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COMPARISON OF THE GEOELECTRIC SIGNATURE WITH DIFFERENT ELECTRODE ARRAYS AT THE JOCKEY CLUB LANDFILL OF BRASÍLIA

Victor José Cavalcanti Bezerra Guedes[1], Victória Basileu de Oliveira Lima[1],
Welitom Rodrigues Borges[1] and Luciano Soares da Cunha[1]

ABSTRACT. The influence of array configurations on the resolution of subsurface electrical resistivity tomography (ERT) imaging is one of the most discussed factors when it comes to resistivity data quality. Despite the flexibility of multichannel data acquisition systems nowadays, there is still a tendency to perform field observations with traditional arrays, mainly because they are already well understood configurations. The present work discusses a comparison between the results obtained with four electrode arrays (dipole-dipole, pole dipole, Wenner-Schlumberger and Wenner) regarding the data resolution and the ability to identify the bedrock over the buried waste in the former Jockey Club landfill of Brasília, an important information to delimit the geometry of the mass of waste. Four electroresistivity lines were acquired with different electrode arrays, using the ERT technique, and models were calculated using the Res2DInv software, by the robust inversion method (L1-norm) and smooth-constrained least squares inversion (L2-norm). All arrangements produced models that presented the mass of waste with low resistivity, indicating strong influence of leachate. The best agreement with borehole information regarding the bedrock level was achieved with the dipole-dipole array. The L1-norm inversion provided more stable and smoothed models than the results obtained with the L2-norm method, also presenting smaller differences between the calculated and observed apparent resistivity.

Keywords: electrical resistivity tomography; electrode arrays, waste disposal.

RESUMO. A influência do arranjo eletródico na resolução de imageamento por tomografia de resistividade elétrica (TRE) da subsuperfície é um dos fatores mais discutidos quando se trata de qualidade de dados de resistividade. Apesar da flexibilidade dos sistemas multicanais de aquisição de dados, ainda há uma tendência em realizar observações em campo com arranjos tradicionais de eletrodos, devido a serem configurações já bem compreendidas. No presente trabalho, é discutida uma comparação entre os resultados obtidos a partir de quatro arranjos de eletrodos (dipolo-dipolo, polo-dipolo, Wenner-Schlumberger e Wenner) quanto a resolução dos dados e quanto a capacidade de identificar o embasamento rochoso sobre o maciço de resíduos no antigo aterro controlado do Jockey Clube de Brasília, uma importante informação para delimitar a geometria do maciço de resíduos. Foram adquiridas quatro linhas de eletrorresistividade com diferentes arranjos eletródicos, com a técnica TRE, e foram calculados modelos no *software* Res2DInv pelo método de inversão robusta (norma-L1) e de inversão de mínimos quadrados com restrição de suavidade (norma-L2). Todos os arranjos produziram modelos que apresentaram o maciço de resíduos com baixa resistividade, indicando forte influência de chorume. As melhores concordâncias com as informações de furos de sondagem foram alcançadas com o arranjo dipolo-dipolo. A inversão norma-L1 forneceu modelos mais estáveis e suavizados do que os resultados obtidos com a norma-L2, também apresentando diferenças menores entre a resistividade aparente calculada e medida.

Palavras-chave: tomografia de resistividade elétrica; arranjos eletródicos; disposição de resíduos.

Correspondent author: Victor José Cavalcanti Bezerra Guedes

[1]Universidade de Brasília – UnB, Geosciences Institute, Asa Norte, 70910-900 Brasília, DF, Brazil – E-mails: viictorjs@gmail.com, basileuvictoria@gmail.com, welitom@unb.br, soares.cunha.l@gmail.com

INTRODUCTION

Geoelectric methods are widely used in subsurface investigation in waste disposal areas, being Electrical Resistivity Tomography (ERT) the most applied technique (e.g. Lago et al., 2006; Cavalcanti et al., 2014; Konstantaki et al., 2015; Park et al., 2016). As with all geophysical methods, data quality strongly influences the interpretation of results. The quality of measurements observed in an ERT survey is related to a number of factors. However, the influence of the electrode array on the resolution of subsurface imaging with the method is one of the most discussed factors when it comes to data quality, and there is a growing interest in comparing results obtained by different configurations. Many electrode arrays have been developed and optimized over the years. The electrode arrangement is generally a user choice, which takes into account the field operator's familiarity with the type of configuration, acquisition speed, equipment logistics, and the data inversion software available. With the advancement of hardware and software around the resistivity method, modern multichannel systems allow the use of various electrode arrays from a set of electrodes.

Despite the flexibility of these systems, resistivity data still tends to be collected with traditional electrode arrays such as Wenner, Schlumberger, Wenner-Schlumberger, pole-dipole, and dipole-dipole, due to being already well-understood configurations. Other researches have already provided comparisons between different electrode arrays with the ERT technique in order to point out their advantages and disadvantages in characterizing specific features in different environments (Zhou et al., 2002; Dahlin & Zhou, 2004, 2006; Martorana et al., 2009, 2017; Moreira et al., 2016; Al-Hameedawi & Thabit, 2017).

