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Original paper

Electrical resisitivity to detect zones of biogas accumulation in a landfill

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Resumen

El biogas producido en rellenos sanitarios puede ser una fuente importante de energía en el futuro. Este gas, constituido por CH_4, CO_2 y vapor de agua, se forma por la descomposición de materia orgánica. Una de las limitaciones técnicas en la planeación de sistemas colectores de este gas es la forma de estimar la producción de metano en un relleno dado. En este trabajo se evalúa la relación entre el flujo de biogas medido en drenes de un relleno sanitario en Brasil con la resistividad eléctrica del material de relleno. La medición en perfiles con el método de Tomografía de Resistividad Eléctrica (TRE) y su inversion a modelos 2D de resistividad muestra una clara correlación entre zonas de alta producción de biogás con áreas de alta resistividad en profundidad. Estos resultados sugieren la posibilidad de usar el método de TRE como una herramienta diagnostica en la colocación de drenes de extracción de biogas en rellenos sanitarios..

Palabras clave: energía, metano, materia orgánica, tomografía de resistividad eléctrica (TRE).

Abstract

Biogas produced in sanitary landfills consists in a potential source, formed by degradation of organic matter, this gas is constituted by CH_4, CO_2 and water vapor. Sanitary landfills represent important depository of organic matter with great energetic potential in Brazil, although presently with inexpressive use. Estimates for production or maintenance of productive rates of CH_4 represent one of the main difficulties of technical order to the planning and continuity of collection systems for rational consumption of this resource. Electrical resistivity measurements are routinuously used in profiling oil wells for the determination of levels with accumulations of oil and gas, facing the contrast among fluids and rocks. This paper aims to evaluate eventual relationship among biogas flow quantified in surface drains of a waste cell in landfill, with characteristic patterns of in depth electrical resistivity. The integration of Electrical Resistivity Tomography (ERT) lines allowed for the generation of 3D blocks and a clear distinction among zones of high biogas production, quantified in surface drains, with areas of high resistivity in depth. The results suggest the possibility of use of the method in studies to place drains in areas promising to the collection of biogas for energetic generation in sanitary landfill.

Key words: energy, methane, organic matter, electrical resistivity tomography (ERT).

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Introduction

The use of renewable resources as a source of clean and sustainable energy gains increasing importance internationally, facing growing energy demands driven by population growth and improved quality of life in developing countries (Smill, 2008). This demand causes inflation in prices of major energy sources like petroleum and coal, as well as increased rates of emission of greenhouse gases (EIA, 2014).

This scenario stimulates the search for alternative energy sources that go from expressionless features to options with growing importance. Renewable sources such as biomass are environmentally sustainable and technically viable, either for direct generation of electricity and heat, or conversion to methane production (IEA, 2011).

Biogas is a natural form of biogenic matter formed from the conversion of biomass through the action of a group of microorganisms when metabolically active (Wellinger *et al*., 2013). This product consists in a gas mixture resulting from the anaerobic degradation of organic matter contained, for example, in landfill solid waste and industrial waste and wastewater. In this context, this substrate represents the available biomass for fermentation (Themelis & Ulloa 2007).

In this scenario, the landfills have significant relevance as depository of large amounts of substrate capable of conversion into biogas (Nozhevnikova *et al.*, 1993; Deublein & Steinhauser 2008). The biogas from landfill has on average between 45% and 55% methane, the major flammable gas and of potential energy use, besides varying amounts of carbon dioxide and water vapor (Tchobanoglous *et al*., 1993; Kjeldsen *et al*., 2002; Xiaoli *et al*., 2010)

The planning of capture plants and energy use of biogas in landfills is initiated by feasibility studies that consider the market for commercialization of energy, infrastructure required for generation and distribution of energy and the potential for methane production of the desired area (Deublein & Steinhauser, 2008; Wellinger *et al*., 2013). This last item depends on estimates of the volume of substrate with potential for conversion into biogas, besides the analysis of physicochemical conditions about the favorability to the process (Manna *et al*., 1999; Kumar *et al*., 2004; Talyan *et al*., 2007; Kamalan *et al*., 2011; Pawtowska, 2014).

