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Electrical resistivity methods to characterize the moisture content in Brazilian sanitary landfill

Nataly Aranda · Vagner R. Elis · Renato L. Prado · Miriam G. Miguel · Mariane Alves de Godoy Leme · Bruno Conicelli · Oswaldo Guzmán

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Abstract The moisture content of the municipal solid waste (MSW) is a physical characteristic that plays a fundamental role in the stability and settlement of landfills. However, this physical index is difficult to monitor within the mass of landfilled MSW because it undergoes great variation due, mainly, to the heterogeneity and biodegradation of the waste. Brazilian MSW generally has a large amount of organic matter, that when biodegraded, generates a considerable volume of gases and fluids, aggravated by climatic conditions, such as high rainfall and temperatures. Hence, the importance of obtaining and evaluating the distribution of moisture content in the MSW mass over time. Currently, the electrical resistivity properties have been presented as an interesting approach to obtain the moisture content in landfills indirectly. This study aimed to apply geoelectrical methods as a tool to obtain and evaluate the moisture content distribution in an experimental cell of a sanitary landfill using Archie's law, which correlates the volumetric moisture content and electrical resistivity. Moisture content values were obtained in laboratory tests with MSW samples collected in two vertical holes and electrical resistivity measurements by means of vertical electrical sounding. The moisture content and the resistivity values of the samples were used to calculate the parameters *a* and *m* of Archie's law. This allowed to convert the resistivity tomography to moisture content tomography. The good correlation achieved between the moisture content calculated by Archie's law and that obtained from samples indicates that the use of electrical resistivity methods is useful to assess and monitor quantitatively the moisture content in landfills using Archie's law.

Keywords Municipal solid waste · Electrical resistivity tomography · Vertical electrical sounding · Archie's law · Moisture content

N. Aranda (✉) · V. R. Elis · R. L. Prado
Geophysical Department - Institute of Astronomy, Geophysics and Atmospheric Sciences, University of São Paulo , São Paulo, Brazil
e-mail: aranda.nata@gmail.com

N. Aranda · B. Conicelli · O. Guzmán
Universidad Regional Amazonica Ikiam , Tena, Ecuador

M. G. Miguel · M. Alves de Godoy Leme
School of Civil Engineering, Architecture and Urban Design, University of Campinas (Unicamp), Campinas, Brazil

Introduction

Worldwide, sanitary landfills are the main method of disposal and treatment of municipal solid waste (MSW). In Latin America and the Caribbean region, an increasing amount of MSW is being disposed of in sanitary landfills, many times without environmental and social controls, as exposed by Kaza et al.

(2018). As a consequence, the demand for information and research regarding efficient and safe landfill projects has also grown. In this region, MSW classified as food and pruning add up to more than 52% by mass (Kaza et al., 2018), which means that landfills constantly suffer displacements due to the biodegradation, which is accelerated by climatic conditions, characterized by high rainfall and temperatures (Paixao Filho & Miguel, 2017).

Physical characteristics such as in situ moisture content and field capacity of MSW are essential and required in landfill design due to the influence they have on the leachate pressure distribution in the waste mass and, therefore, on the magnitude and distribution of the shear strength and stress (Dixon et al., 2005). The compressibility is also affected by dynamic changes in the moisture content within the landfill. According to Matasovic et al. (2011), an increase beyond the field capacity of in situ moisture content of MSW may raise the gas and water pressures within MSW mass and compromise the landfill stability, as also contributes to change the shear strength and specific weight (Zekkos et al., 2010). Although other factors can trigger the mass's MSW instability, a high leachate level is undoubtedly one of the most important, as already highlighted by Jianguo et al. (2010).

MSW is composed of several materials that have different characteristics in terms of liquid retention and release. In addition, these different materials present different behaviors regarding degradation and, consequently, the formation of leachate and gases within the waste mass. Thus, the heterogeneity and biodegradation of MSW make monitoring the moisture content within the mass of waste quite complex and variable over time. Therefore, geoelectrical methods have been the most suitable for indirectly monitoring landfills' moisture content through electrical resistivity measures.

The methods most commonly used to find the moisture content of MSW from landfills, according to Imhoff et al. (2007), are neutron probe, electrical resistance sensors, electromagnetic techniques, electrical resistance tomography, gas partitioning markers, and fiber optic sensors, as well as holes and sample analysis. Analysis employing sensors or probes, as well as direct measurements of samples, give measures of the moisture content in a specific point but do not give the distribution of the property in the whole mass or in an extended area, which makes the use of these methods unattractive, as pointed out by Grellier et al. (2006a, b).

Within the geophysical methods used to indirectly assess the moisture content of the waste mass, measuring the electrical resistivity of the waste mass has emerged as a promising strategy (Guerin et al., 2004; Grellier et al., 2006a, b; Jianguo et al., 2010; Helene et al., 2020). The technique of electrical resistivity tomography (ERT) is one of those that provides values for large-scale distribution of the electrical resistivity of MSW and is one of the most used for being cost-effective and non-invasive (Hu et al., 2019). Nevertheless, the resistivity measures give an idea of the distribution of the moisture content instead of giving the moisture content itself.

Various geoelectrical techniques have been used in previous studies to (a) detection of landfill coverage or base system damage (Carpenter et al., 1991; Genelle et al., 2011), (b) mapping and monitoring leachate plumes and infiltrations (Feng et al., 2017; Helene et al., 2020; Melges Bortolin & Malagutti Filho, 2010; Mishra et al., 2019; Moura & Malaguetti Filho, 2003), and obtaining the moisture content using the relationship between the resistivity (ρ) and the volumetric moisture content (θ) by Archie's law fitting (Dumont et al., 2016; Feng et al., 2017; Grellier et al., 2007; Hu et al., 2019).

Obtaining a correlation between waste moisture content and electrical resistivity is challenging because Archie's law empirical parameters highly depend on the features of the waste mass and landfill conditions. Therefore, those empirical parameters vary from landfill to landfill, as pointed out by Grellier et al. (2007). In addition, Hu et al. (2019) highlight the influence of the food waste content on the moisture content and resistivity values of the MSW. The authors compared the Chinese and British MSW and observed that high food waste content implies higher moisture content and fewer resistivity values. Therefore, it is crucial to characterize the relationship between moisture content and resistivity for MSW in landfills with different properties and conditions. A few studies are found that establish this direct relationship between resistivity and moisture content within the waste mass.

This study aims to obtain the moisture content in an MSW experimental cell located at the Delta-A sanitary landfill of Campinas city, southeastern Brazil. The main objectives of this survey were to (1) establish an empirical correlation between the moisture content of waste samples and electrical resistivity data obtained by vertical electrical sounding, (2) use this empirical correlation to convert electrical resistivity tomograms into moisture content tomograms, and (3) monitor changes of moisture content into the MSW experimental cell as well as identify possible leachate pockets for 2 years.