Dahlin & Zhou (2004) used numerical simulations to compare the resolution and efficiency of 2D ERT for 0 electrode arrays. The authors mainly recommended the gradient (GD), pole-dipole (PD), dipole-dipole (DD) and Schlumberger arrangements, since they returned higher resolution images than the other arrangements. In addition, one of the synthetic models analyzed was inspired by a waste disposal area, where the arrangements PD, DD, GD and Wenner-β produced the best images for the identification of low resistivity ditches. Dahlin & Zhou (2006), comparing the results obtained in a landfill area with the Wenner (WN), dipole-dipole and multiple gradient arrangements, pointed out that the inverted models of the WN and GM data had good agreement, but the DD section showed resistivities with significant differences in the deeper parts of inverted models, and the GM arrangement was less sensitive to noise than DD. In this context, the present work aims to compare the results obtained from four electrode arrays (dipole-dipole, pole-dipole, Wenner-Schlumberger and Wenner) in a practical application, to analyze data resolution and the capacity to characterize the bedrock level at the Jockey Club landfill (JCB), the former controlled landfill of Brasília. Information concerning the rock layer depth is an important aspect when characterizing a landfill, especially for energy recovery purposes, since it can be used to estimate the volume of waste deposited, and the energy potential of such a volume.

STUDY AREA

By 2018, most of the municipal solid waste (MSW) generated in the Federal District of Brazil was destined to the JCB landfill. The site is known as the largest open-air waste disposal area in Latin America (Campos et al., 2018). The main access road to the landfill is the EPCL highway (DF-095).

Located in the City of Estrutural in Brasília, with just under 2 km², the landfill is bordered by the National Park of Brasília to the north, and to the south, with inhabited area.

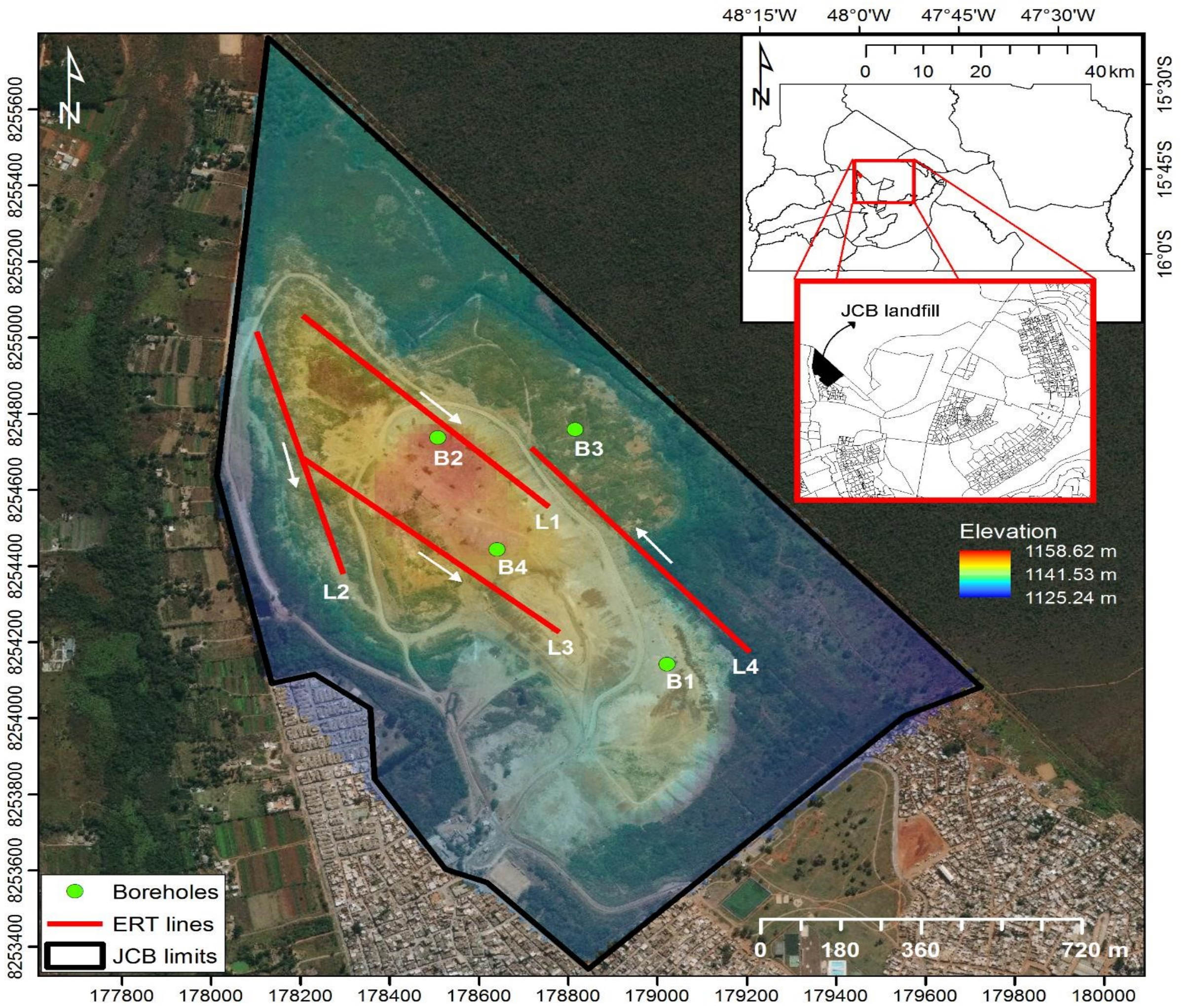

Figure 1 - Location map of the Federal District of Brazil. ERT lines and boreholes at the JCB landfill, with area elevation and the study area limits. The white arrows indicate the direction of the data acquisition.