The extraction of biogas has a series of vertical wells distributed in various locations of the landfill, which may be constructed as layers of waste disposal are placed, in a system of ramps and soak or subsequently drilled at the end of waste discharge operations (Christensen *et al*., 2011; Pawtowska, 2014). Alternative systems consist of horizontal pipes installed at various depth levels, during the waste disposal, interconnected to horizontal systems.

In any of these systems, efficiency in biogas collection is determined by the permeability of the landfill covering material and the mass of waste (Christensen *et al*., 2011). In the first case, the use of low permeability materials such as clay soils or membranes enables increased efficiency of the collection system in the wells in face of minimizing points of release to the atmosphere.

The second case, as the waste setting occurs by compacting, consumption of organic material or variations in moisture content, occurs a large variation in permeability in the mass of waste, conditions that can generate or eliminate zones of biogas accumulation. At this moment, the application of diagnostic methods to the accumulation of biogas in landfills can provide a substantial increase in the efficiency of the collection system, with the drilling of wells in new areas of accumulation and elimination of points of low biogas flow or contamination by the input of atmospheric oxygen.

The geophysical gathers a group of indirect methods of investigation, some of which are sensitive to the physical properties characteristic to areas of accumulation of gases in the subsurface. This tool is widely used in studies of environmental diagnosis in cases such as investigation of contaminants in soil and groundwater from landfills (Ustra *et al*., 2011; Belmonte-Jiménez *et al*., 2012; Moreira *et al*., 2013; Moreira *et al*., 2014).

Although there are several studies that describe the use of geophysical methods in environmental diagnosis of landfills, most of these works mainly focus on the characterization of the area with percolation of leachate. However, few studies aim to determine relationships among electrical resistivity, natural electrical potential, biological, and physicochemical processes and their relationship to the production of leachate and biogas in landfill (Georgaki *et al*., 2008; Moreira *et al*., 2011).

In this sense, the present study evaluates the potential application of DC Resistivity as a tool for characterization of areas with accumulation of biogas, by means of measurements of electrical resistivity in unsaturated waste layer and crossing with direct measurements of the flow of biogas, in a deactivated waste cell at the landfill in the municipality of Rio Claro (Brazil).

Materials and methods

Study Area

The area of studies consists of landfill of solids residues of the municipality of Rio Claro, São Paulo State, Brazil, distant about 180km from the state capital (Figure 1). The beginning of activities dates from 2001, in an area of approximately 98,000m^2 destined for disposal of solid waste, with a daily average of 190 tons and a monthly average of 5,000 tons. In July 2012, the landfill was expanded by the installation of a new cell, currently in use.

The area presents a relief with gentle slope and descending towards the northeast, consisting of sandy soils and sandy clay soils produced by alteration of sandstones belonging to the Rio Claro Formation, covered by siltstones and mudstones gathered in Corumbataí Formation.

The construction scheme of the landfill comprises the local topography and consists of opening individual cells with 200m long and 50m wide, for the excavation of rock types from Rio Claro Formation and from the top of Corumbataí Formation from northeast to southeast direction, with gradients of about 1% to northeast. The landfill has basal and side impermeabilization sealing with a blanket of HDPE 2mm thick. A network to collect and drain the leachate leads the flow by gravity to the terminal boxes, and then to aeration lagoons for treatment.

The waste is dumped directly into cells by tipper trucks of urban collecting, later leveled to horizontal landings by action of bulldozers, daily covered by soil/sediment stored after excavation of the cell, with plastic, rubber, paper and other materials are distributed randomly, together with organic matter (Figure 2A). At this stage, vertical drains are installed for plumbing and atmospheric dissipation of biogas generated by the decomposition process of organic matter in waste, constantly alternated as new levels are built.

The final level is covered by a layer of about 1m of soil/clay pellet, with a slope of 2% for surface water runoff (Figure 2B). Dikes marginal to the limits of the upper level are