Materials and methods

Study area

All the tests were conducted in the experimental cell built-in 2012 on the top of the Delta-A Sanitary Landfill located in Campinas city, Southeast Brazil (Fig. 1). The experimental cell occupied an area of 5080 m^2 and was filled with approximately 15,000 m^3 of municipal solid waste from Campinas city. The experimental cell was constructed according to the current concepts of landfill engineering with the following characteristics: a base system composed of 60-cm-thick compacted clayey-sandy silt layer (liner), followed by a 1.5-mm high-density polyethylene (HDPE) geomembrane and a non-woven geotextile (300 g/m^2); a leachate drainage system formed by a 30-cm-thick layer with stone and a 1.0-m-wide and 30-cm-deep drainage channel located at the base of the cell, diagonally, with a slope of 1.5%; a 5.0-m-thick compacted MSW layer with a gas drainage system constructed with five vertical section drainage tubes having a diameter of 1.5 m; and a 50-cm-thick layer of soil (conventional cover) composed of clayey-sandy silt. Further details on the construction of the experimental cell can be seen in Benatti et al. (2013).

The experimental cell was designed to receive the MSW classified as class II-A and II-B waste, according to the technical standard NBR 10,004 (ABNT, 2004), which includes non-hazardous inert and non-inert wastes. The waste composition of this cell is approximately 47.3% organic materials, 12.9% paper, 13% plastics, 1.2% metals, 1.9% glass, 1.9% debris, 0.9% wood, 5.3% diapers and sanitary pads, and 15.6% other materials (Miguel et al., 2016).

At the time this study was conducted, the experimental cell MSW had already been confined for 6 years, and it was in the phase of methanogenic anaerobic biodegradation, according to Paixao Filho and Miguel (2017) and Manzatto and Miguel (2019), which analyzed the physical and chemical variables of leachate generated in the experimental cell.

The Delta-A sanitary landfill is located in a humid subtropical climate area, characterized by generally dry and mild winters and rainy summers with warm to hot temperatures. The landfill is located on rocks of the Itararé Subgroup, composed of mudstones with rhythmic intercalations of sandstones in the lower portion and siltstones in the upper portion.

Geophysical surveys and data processing

The geophysical survey applied was the resistivity method, which consists of measuring the potential generated at the surface when artificially generated electric currents are introduced into the ground. By measuring the potential difference and the applied current, it is possible to calculate the resistivity or its inverse, the conductivity of the soil (Kearey et al., 2013). In this study, we used two types of procedures for the resistivity surveys, the electrical resistivity tomography (ERT), and the vertical electrical sounding (VES).

Four ERTs were performed over 3 years in different weather seasons, and the vertical electric soundings were performed just before drilling and sampling the boreholes used to perform the cross-hole seismic test described in Aranda et al. (2019). The location of ERT and VES is presented in Fig. 1. The central points for the VES were located in the position where boreholes 1 and 2 were drilled.

ERT

The ERT is used to determine 2D variations of resistivity. The current and potential electrodes are maintained at a fixed separation and progressively moved along the profile. This technique is used to detect localized bodies of anomalous conductivity as in the case of contamination plumes by leachate. The apparent resistivity obtained from ERT is subjected to a data inversion process to obtain the real resistivity of the terrain. Figure 2 shows a schematic of the ERT procedure using the dipole–dipole electrode configuration applied in this study. As the

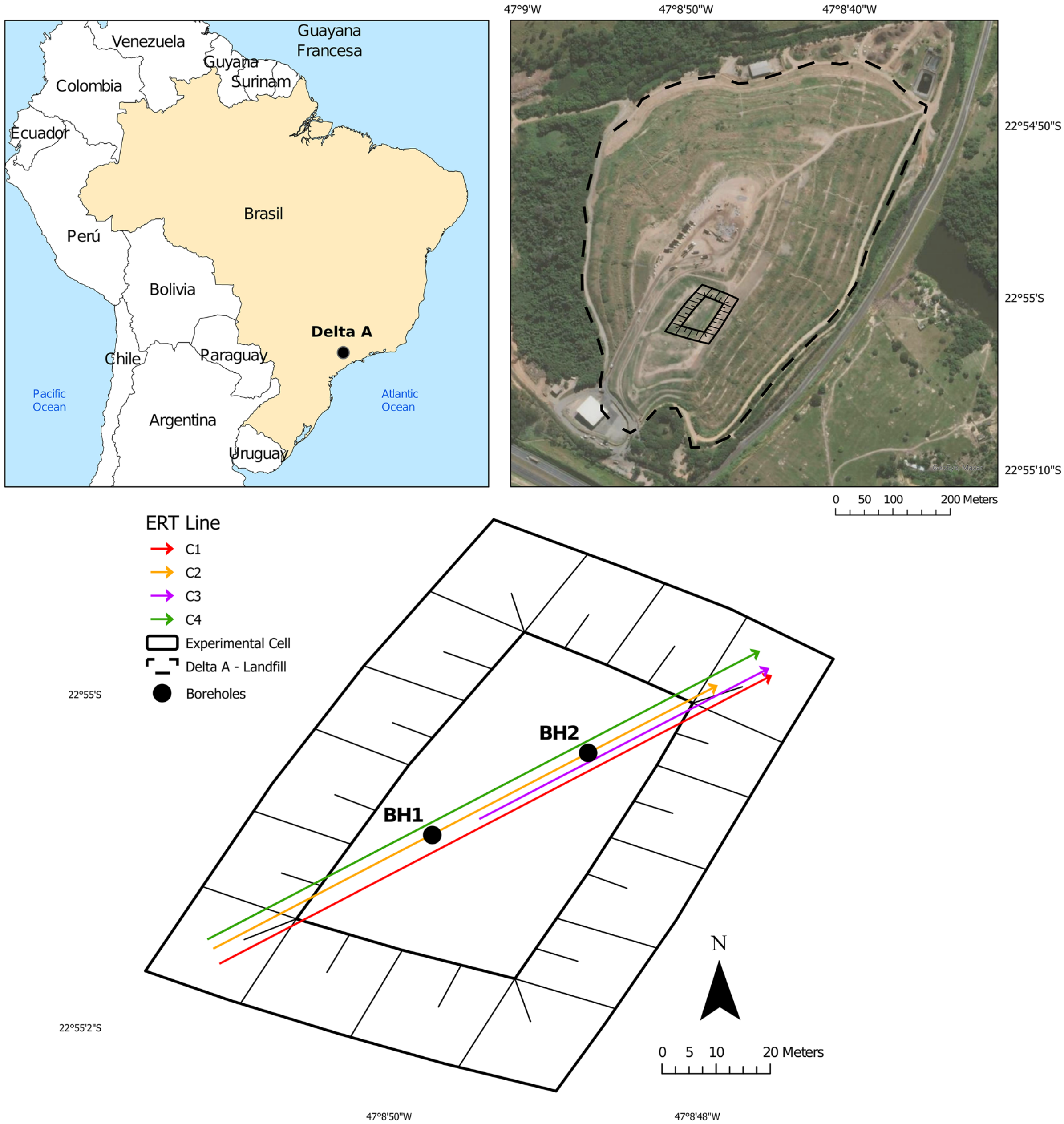

Fig. 1 Up experimental cell (landfill) location on the Delta-A landfill in Campinas-SP in Brazil (UTM coordinates—zone 23S/WGS84). Down: experimental cell, acquisition line, and boreholes locations; ERT surveys were implemented along the red line starting at the same point and with lengths as follows: C1—115-m length, C2—105-m length, C3—60-m length, and C4—115-m length. The two VESs were centered into borehole 1 (BH1) and borehole 2 (BH2), respectively