Geologically, the JCB landfill area is in the Brasília folding range, under the slate and metarrhythmite rocks of the Ribeirão do Torto formation, Paranoá Group (Campos et al., 2013), with occurrence of saprolitic soil and dark red oxisol (Pereira et al., 1997).

Currently with its capacity depleted, the JCB landfill acts only as a rubble receiving unit. Waste at the site is believed to be mainly of domestic origin and is covered by landfill which varies in thickness and composition, with some areas dominated by construction waste.

MATERIALS AND METHODS

Recordings of four boreholes (B1 to B4) performed by Pereira et al. (1997) were used to contribute to the interpretation of resistivity models. As these direct information are today where there are embargoed areas, with difficult access or dense vegetation, the resistivity data were acquired parallel to nearby roads (Fig. 1), the most straightforward approach to avoid the heavy vehicle traffic from daily activities of the landfill.

The technique used in the investigation was Electrical Resistivity Tomography (ERT). This work analyzes the four lines acquired at the JCB landfill in 2019 (L1 to L4), in order to guide denser further acquisitions at the area. Four different electrode arrays were used: Wenner (WN), Wenner-Schlumberger (WS), dipole-dipole (DD) and pole-dipole (PD).

As all ERT lines are not precisely positioned upon the boreholes, it is assumed, for the purposes of correlating direct and indirect information, that there is not a strong variation in the topography of the bedrock. Lines L1 and L3 are approximately 30 and 75 m away from B2 and B4, respectively. The most distant correlation is between L4 and B1, around 150 m apart; however, the objective in this case is to identify the decreasing thickness of the landfill layer south of the area. Correlation between B3 and L4 is ignored, due to the trapezoidal shape of the resistivity section, which does not present enough information at that extremety point. Prior to starting data acquisition, sequences were created for each electrode array with the Electre II software (IRIS Instruments), which set the parameters for field data acquisition. Table 1 presents the configured parameters. The approximate depth of investigation is defined by the variation of specific internal parameters from the geometric factors of each array used (Edwards, 1977). The acquisition system used was the resistivimeter Syscal Pro (IRIS Instruments). After field acquisition, data stored in the equipment's memory was transferred to the Prosys II software (IRIS Instruments). Observed resistivity values greater than twice the standard deviation of the data were removed during filtering process. Table 2 presents statistics of all arrays in all survey lines after filtering.

The Wenner array acquisitions required the least time during data reading, followed by Wenner-Schlumberger, dipole-dipole, and pole-dipole arrangements, respectively. The correlation between the amount of data measured and the acquisition time is evident, so that the greater the number of measurements performed, the longer the xequipment was observing. In addition, the pole-dipole arrangement, by requiring the placement of a remote current electrode, which is a limitation of the arrangement, set an additional time, since the placement of this extra electrode made the fieldwork logistics more complex.

Table 1 - Sequence configuration parameters for each array: dipole-dipole (DD), pole-dipole (PD), Wenner (WN) and Wenner-Schlumberger (WS).

Parameter	Arrays			
	DD	PD	WN	WS
No. of steel electrodes	72	73	72	72
No. of data	1636	1705	828	1216
Line length (m)	710	710	710	710
Voltage (Vab)	400	400	400	400
Injection time (ms)	250	250	250	250
Approximate depth of investigation (m)	80	120	120	120

The filtered data was exported to the Res2DInv software input format. For the interpretation of the data, both available inversion methods were used for comparison: robust inversion, or L1-norm (Loke et al., 2003) and smooth-constrained least squares inversion, or L2-norm (Loke & Dahlin, 2002). The data was inverted using, for the most part, the standard software inversion parameters, with vertical to horizontal leveling filter ratio equal to 0.5, to highlight horizontal structures, and grid size model equal to the actual spacing between the electrodes. The residual values of the models presented for the L2-norm and L1-norm inversions were given as root mean square errors (RMS) and absolute, respectively (ABS).

Table 2 - Statistics of each line with minimum, maximum, mean ± standard deviation (STD), median no. of observed data, acquisition time and % of data loss after filtering.

Line	Array	Minimum	Maximum	Mean ±STD	Median	No. of data	% of data loss	Acquisition time (min)
1	DD	0.45	687.73	28.95 ± 54.58	12,23	1497	8.5	57
	PD	0.15	220.83	9.4 ± 14.19	6.58	1595	6.45	60
	WN	3.96	58.67	14.34 ± 7.92	11.18	805	2.78	36
	WS	0.16	305.38	16.37 ± 19.63	10.95	1174	3.45	51
2	DD	0.73	1125.01	42.08 ± 87.79	14.5	1424	12.96	55
	PD	0.29	278.8	14.26 ± 22.38	8.07	1619	5.04	56
	WN	0.92	212.62	21.54 ± 23.72	14	786	5.07	32
	WS	0.71	303.89	22.03 ± 26.52	13.86	1151	5.35	48
3	DD	0.25	1122.03	30.44 ± 75.16	9.49	1463	10.57	57
	PD	0.35	267.94	25.57 ± 30.26	15.95	1619	5.04	59
	WN	1.99	53.49	15.05 ± 9.65	11.53	801	3.26	32
	WS	0.23	535.18	19.86 ± 34.48	11.77	1168	3.95	47
4	DD	0.45	218.34	23.24 ± 18.63	18.7	1608	1.71	50
	PD	1.53	136.46	35.36 ± 21.15	31.74	1704	0.06	52
	WN	8.1	140.47	39.47 ± 30.58	27.22	828	0.00	30
	WS	1.69	168.24	41.52 ± 35.28	26.75	1216	0.00	44