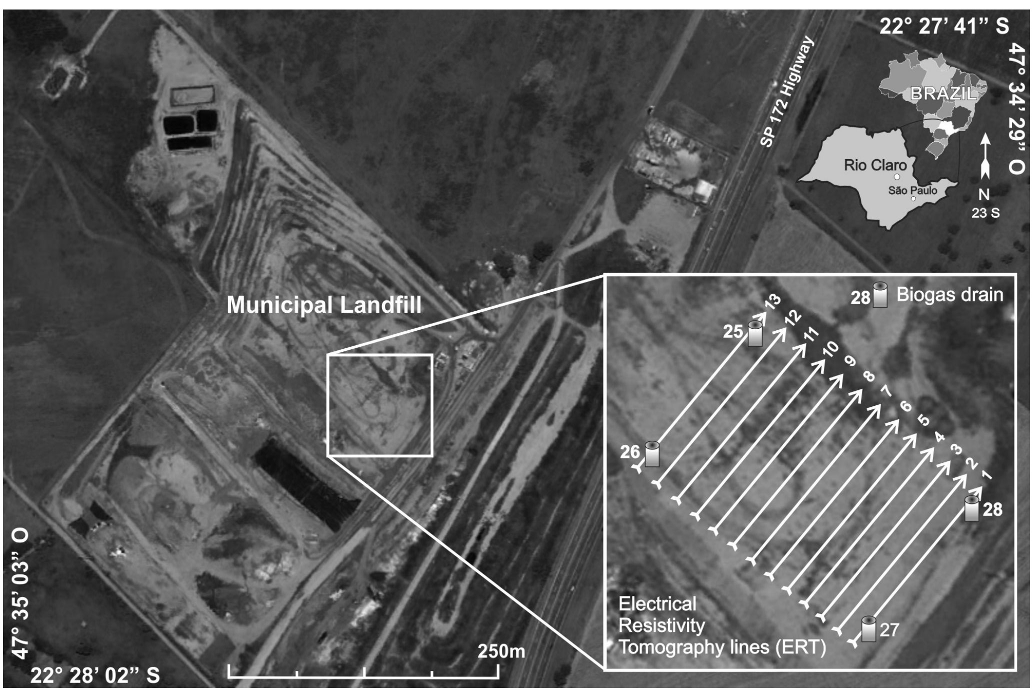

Figure 1. Location of the area of studies with position of the lines of data acquisition and drains for measuring the flow of biogas.

built, to direct the flow of rainwater by laminar flow and attenuation processes of lateral erosion (Figure 2C). Drains are ended by steel tubes coated by concrete pipes for burning biogas and dissipation of the generated heat (Figure 2D). Drains are constantly lit for consumption of the biogas by burning in an attempt to prevent accumulation in large scale and minimize the risk of explosion.

Relevant aspects in generating biogas at landfills are represented by forms of packaging waste and operational procedures, content of organic matter in the overall composition of the residue, which can stimulate anaerobic processes. The moisture content is something crucial to the development and metabolism of bacteria, such as agent to transport the nutrients and as a facilitator for colonization of new areas within the landfill scope (Deublein & Steinhauser, 2008; Christensen *et al*., 2011). These factors, combined with physic-chemical conditions, temperature and access to nutrients, directly influence the survival of microorganisms and biogas generation.

The understanding of the genesis of biogas enables some important considerations on the action of processes of anaerobic degradation of organic matter and their effects on physical properties change in the mass of waste.

Biogeochemical reactions are initiated immediately after the coverage of waste in landfills. Organic compounds are oxidized in aerobic processes in shallow locations where aeration is by contribution of atmospheric oxygen or infiltration of rainwater, similar to combustion reactions, generating CO_2 and water vapor, both quickly dissipated (Pohland & Gould, 1986).

However, the effect of chemical and biological processes is enhanced by anaerobic digestion in three main stages (Themelis & Ulloa, 2007). At first, there occurs hydrolysis of complex organic matter by the action of fermentative bacteria in soluble molecules. Then, these molecules are converted into simple organic acids such as acetic acid, propionic acid, butyric acid and ethanol, besides CO_2 and H_2. In the third stage the generation of CH_4 by methanogenic bacteria, by breaking acids in CH_4 and CO_2 or by the reduction of CO_2 and H_2 occurs.