objective of the work was to investigate variations in moisture content within the waste mass, it was chosen the dipole–dipole array. Due to the heterogeneity of components in the waste deposits, lateral variation in moisture content and the presence of leachate pockets are common. The dipole–dipole array has an excellent lateral resolution, and according to Dahlin and Zhou (2004), this array allows obtaining reliable well-resolved images. These authors concluded this by means of numerical

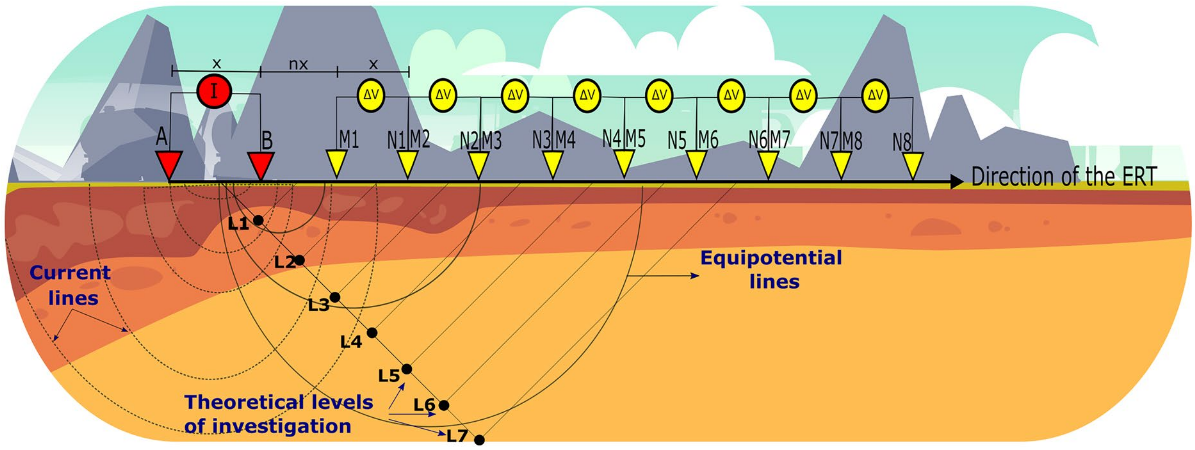

Fig. 2 ERT measurement using the dipole–dipole electrode configuration

2D acquisition simulation with several electrode arrangements and evaluation of its advantages and limitations, considering the sensitivity to noise and anomaly effects.

Four ERT surveys (C1 to C4) were performed from August 2015 to September 2017, after periods of rain and drought in Campinas, Southeast Brazil, as observed in Table 1. All of the ERTs were conducted on the largest diagonal of the experimental cell area (Fig. 1). The ERT line is over the drainage channel and in the same direction as the leachate follows to the collection box.

For the ERT surveys, it was used the Syscal-Pro (for C1 and C2) and Syscal R1 + Elrec Pro (for C3 and C4) equipment with non-polarizable electrodes. It was employed the dipole–dipole electrode configuration for the acquisition (Fig. 2), with nine potential electrodes (MN) and two current electrodes (AB), spacing 2.5 m. Table 1 shows the parameters and model errors for each acquisition.

The ERT data were inverted using the RES-2DInv software (Loke, 2000), which enables different approaches for the inversion process to obtain the resistivity model from the apparent resistivity. The first one is the smoothness-constrained Gauss–Newton least-square inversion technique (L2 norm), the second combines the smoothness-constrained method with the Marquardt-Levemberg, and finally, the L1 norm or robust inversion method, which modifies the formulation of the smoothness-constrained method so that different elements of the model parameter change and data misfit vectors have the same magnitudes (Loke & Dahlin, 2002). The robust inversion is better for heterogeneous soils in which there are sudden changes in the resistivity values, as is the case of MSW.

Data from the four acquisitions were processed following the same steps and parameters in order to simplify the comparisons and interpretations of temporal variations, and all of them included the topography and were processed using robust inversion.

Table 1 Surveys and model parameters

Survey	Acquisition date	Length	RMS model error (%)
C1	August, 2015	115	6.3
C2	May, 2016	105	6.9
C3	April, 2017	60	3.4
C4	September, 2017	115	6.3

Vertical electrical sounding

The VES is used in the study of horizontal interfaces or with up to 30% slope of the layers. The current and potential electrodes gradually extend around a fixed central point. This technique is used to determine strata thicknesses and to define horizontal areas of porous strata (Kearey et al., 2013), as well as to determine changes of resistivity in-depth (the aiming in this study). Fig. 3 shows the Schlumberger electrode configuration for the VES method used for this study. This electrode configuration was selected because it is less susceptible to interpretive errors due to lateral heterogeneities (Orellana, 1972; Telford et al., 1990),

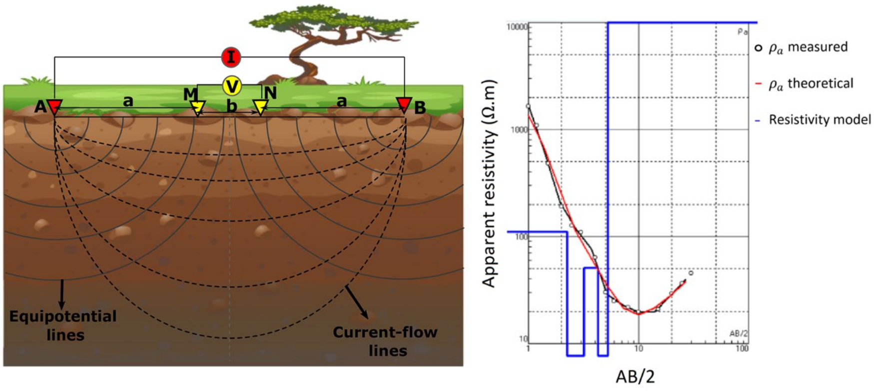

Fig. 3 Left: VES measurements with Schlumberger electrode configuration. Right: example of an electrical resistivity section from VES

which is the case of the MSW landfill. The theoretical depth achieved by this technique is AB/4, with AB being the distance between the current electrodes.