RESULTS AND DISCUSSION

The predominance of low resistivity values, evident in the frequency distributions in Figure 2, suggests the strong presence of conductive material in the composition of the landfill. This is probably caused due to the high influence of leachate generated by the decomposition of organic waste.

The inverted sections of line L1 are shown in Figure 3. Borehole B2 is used to mark the dimensions of the top of soil and bedrock.

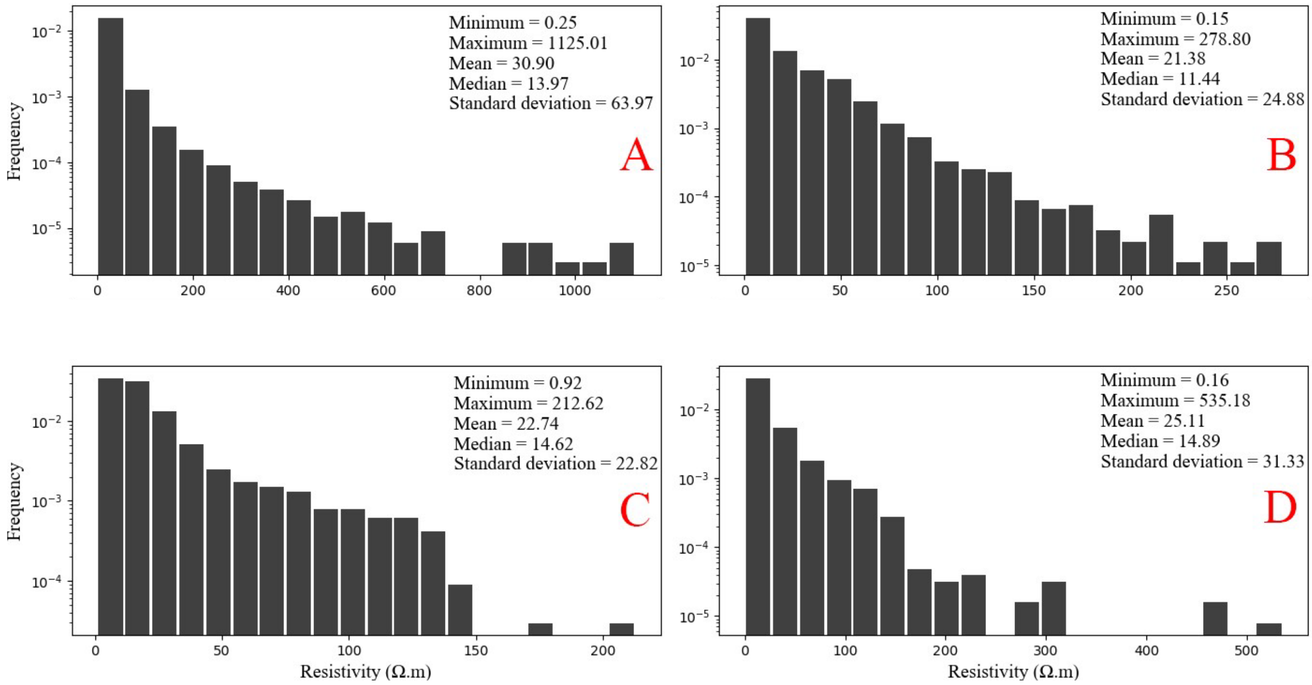

Figure 2 - Histograms of the grouping of all distributions of filtered data. A) All dipole-dipole acquisitions; B) All pole-dipole acquisitions; C) All Wenner acquisitions; D) All Wenner-Schlumberger acquisitions.

All sections suggest a large zone of low resistivity in the body of the landfill, between 5 and 20 Ω.m, with more conductive localized portions smaller than 5 Ω.m. Such portions are possibly correlated with subsurface leachate. The L2-norm inversion of the DD array presented an irregularly shaped area of higher resistivity that approximates the surface between 200 and 300 m along the profile. In the image of the L1-norm inversion, this area was smoothed and presented more satisfactory horizontal features to represent the geometry of the geology. With direct information from the borehole, the soil starts at approximately 1124 m and the rock at 1105 m. None of the arrangements returned a noticeable contrast between the waste and the beginning of the soil. It is possible that due to the long period of landfill operation, the soil level is contaminated, assuming low resistivity values in relation to the expected resistivity for the region oxisols (Cavalcanti et al., 2014). The PD array images did not correspond to the expected resistivity values for the bedrock, while the WN and WS array images pointed to higher resistivity horizontal zones at higher depth than expected. The sections obtained with the DD array presented greater coherence with the expected level for the bedrock, in relation to the other array configurations. The beginning of the bedrock layer is estimated at 44 m depth with resistivity values between 30 and 40 Ω.m, which Indicates the beginning of a probably unsaturated zone.