This exothermic reaction for anaerobic decomposition releases a small amount of heat and produces a gas with average levels of 54% CH_4 and 46% CO_2. The biogas produced in landfills also contains water vapor near the saturation point, and small amounts of NH_4, H_2, H_2S and other minor constituents. The

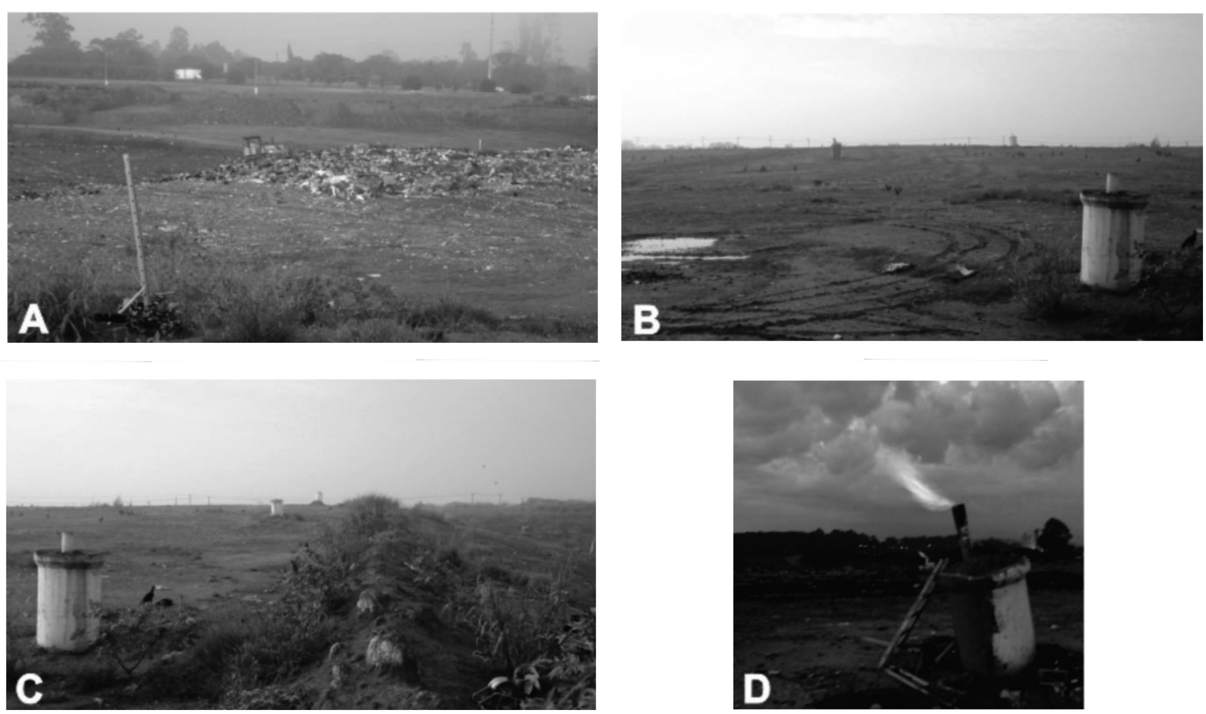

Figure 2. A) Waste disposal in active cell. B) Partial view of studied cell. C) Guidance of drains crossed by line 2. D) Drain number 28 with burning of biogas.

maximum amount of biogas can be produced by anaerobic decomposition can be estimated (Equation 1).

$$C_6H_{10}O_4 + 1{,}5H_2O \Rightarrow 3{,}25CH_4 + 2{,}75CO_2 \quad (1)$$

This exothermic reaction releases a small amount of heat and produces a gas consisting of 54% of the CH_4 and 46% of the CO_2. The biogas produced in landfills also contains water vapor near the saturation point, addition of small amounts of NH_4, H_2, H_2S and others compounds (Wellinger *et al.*, 2013).

Methods

The biogas flow is determined from velocity measurements in the drains, with the aid of a galvanized pipe with standard diameter of 100mm, and a digital thermal anemometer with an accuracy of 0.01m/s.

The procedure initially involved extinguishing the combustion of biogas at the end of the drain hose, coupling of the galvanized pipe to canalize the biogas and introduction of a telescopic handle of the thermo anemometer into a side hole of the tube, located 1m from its upper extremity. This routine was adopted for the protection of the measurement probe from the influences of wind or any air movement that could exert influence on the measurements of biogas velocity, besides standardizing a piping with a single diameter for flow calculation.

Subsequently, was applied DC Resistivity method for geophysical acquisition data, which uses electrodes fixed on the surface of the ground, connected to the measuring instrument via a cable assembly (Keller & Frischknecht, 1966; Telford *et al*., 2004).