In the processing of the VES data, the resistivity values are plotted against the aperture values (AB/2 for the Schlumberger array) using a logarithmic scale, providing the apparent resistivity curves, which are interpreted quantitatively.

The vertical electric sounding was performed in order to correlate the resistivity and the moisture content through Archie's law of the samples taken of the boreholes BH1 and BH2. The VES acquisitions were performed in May 2018 (in the dry season) just before drilling the boreholes into the experimental cell.

The location of the central point for two VES can be seen in Fig. 1, in the same position where the samples boreholes were subsequently drilled. The electrode spacing (AB/2) used ranges from 1 to 60 m. The equipment used was the Syscal R1 with non-polarizable potential electrodes. The VES data were processed and analyzed using the free software IPI-2win from Moscow State University used for 1D VES interpretation (Shevnin & Modin, 2003).

Resistivity and moisture content correlation

The resistivity data were obtained by the vertical electrical sounding. Subsequently, the MSW was drilled and sampled in the same area where the VES was performed. The MSW samples were analyzed in the laboratory to obtain the moisture content. Finally, the correlation between the resistivity and the moisture content using Archie's law was obtained.

Archie's law

The correlation between the electrical resistivity and the moisture content was done through Archie's law simplified for MSW by Grellier (2005), where the volumetric moisture content (θ) replaces porosity and saturation, which are difficult to measure in MSW, the relation is:

$$\rho = a\rho_1\theta^{-m} \tag{1}$$

where ρ is the interpreted electrical resistivity, ρ_1 is the electrical resistivity of the leachate, θ the volumetric moisture content, and a and m are empirical parameters. For general cases, Archie (1942) proposed values for m around two and values for a varying between 0.6 and 2, with $a < 1$ for intergranular porosity (which is the case of MSW) and $a > 1$ for fractured porosity.

The electrical conductivity of the medium (and then the resistivity) is also affected by the temperature. For MSW, Grellier (2005) and Grellier et al. (2006), Grellier et al. (2006) validated the correlation between the temperature and electrical conductivity experimentally, finding that the conductivity increases by 2% as each degree of temperature increases as follows:

$$\sigma_{\mathrm{Tref}} = \frac{\sigma_{\mathrm{med}}}{1 + 0.02\left(T_{\mathrm{med}} - 25\right)} \tag{2}$$

where σ_{Tref} is the temperature corrected at 25 °C, and σ_{med} and T_{med} are the conductivity and temperature measured in situ, respectively.

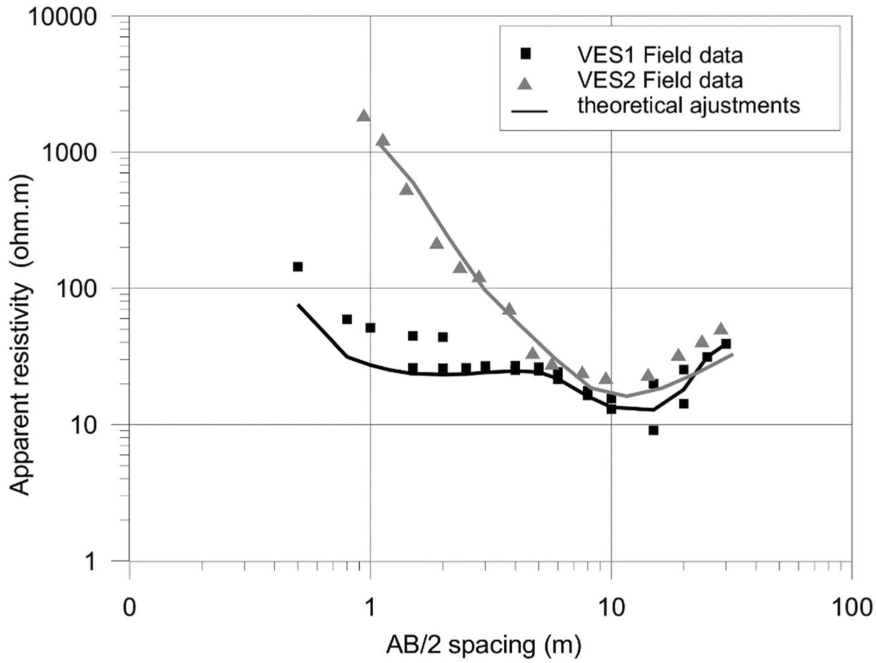

Fig. 4 Results and interpretation of VES 1 and VES 2 using IPI2win software

MSW sampling and laboratory measurements

The two boreholes were drilled and sampled using a 10-in external diameter hollow stem auger. The MSW samples were collected every 0.5 m from the top to 3-m depth using a split barrel sampler. The maximum depth of the boreholes was 3 m to avoid any damage to the bottom, geomembrane, and geotextile of the experimental cell. The waste temperature was measure in situ as the samples were obtained and immediately inserted and sealed in a plastic bag for further laboratory analysis.

For the moisture content analysis, firstly, each sample was placed in a paper bag and weighed on a precision scale, and then it was dried in the oven at 60 °C for 15 days. Afterward, the dry mass of each sample was weighed. The mass of the liquid in the sample (m_w) was determined by subtracting the dry mass and the wet mass (m_t) of the sample.

The gravimetric moisture content W_w was determined by Eq. (3):

$$W_w = \frac{m_w}{m_t} \tag{3}$$

To correlate the moisture content with the resistivity of the MSW through Archie's law (Eq. (1), the volumetric moisture content (θ) defined by the relationship

Table 2 Interpretation of VES 1 and VES 2

VES 1				VES 2			
Layer	Thickness (m)	Resistivity (Ωm)	Interpretation	Layer	Thickness (m)	Resistivity (Ωm)	Interpretation
1	0.181	229	Cover layer	1	0.477	3225	Cover layer
2	1.51	22.3	Wet soil + waste	2	1.76	110.6	Dry waste + soil
3	1.47	43.2	Dry waste	3	0.92	4.24	Leachate + waste
4	1.74	1.75	Leachate + waste	4	1.09	51.2	Dry waste
5		5000	Cell bottom	5	1.01	2.26	Leachate + waste
Error = 11.2%				6		10,000	Cell bottom
				Error = 13.7%			

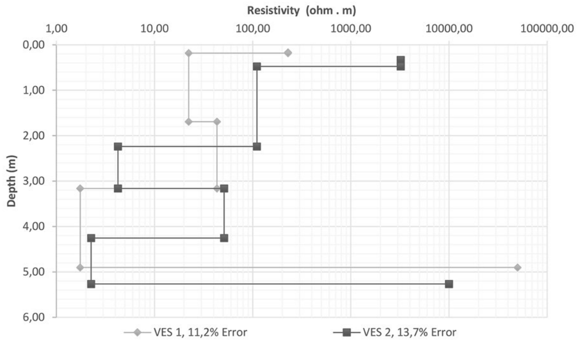

Fig. 5 Resistivity profiles obtained for VES 1 and VES 2

between the volumes of the liquid phase (V_w) and the wet sample (V_t) is required. The following equation relates the volumetric and gravimetric moisture contents:

$$\theta = \frac{W_w D_t}{D_w} \quad (4)$$

where D_w is the specific mass of the water or leachate ($D_w = 1000\,\mathrm{kg/m^3}$), and D_t is the specific mass of the wet sample.