Such low resistivity contrast associated with the bedrock may be related with structural features of the rock, such as fractures and faults, which would corroborate with the infiltration of the contaminant over the years. A similar situation was discussed by Chambers et al. (2006).

The disposal of solid waste in the studied area occurred between 1977 and 1993 (Orrego, 2013). Most recent disposals occurred mainly in the upper portion of the landfill, where the ERT lines do not have significant coverage. Thus, the decomposition of organic waste and leachate production has been going on for over 40 years. With this large interval of time, it is possible that the contaminant infiltration has reached the rock level, causing the resistivity values to drop.

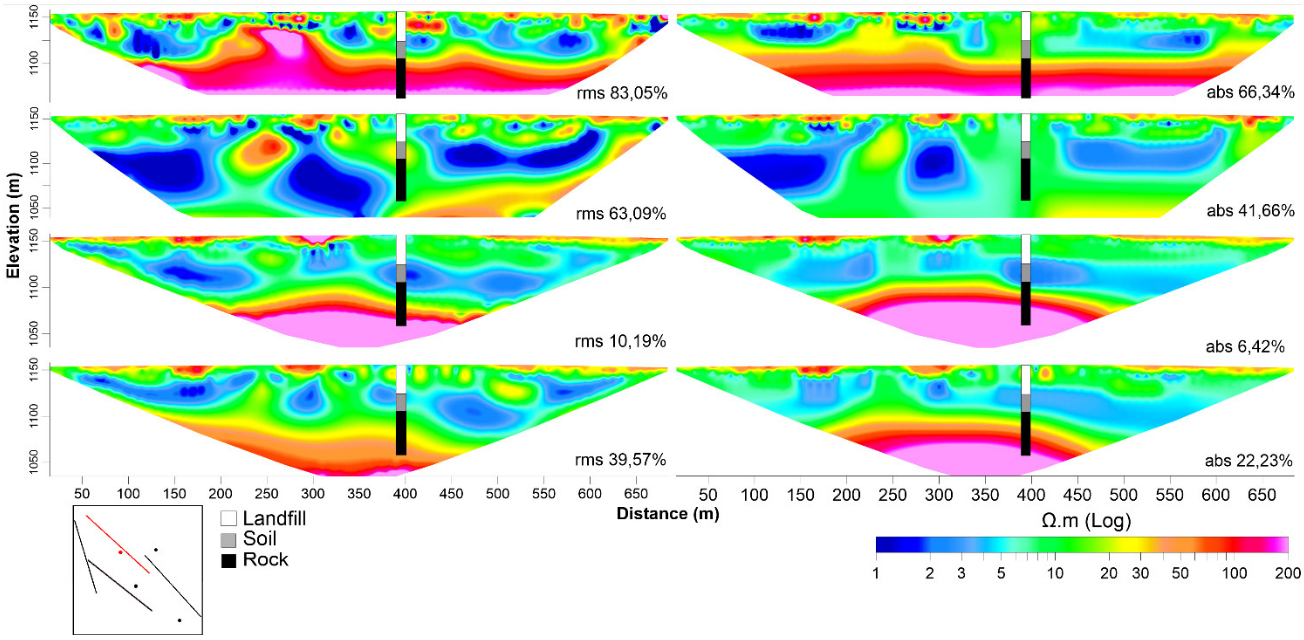

Figure 3 - Comparison between resistivity sections for line L1 obtained with the four arrangements, with borehole B2. On the left, the sections after inversion by the L2-norm method, with errors in RMS; and to the right, sections after inversion by the L1-norm method, with absolute errors.

The sections of line L2 after inversion are shown in Figure 4. Due to their positioning, none of the boreholes could be correlated with the models.

All sections indicated a surface resistive layer between 70 and 200 Ω.m, possibly corresponding to the gravel and soil deposited on the surface of this region. However, the predominantly conductive character of the waste mass is still represented in all images. As in the L1 line, inverted models with the PD arrangement could not point to high resistivity contrasts at greater depths. Images from the WN and WS arrays also suggest deeper resistive horizontal features than those indicated by the DD arrays, which delimited the higher resistivity horizontal contrasts at lower depth. Again, the L1-norm inversion models indicated more horizontal and smoothed features than the L2-norm, noted mainly in the DD, WN, and WS models. It is possible that the rock level is better represented in inverted models with DD array, at an average depth of 50 m, between 30 and 40 Ω.m (unsaturated zone boundary).

The inverted sections of line L3 are shown with borehole B4 in Figure 5. The inverted models in the DD array, especially with the L2-norm inversion, showed localized circular high resistivity portions at intermediate depths, also suggested in the L1-norm inversion in the PD array. Pockets of low resistivity were observed in all models, as well as the predominantly conductive character of the waste mass in all images. All arrangements were able to delineate higher resistivity horizontal features at high depths. From the boreholes, the soil starts at approximately 1124 m and the rock at 1101 m.