Was adopted the Schlumberger arrangement, which consist in the alignment of a series of electrodes and the selection of four electrodes on each measure, where a pair of external electrodes for current transmission and the other internal pair of voltage readings. The lateral movement of this device along with the constant distancing of current electrodes with respect voltage electrodes enables lateral investigations and at various depths, that is, a two-dimensional product.

Were conducted 13 lines of electrical resistivity tomography (ERT) with individual length of 60m, 1.5 m spacing between electrodes and readings at 22 investigation in depths. The Terrameter LS resistivity meter, manufactured by ABEM (Sweden), consists in a single transmission and reception automatic system, calibrated in field to injection of 60mA.

The arrangement of lines in the study area emphasized the proximity of drains emission biogas in an attempt to check the resistivity in their respective areas of influence (Figure 1).

The field assessed measurements were processed in the software Res2dinv and resulted in sections of resistivity in terms of distance x depth, with logarithmic graphical scale and intervals of interpolation of values in color. This is a program that automatically determines a two-dimensional model of the subsurface, from chargeability or resistivity data obtained from ERT (Griffiths & Barker 1993). This optimization aims to reduce the difference between the apparent resistivity values, calculated and measured in the field, by adjusting the resistivity of the block model, which difference is expressed by the error RMS (Root Mean Square) (Loke and Barker 1996).

The data generated after the 2D inversion were gathered in a single file, later used as a database for generating pseudo-3D models and depth maps (Figures 2, 3 and 4). This process was developed in Oasis Montaj platform where 2D data obtained in Res2Dinv program were interpolated and modeled using the kriging method, for enhancement of extreme values in a model of pseudo-3D blocks, where ERT lines were positioned.

Results and discuccions

The electrical resistivity measurements were processed in the software Res2dinv and resulted in sections of resistivity in terms of distance x depth, with logarithmic graphical scale and intervals of interpolation of values in color (Figure 3).

The 2D model used in the program divides the pseudo-section into rectangular blocks, which will represent the pseudo-section by the adjustment of the field measurements. This optimization aims to reduce the difference between the apparent resistivity values, calculated and measured in the field, by adjusting the resistivity of the block model, which difference is expressed by the error RMS (Root Mean Square) (Loke and Barker, 1996).

The data generated after the 2D inversion were gathered in a single file, later used as a database for generating pseudo-3D models and depth maps (Figures 3, 4 and 5). This process was developed in Oasis Montaj platform where 2D data obtained in Res2Dinv program were