The gravimetric moisture content was calculated using Eq. (3) after the measure of the sample dry mass in the laboratory. The volumetric water content was calculated using Eq. (4), where the specific mass of the wet sample used was $\rho_s = 622.4$ kg/m^3, and this value was calculated as the correlation between the speed of the S wave and the specific weight, which is detailed in Aranda et al. (2019).

Results and discussion

Resistivity and moisture content correlation—Archie's law

VES

The data of the VES were processed and analyzed using the IPI2win software. Fig. 4 shows the model obtained, and Table 2 its interpretation. The errors obtained for each profile are of the expected magnitude, knowing that MSW is a heterogeneous material with high moisture content contrary to the commonly found in geological materials. For VES 1 (located at BH1 position), it was recognized five layers. At 3-m depth is a low electrical resistivity anomaly, associated with high leachate content. For VES 2 (located at BH2 position), it was recognized six layers. Two low resistivity anomalies were identified associated with high leachate content: at 2.2 m, probably due to the presence of leachate pockets, and at 4.3 m due to the liners at the bottom.

The apparent electrical resistivity profiles are presented in Fig. 5. The VES 1 and VES 2 reach maximum depths of 4.9 m and 5.3 m, respectively. The resistivity behavior for VES 1 and VES 2 is very similar, showing high resistivity in the cover layer (mineral cover) and decreasing with depth. Those low resistivity values at the bottom of the experimental cell are expected and correlated with the saturated zone. The VES 1 profile has lower resistivity values than the VES 2 profile's resistivity values, probably due to the higher moisture content in the VES 2 location.

Table 3 Measure of moisture content made in the laboratory on waste samples for boreholes 1 and 2. The temperature was taken in situ for each sample when collected

Sample depth (m)	Borehole 1				Borehole 2			
	Temperature (°C)	Ww (%)	Θ (%)	Composition	Temperature (°C)	Ww (%)	Θ (%)	Composition
0.5	22	15	9	Soil	25	8	5	Soil
1.0	24	18	11	Soil + waste	25	12	8	Soil + waste
1.5	25	20	12	Soil + Waste	26	56	35	Waste
2.0	29	23	15	Waste	31	28	17	Waste
2.5	29	27	17	Waste	30	69	43	Waste
3.0	30	62	38	Waste	35	85	53	Waste

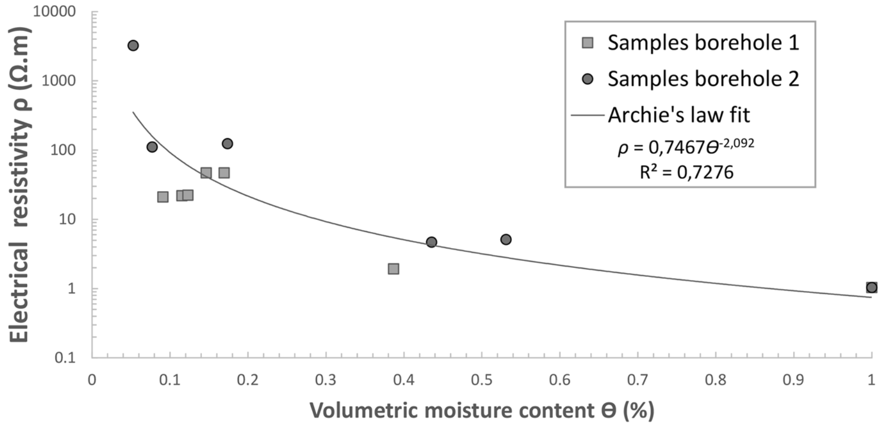

Fig. 6 Relationship between the electrical resistivity determined by VES and the volumetric moisture content of the samples collected in two boreholes of the experimental cell in the Delta-A landfill

Laboratory measurements

The gravimetric and volumetric moisture content found are given in Table 3. For borehole 1, the material is unsaturated up to 2.5-m depth increasing the moisture at 3-m depth. For borehole 2, the waste is unsaturated up to 1 m, and the volumetric moisture content increases at 3-m depth up to 53% of water.

Resistivity and moisture content correlation

In order to derive Archie's law (Eq. (1)) for the MSW in the experimental cell, the electrical resistivity was corrected according to the temperatures obtained in situ by Eq. (2). The corrected resistivity values were then plotted as a function of volumetric moisture content (Fig. 6). The resistivity and moisture content data were fitted in the Gnuplot software using the fit function, which uses the non-linear least-square (NLLS) Marquardt–Levenberg algorithm (Racine, 2006). The data were fitted to a potential function of the form $n\,\theta^b$, and the n and b parameters were estimated. The empirical correlation between electrical resistivity and volumetric moisture content through Archie's law obtained is given by $\rho = 0.7467\ \theta^{-2.092}$, with coefficient of determination of 0.73. To convert the fitted equation into Archie's law form was necessary to calculate the leachate electrical resistivity as the average of resistivity values measured at four piezometers in the experimental cell, obtaining a leachate resistivity $\rho_1 = 1.03\Omega$m. Therefore, the estimated Archie's law for the MSW for the experimental cell is:

$$\rho = 0.725 \times 1.03 \times \theta^{-2.092} \quad (5)$$

where $a = 0.725$ and $m = 2.092$. The values for a and m found here are in the expected range and in agreement with Archie (1942), who indicated values for $a < 1$ for intergranular porosity, which is the case of MSW. An additional data point corresponding to the leachate resistivity was added to the field data to improve the correlation, assuming a resistivity of 1.03Ωm for 100% volumetric moisture content.