Again, none of the arrays showed a relevant contrast between the buried waste and the beginning of the soil. The L2-norm inversion in the DD array also suggests an irregularly shaped high resistivity anomaly that approaches the surface between 350 and 500 m along the profile. However, in the L1-norm model the anomaly is smoothed, which corroborates best for a rock geometry. The arrangements WN and WS were also able to delimit horizontal features of high resistivity, but the inverted models do not satisfactorily correspond to the rock level obtained by the boreholes. However, the models of the PD array suggested a horizon of high resistivity (> 100 Ω.m), well horizontal and close to the rock level. The DD arrangement also corresponded well to direct rock level information, at approximately 50 Ω.m, at a depth of 45 m, again showing good coherence in demarcating the contrast between the materials at depth.

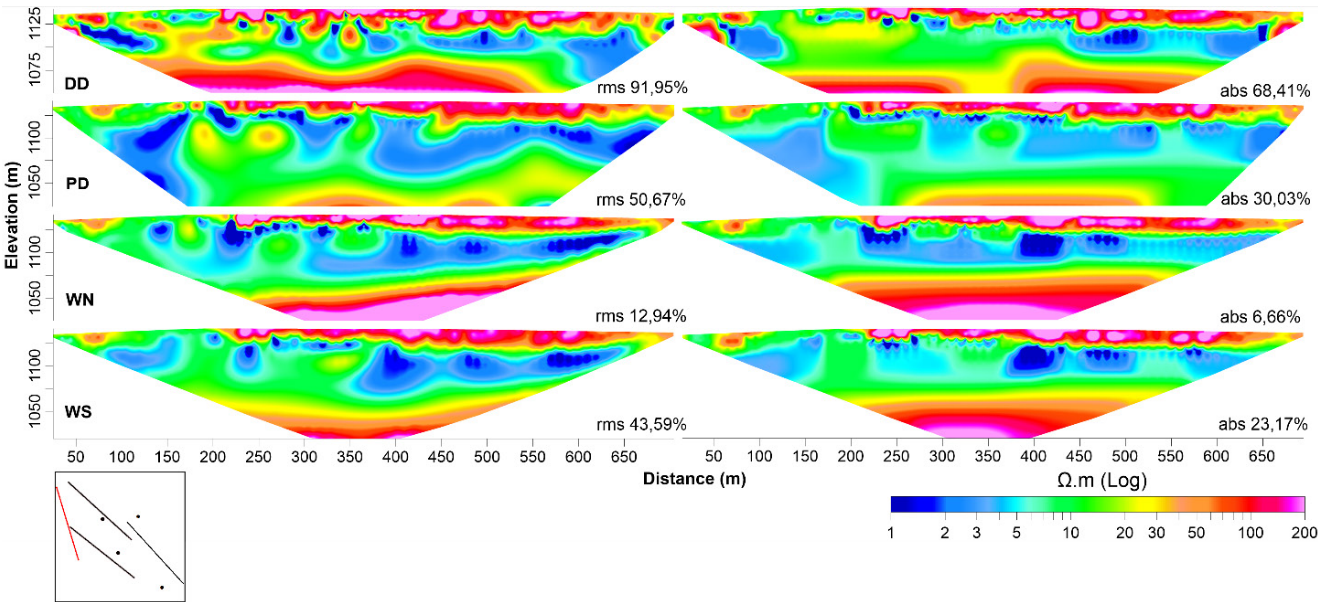

Figure 4 - Comparison between resistivity sections for line L2 obtained with the four arrangements. On the left, the sections after inversion by the L2-norm method, with errors in RMS; and to the right, sections after inversion by the L1-norm method, with absolute erros.