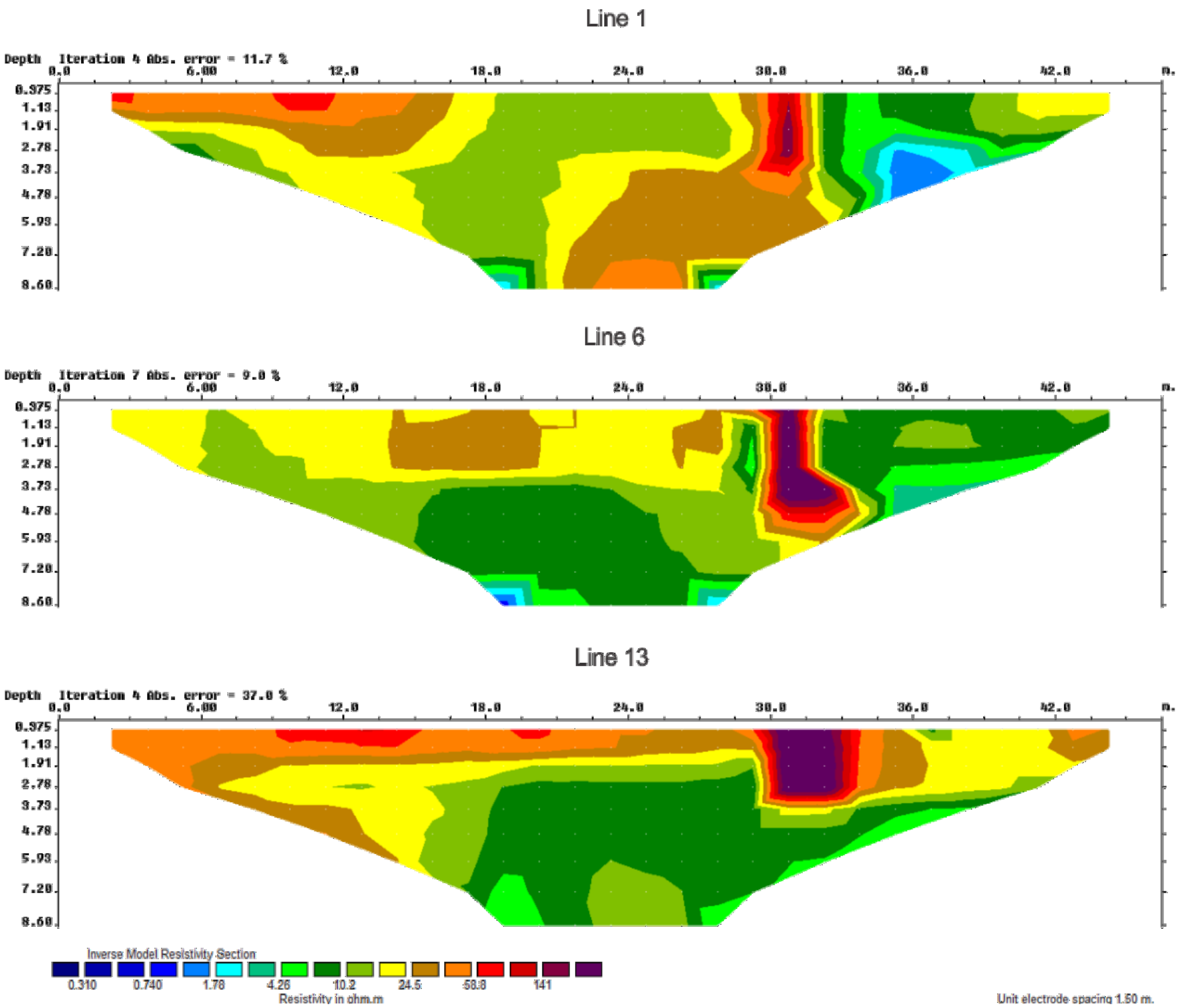

Figure 3. Inversion model section for the line 1, line 6 and line 13.

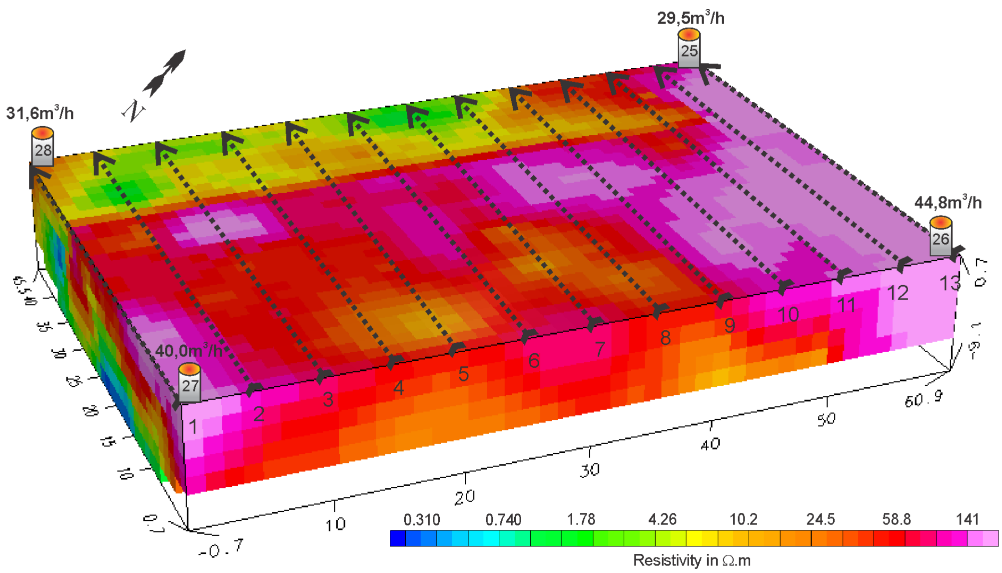

Figure 4. Pseudo 3D model of the electrical resistivity, with position of ERT lines, biogas drain with respectively flow (in m^3/h).