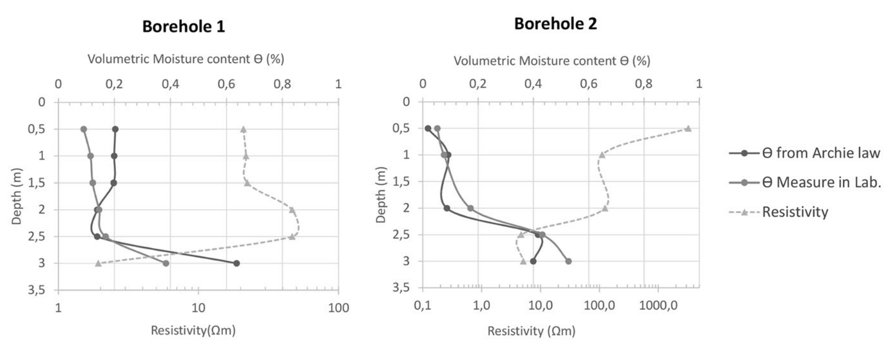

Fig. 7 Variations in depth of the measure and calculate the volumetric moisture content θ (%) and resistivity for boreholes 1 and 2

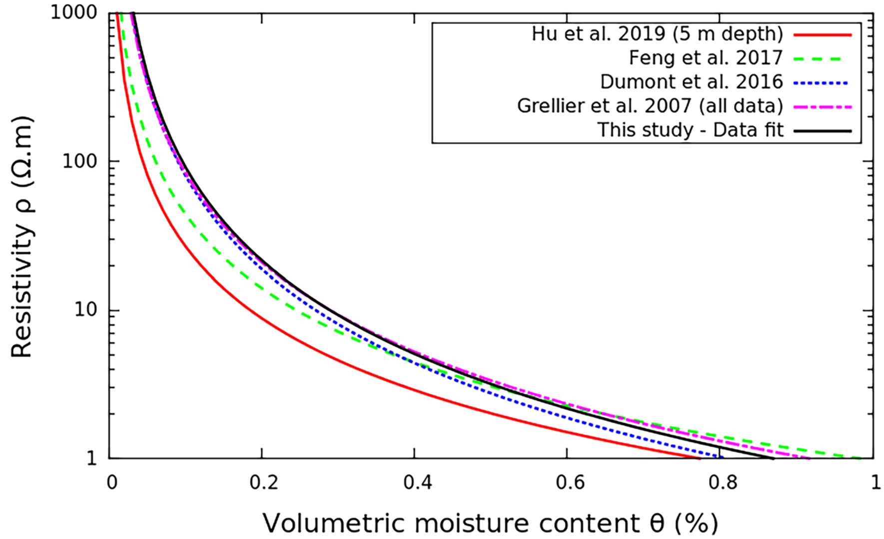

Fig. 8 Relationship between the electrical resistivity and the volumetric moisture content of this study and others

Figure 7 shows the depth variation of the resistivity and volumetric moisture contents obtained in laboratory and by Archie's law (Eq. 5) for both boreholes. A good correlation between the measure volumetric moisture content and the one calculated from Archie's law is observed. For borehole one, the correlation between moisture contents is 0.92, while for borehole, two is 0.97. It is also observed an inverse relationship between electrical resistivity and moisture content as expected. Besides, there is a general trend of increasing the moisture content with depth observed in both boreholes. For BH1, the most significant differences noticed between Archie's law's moisture content and the samples are 25% for 3-m depth and 11% for 0.5-m depth, and for BH2 is 12% for 3-m depth data. In general, the difference between the volumetric moisture contents from Archie's law and the lab is about 6%, which is a reasonable estimate.

A comparison between the electrical resistivity and volumetric moisture content correlation for this and other studies is in Fig. 8. The maximum volumetric moisture content for Hu et al. (2019) was 60%, Feng et al. (2017) was 68%, Dumont et al. (2016) was 42%, and 40% for Grellier et al. (2006), Grellier et al. (2006). For the experimental cell, the maximum volumetric moisture content measured was 53%. The parameters a and m obtained in this study and others are listed in Table 4.

Resistivity and moisture content tomograms

Electrical resistivity tomography results

The ERT data were acquired in the period between August 2015 to September 2017. The VES acquisitions and drills were made in May 2018.

Figure 9 shows the measured electrical resistivity tomograms obtained in the experimental cell. Due to some equipment issues, the first part of the C3 line (Fig. 1) was not recorded correctly, and C3 starts from 50 m of lateral position.

In the ERT tomograms, the geomembrane at the experimental cell base is easily identified by resistivities greater than 40 Ωm. Higher resistivity values at the top of the profiles are associated with the covering layer composed of sandy-clay silt. In the middle of the tomograms, the MSW layer is characterized by intermediate resistivity values; areas with higher and lower moisture content in the MSW layer are clearly identified with resistivity changes. Low resistivity

Table 4 Archie's law fitted values between this study and others

Study	a	m	ρ
Hu et al. (2019) (first 5-m depth)	0.87	1.61	0.76
Feng et al. (2017)	0.81	1.66	1.20
Dumont et al. (2016)	1.53	2.10	0.42
Grellier et al. (2007)	0.70	2.00	1.20
This study	0.73	2.09	1.03