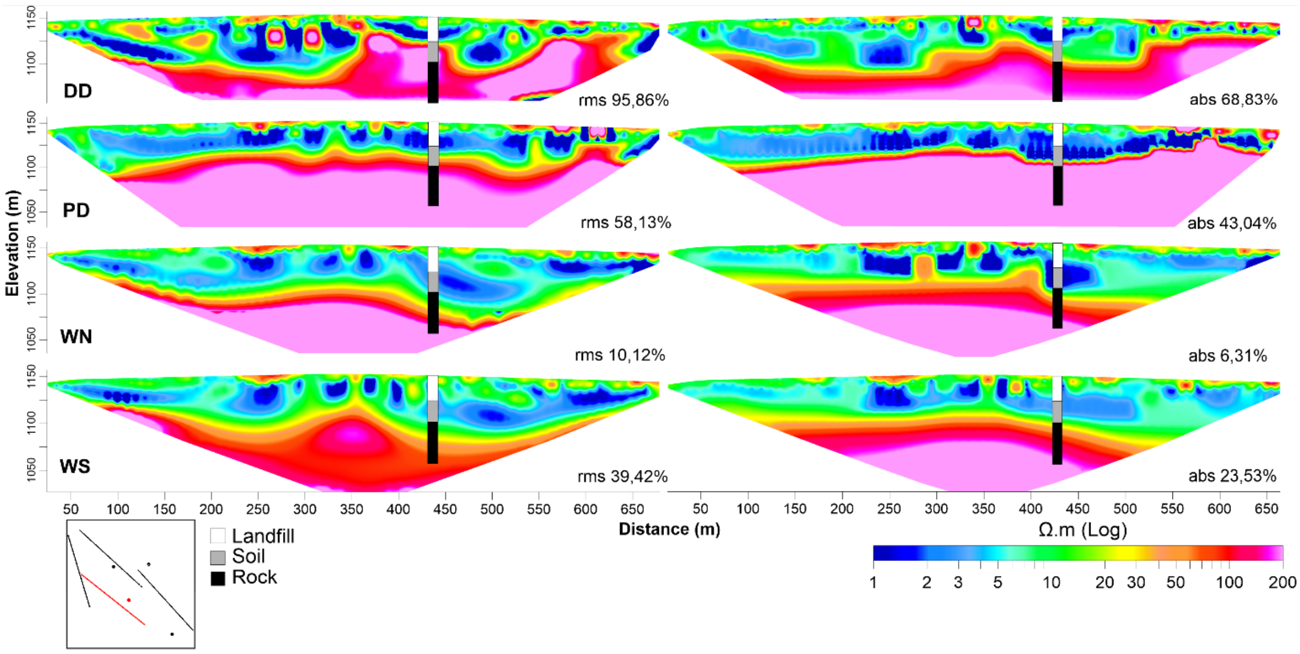

Figure 5 - Comparison between resistivity sections for line L3 obtained with the four arrangements, with borehole B4. On the left, the sections after inversion by the L2-norm method, with errors in RMS; and to the right, sections after inversion by the L1-norm method, with absolute errors.

The inverted sections of line L4 are shown with borehole B1 in Figure 6. The DD, WN and WS arrays presented a slope with higher homogeneity of low resistivity in the left portion of the profile. However, this feature does not occur in models obtained with the PD array, where there is an irregular lateral continuity in the horizontal zone of high resistivity. Some small high surface resistivity anomalies can also be noted in the PD array model. The PD models suggested a horizontal continuation of conductive points not shown in the other arrays, between 1 and 5 Ω.m. From the

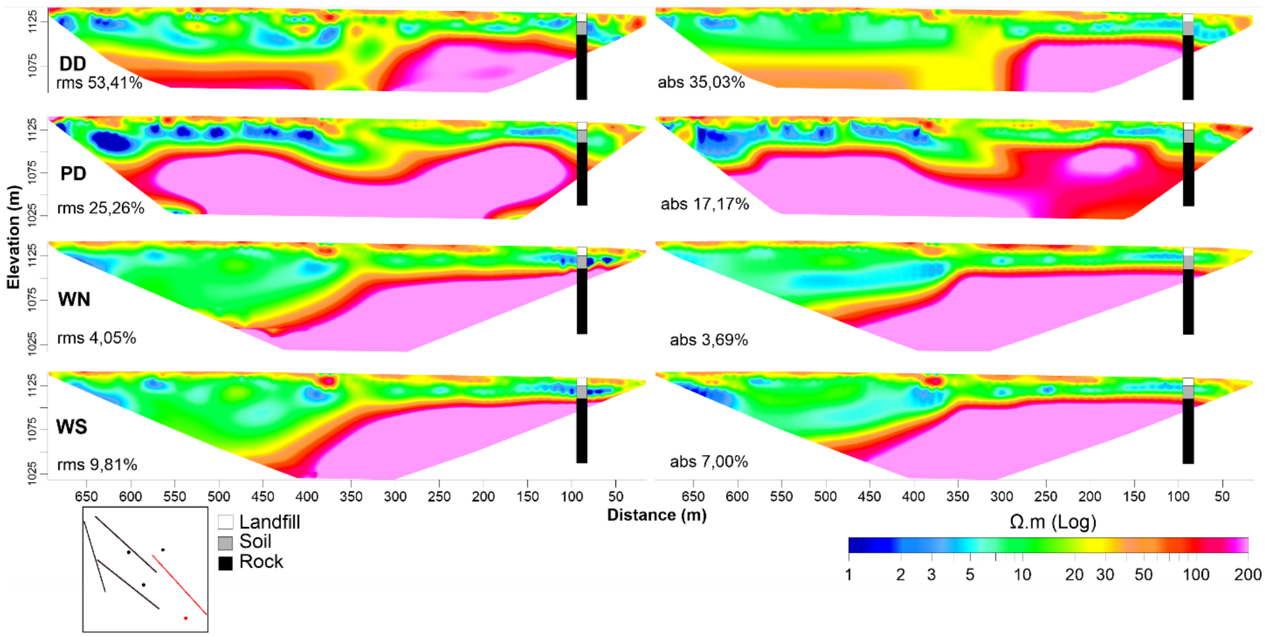

Figure 6 - Comparison between resistivity sections for line L4 obtained with the four arrangements, with borehole B1. On the left, the sections after inversion by the L2-norm method, with errors in RMS; and to the right, sections after inversion by the L1-norm method, with absolute errors.

boreholes, the soil starts at 1125 m and the rock at 1110 m. Again, none of the arrangements showed a satisfactory contrast between the waste and the beginning of the soil. All sections showed a considerable correlation with rock level at approximately 25 m depth. However, it is noted hat the best matches were achieved with the arrays WN, WS and DD.

In general, robust inversion (L1-norm) provided more stable inversion models (Fig. 7), as pointed out by Zhou & Dahlin (2003) and Dahlin & Zhou (2004), smoothing out irregularly shaped anomalies and producing more horizontal features that better delimit the top of the rock level. This can be explained by robust inversion seeking to find a model that minimizes absolute values of data mismatch, while the L2-norm method seeks a smooth model that minimizes the mismatch square, being more sensitive to discrepancy in observed data (Dahlin & Zhou, 2004), which can often occur in highly heterogeneous environments, such as landfills.

