and February 2020 (below)

Nevertheless, in this line, some regions of lower resistivity values could be also identified, and can be associated with leachate pockets that still exist in the waste body, even after capping construction.

The profiles of lines 5, 6, and 7 are presented in the *Supplementary Material*, considering that they presented behaviors similar to lines 3, 2, and 1, respectively.

The main considerations regarding the performed ERT surveys can be summarized as follows:

1. Wet seasons have a significant impact on leachate production and contaminants migration, causing a wide saturation of the waste body and a mixture of leachate and groundwater. Thus, rainfall infiltration contributes to the contaminant spreading to the surroundings, and reducing water entrance would significantly reduce the landfill's impacts.
2. During the dry season, a clear delineation of the waste body could be identified, with the verification of high resistivity values in the surroundings, possibly associated with sandy soils from the lateral portions of the gully. Additionally, it was possible to observe in-depth contaminants transport in the central part of the landfill.
3. Zones just below the constructed cover could be differentiated from the external zones using ERT surveys, which show a decrease in humidity values with the intervention measure. Additionally, the observed resistivity values were lower than the ones observed before the capping construction, during the dry season, showing that the cover could maintain its efficiency even in critical conditions ($\sim$ 275 mm accumulated rainfall in the month previous to the surveys).
4. Capping construction permitted to create more resistive zones until about 6 m deep, which approximately corresponds to the waste body limits. Lateral flow influenced zones distant about 2.5 m from the cover borders, which permits us to assume that about 70% of the covered area (625 m^2 out of 900 m^2) could be effectively isolated from the surroundings. Thus, vertical flow showed to be the most important component in the studied area, and, hence, capping can be applied to mitigate impacts from unlined landfills. Similar research has not been conducted in dumpsites or non-sanitary landfills before; the results highlight the importance of constructing capping layers over such areas, even without the complete isolation from the surroundings. Additionally, it is important to emphasize that capping can also contribute to creating reducing conditions, enhancing heavy metals precipitation as sulfide minerals (Morita et al., 2023).
5. ERT showed to be efficient in the monitoring of intervention measures in landfills, being able to clearly: (a) identify zones with a greater influence of rainfall infiltration; (b) differentiate the waste body from the surroundings (gully and groundwater); (c) distinguish the events of contaminants plume expansion and retraction.

4. Conclusions

The present study aimed to evaluate the effectiveness of capping in an old unlined landfill using ERT surveys. ERT showed to be an efficient tool to assess the intervention measure, being able to clearly differentiate capped and uncapped zones, as well as border areas and the waste body. The capping construction was able to reduce humidity values, which can be associated with a reduction of leachate production, even during wet seasons. Therefore, it is suggested that the capping of old unlined landfills can be an effective method to reduce contaminants' migration to the surroundings, being highly recommended to mitigate their long-term environmental impacts.

Author contributions Alice K.M. Morita: Conceptualization; Methodology; Formal analysis; Investigation; Writing-original draft; Visualization; Writing-Review and Editing Natalia S. Pelinson: Writing-original draft; Validation; Writing-Review and Editing Douglas Bastianon: Visualization; Writing-Review and Editing Fernando Saraiva: Methodology; Investigation; Visualization. Edson Wendland: Conceptualization; Resources; Supervision; Project administration; Funding adquisition

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Data availability

The data that support the findings of this study are available from the corresponding author, A. K. M. Morita, upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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