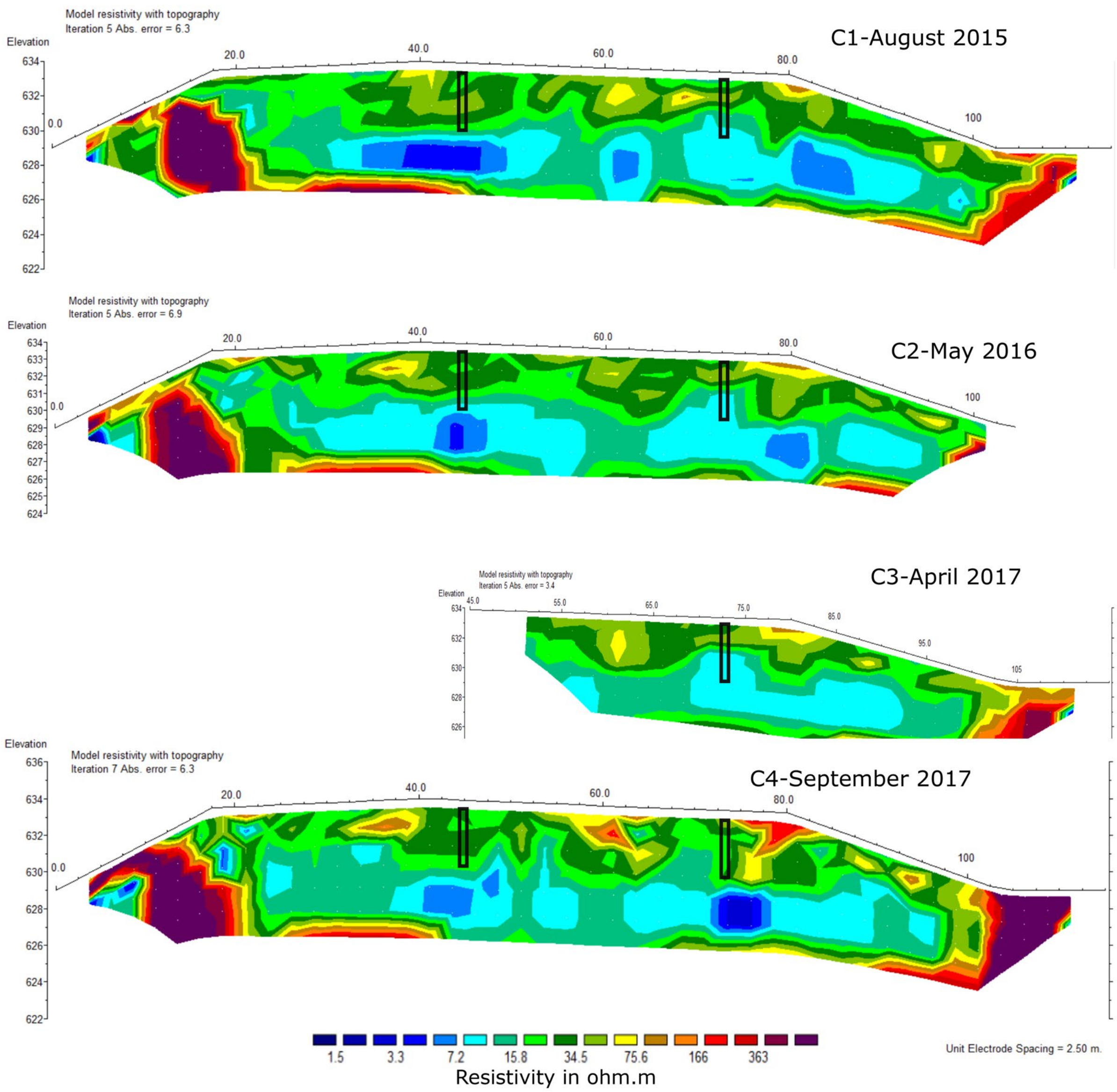

Fig. 9 Comparison of resistivity profiles C1 to C4. Profiles C1 to C4 were obtained along the ERT line (Fig. 1) with lengths as follows: C1—115-m length, C2—105-m length, C3—60-m length, and C4—115-m length. The location of the two boreholes drilled in May 2018 is presented with black rectangles, BH1 at 42 m and BH2 at 74 m

values (represented in blue) are associated with high moisture content, while high resistivity values (represented in green and yellow) are associated with low moisture content.

It is evident a trend of increase in resistivities over time. In the C4 profile, on average, the lowest resistivities are above 7.2 Ω*m*, which are higher than the lowest values observed in C1, C2, and C3 profiles. This behavior is expected, attributed to the biodegradation evolution, which leads to a decrease in moisture content, an increase in inert particles, and a change in porosity due to the stress suffered over time. According to Hu et al. (2019), the increase in inert particles due to longer degradation increases the resistivity if compared with organic matter. However, between 70 and 80 m of lateral position in C4 profile, there is a low resistivity anomaly that did not exist in the previous profiles.

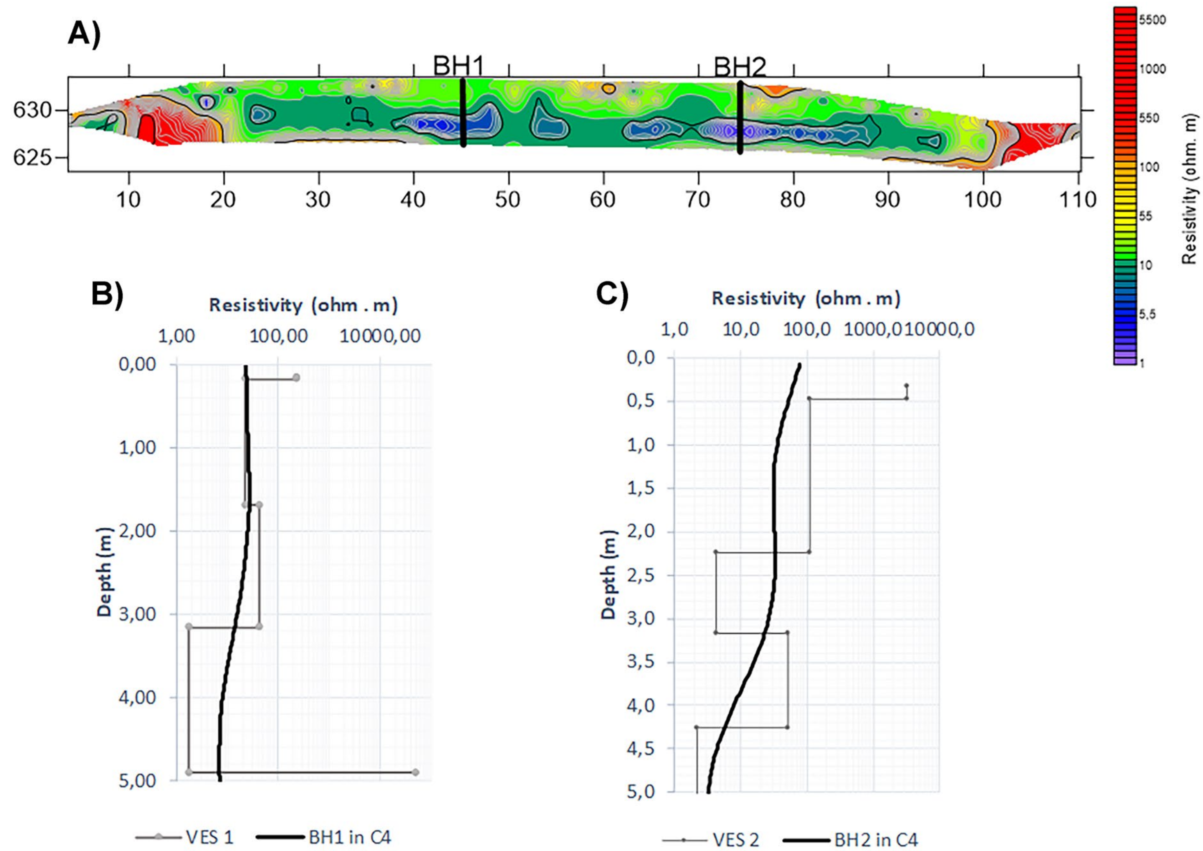

Fig. 10 **a** Electrical resistivity tomography C4. BH1 and BH2 represent the position in which boreholes one and two were later drilled. **b** Comparison of resistivities values of the VES1 and ERT C4 in the location of borehole 1. **c** Comparison of resistivities values of the VES2 and ERT C4 in the location of borehole 2

This anomaly might be produced by an accumulation of leachate in this area.