Models with the smallest difference between calculated and measured apparent resistivity do not necessarily correlate with the result that best represents the reality of the environment. It is also possible that models with small differences between the observed and the calculated model may show large and unrealistic to variations in resistivity values, not always being the best representation of the geological context of the investigated area (Geotomo, 2010). Dahlin & Zhou (2004) also pointed out this observation in their analysis, where results obtained with arrays that produced smaller misfit erros, such as the WN configuration, did not always correlate well with the real geological models. In general, the most prudent approach is choose the iteration model where the reported difference does not change significantly compared to the previous iteration (Geotomo, 2010). In the inverted models in this work, this ideal iteration was always reached between the third and fifth iterations.

Among the arrays configurations used, DD presented the largest differences between calculated and measured apparent resistivity, followed by PD, WS and WN, respectively. This behaviour is in accordance with the comparison between electrode arrays of Dahlin & Zhou (2004), which reported a higher signal to noise ratio with results obtained with the WN array, while the results obtained with DD and PD usually produced larger missfit erros for most

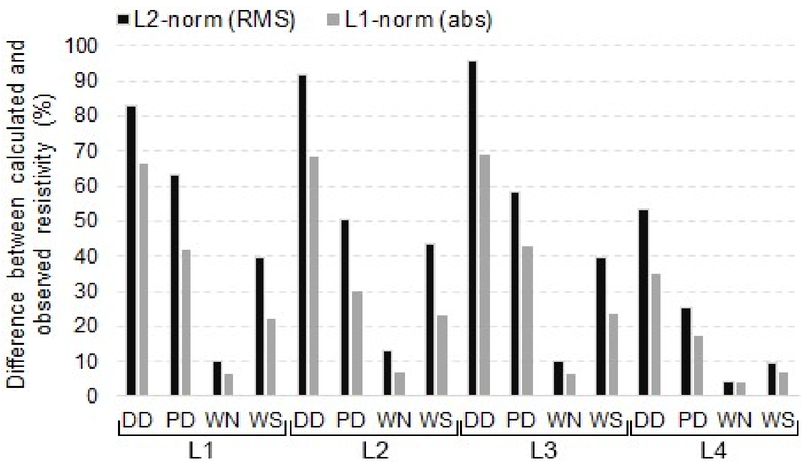

Figure 7 - Misfit errors for models inverted by L1-norm and L2-norm methods for all ERT lines and all array configurations.

studied cases. For data-quality control, it is often convenient to display the data as profiles with the same median depth of investigation (Dahlin & Zhou, 2006). In this processing step, it was noted that apparent resistivity values observed at greater depths, with DD and PD arrays, had a lower signal to noise ratio than points measured at more superficial levels. This behavior can be correlated with the loss of the received signal with increasing the value of n in the geometric factor of these arrays during data acquisition. The further apart the electrode pairs are (*i.e.*, the deeper the investigation level) the smaller the signal will be with such configurations (Borges, 2007).

The amount of observed data used (Table 2) in each arrangement might also be related with the RMS and ABS errors calculated for inverted models. It is possible that the increase in the number of measurements may cause an increase in the minimal misfit obtained by inversion, since a larger amount of highly heterogeneous observations, expected for landfills, may bring instability to the inversion of the data matrix. However, reducing the quantity of resistivities observed during measurement, to speed up the field acquisition process or to look for minor model adjustment errors, reduces imaging resolution, which may compromise research quality. In addition, a high data density makes information loss due to ignored electrodes and points with high ground contact resistance to be less severe, so as not to significantly impair the quality of the inverted model (Dahlin & Zhou, 2006).

CONCLUSIONS

A comparison between electrical resistivity models developed at the former JCB landfill with four different electrode arrays was discussed. Boreholes information were used to corroborate the interpretation of the sections and evaluation of the resolution.

The L1-norm inversion provided more stable and smoothed models than the results obtained with the L2-norm. It is likely that the large amount of heterogeneous observations in matrix inversion may have caused an increase in the minimal misfit calculated. The predominance of low resistivity values for all models was evident. This was probably caused due to the high influence of leachate generated by the decomposition of organic waste.

The best agreement with the direct information regarding the level of the bedrock was achieved with the dipole-dipole array. The Wenner and Wenner-Schlumberger arrays, although able to delimit deep, high resistivity horizontal features, did not satisfactorily match the rock level on most lines. On line L3, the pole-dipole arrangement showed a considerable correlation with the rock level, but failed to suggest high resistive horizons on most lines.

It was not possible to identify the resistivity contrast in any of the models concerning the soil level from direct information, probably due to the long period of leachate flowing between the waste and the natural soil. In general, the models suggested values between 25 and 50 m deep for the rock level at the JCB landfill. The low resistivity values, interpreted in this work as bedrock contrast (usually between 30 and 50 Ω.m) may be directly associated with structural rock features that would contribute to the infiltration of the contaminant over the 40 years of waste decomposition and leachate production at the area. Information regarding new boreholes and a denser ERT cover would provide updated information that could confirm the hypothesis of rock contamination.

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