Moisture content tomography

To get information about the moisture content spatial variation over time in the experimental cell, we converted the ERT into moisture content tomograms using the empirical Archie's law (5). Resistivity data were transformed into volumetric moisture content and then into gravimetric moisture content to finally plot it using the Surfer software.

Figure 10 shows a comparison between the resistivity profiles obtained with VES 1 and 2 and the resistivity profiles at the same locations obtained from ERT-C4. In both cases, the resistivity varies between the same ranges and present similar behaviors. This behavior allows us to use the correlation obtained from Archie's Law to convert resistivities into moisture content for the ERT tomograms.

The gravimetric moisture content tomograms estimated from Archie's law are presented in Fig. 11. All the moisture content tomograms reveal the waterproof base, characterized by very low moisture content, which is also proof of the geosynthetic waterproof layer's excellent performance. This waterproof base well performance indicates that the waste is in an ongoing drainage process so that the moisture content contained in the waste must be due to field capacity, and variations in moisture content may be due to the biodegradation process or to weather conditions on each geophysical survey.

The maximum gravimetric moisture contents for each profile were 123% for C11, 171% for C2, 95% for C3, and 84% for C4. The average moisture contents for each profile were 34.6% for C1, 35.9% for C2, 34% for C3, and 33.9% for C4. These results show that C2

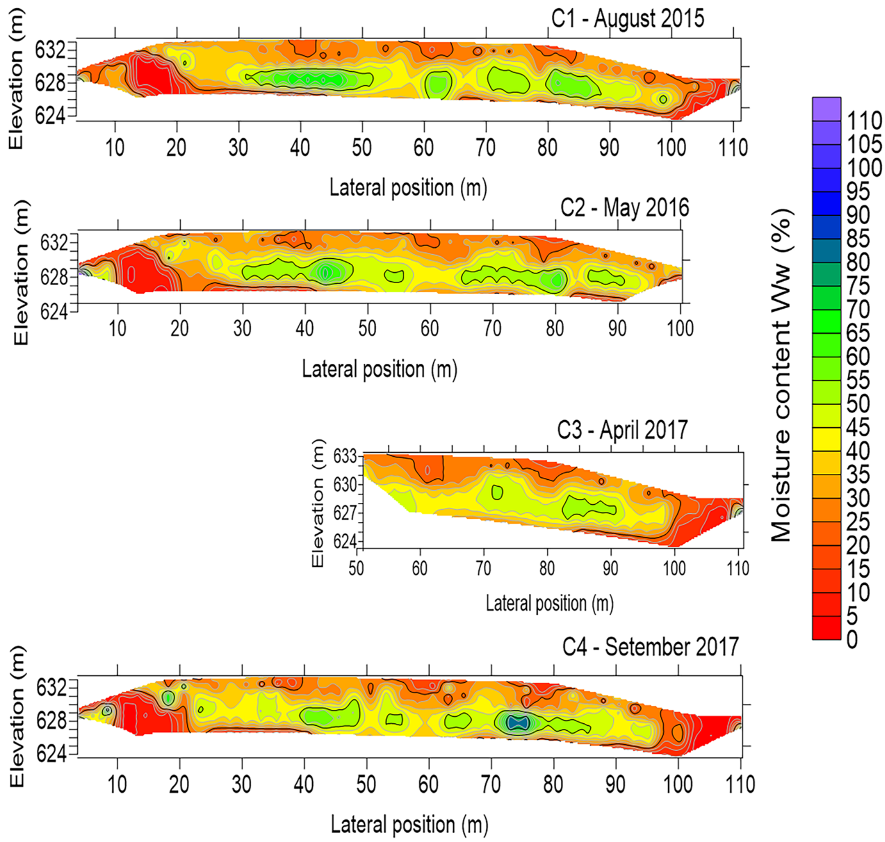

Fig. 11 Comparison of gravimetric moisture content profiles C1–C4

tomography has the highest moisture content, being 1.2% higher than the average of all profiles.

Due to gravity, it is expected the area with the highest moisture content of the experimental cell be the base of the cell. The ERT profiles were made on the line of the drain channel in the direction that the leachate is drained; so, in all the profiles, we observe a higher concentration of moisture content at the base of the cell, which is a signal of the correct operation that this drainage layer is having.

In this deepest layer, it is also evident a decrease in the average moisture content over time. However, between 70 and 80 m in C4 profile appears a high moisture content anomaly, which is also visible in the ERT C4 with a low resistivity anomaly. This moisture content anomaly is probably due to an accumulation of leachate in this area because the C4 profile was obtained at the beginning of the rainy season. Nevertheless, this anomaly was confirmed by the samples from BH2 (obtained eight months later of C4 profile), with high moisture content close to saturation for depths between 2.5 and 3 m (see Table 3). A previous study developed in the same experimental cell by Moretto et al. (2017) also showed a leachate pocket in the same area, confirming that this is a leachate accumulation zone, and it is more reliable in C4 profile because it was obtained during the rainy season.

Profiles C1–C3 were obtained during the dry season, while C4 was obtained at the beginning of the rainy season. We could expect that, during the dry season, the moisture content of the MSW decreases, and the resistivity increases. Nevertheless, this expected behavior was not observed in this study. The first three profiles show, in general, lower resistivities and higher moisture content in contrast to the obtained for the C4 profile. This behavior may be because, over time, the biodegradation has decreased and, therefore, the average moisture content. It suggests that the effect of the climate conditions is not as significant as biodegradation over time. However, a more detailed analysis is necessary to conclude this effect on MSW resistivity and moisture content.

Conclusions

The present study demonstrated that it is possible to estimate the moisture content distribution from electrical resistivity data through Archie's law relationship for sanitary landfills located in humid subtropical areas and characterized with high organic content, which is the case of Delta-A sanitary landfill in Campinas city, Southeast Brazil.

The two empirical parameters $a = 0.725$ and $m = 2.092$ of Archie's law were determined using the electrical resistivity measure in situ and the moisture content (measure in the laboratory) from MSW samples obtained from two boreholes drilled in the experimental cell. It was obtained a suitable correlation ($R^2 = 0.73$) between the moisture content measure from Archie's law and the measure directly from the samples.

Using the characterized Archie's law, we converted four electrical resistivity tomograms into moisture content tomograms of the experimental cell. In these profiles, changes in moisture content over time were evident. Also, it was possible to check the excellent condition of the geomembrane liner and correct operation of the drainage layer, evident by the low moisture content under the waterproof base and by the absence of gaps.

The results obtained here indicate that the effect on the moisture content of the climate conditions is not as significant as biodegradation over time. For 2 years of analysis, the experimental cell's average moisture content decreased, and no significant influence of weather was observed.

Finally, an anomaly of low resistivity and high moisture content was identified in C4 profile, and it was confirmed with samples and by a previous study. In conclusion, that area is prone to the accumulation of leachate or water in the rainy season.

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