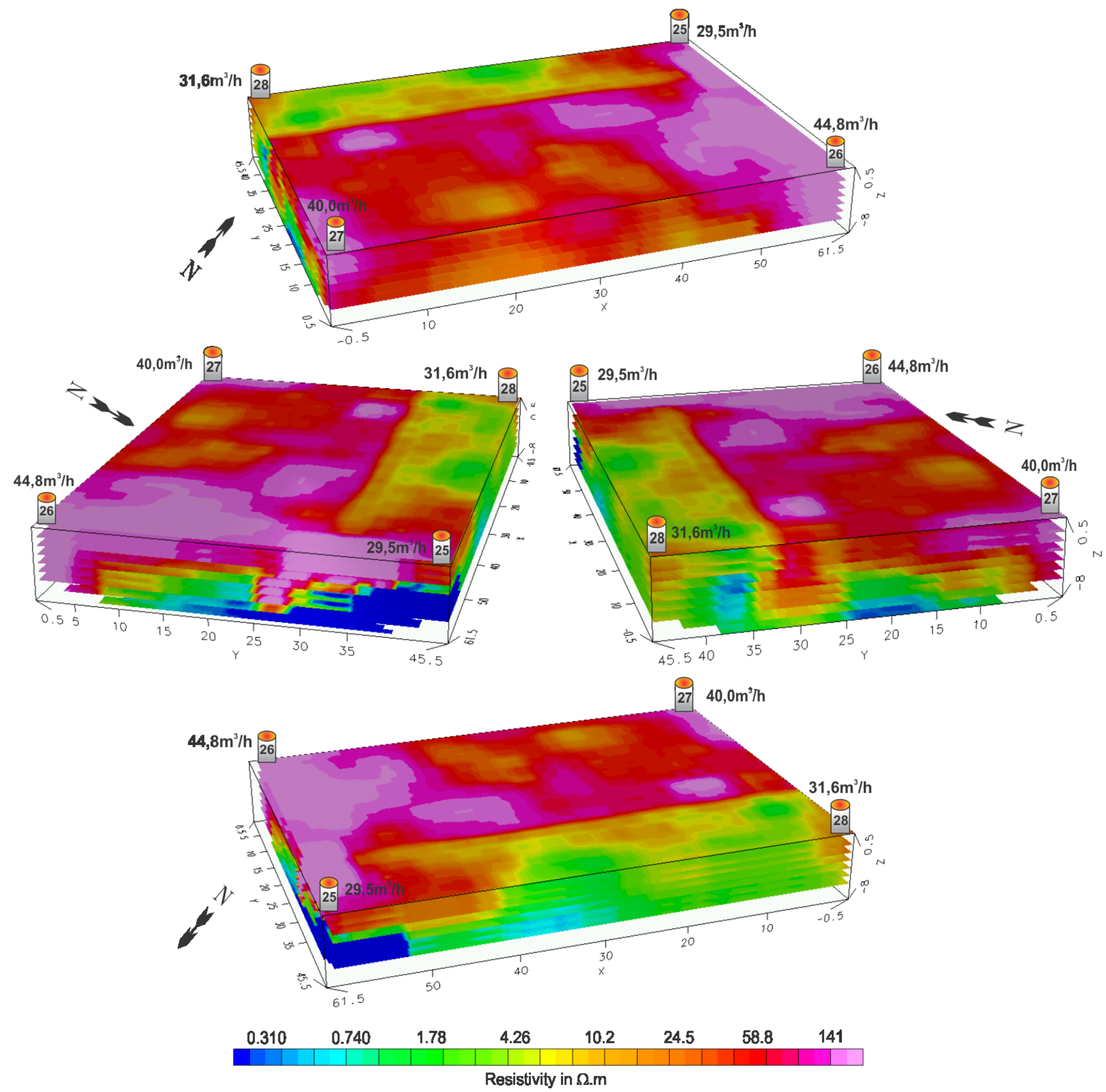

Figure 5. Isosurface levels of the electrical resistivity in various viewing perspective, with biogas drain and respectively flow (in m³/h).

interpolated and modeled using the kriging method, for enhancement of extreme values in a model of pseudo-3D blocks, where ETR lines were positioned.

Even on a relatively small area (60x40m), drains with a constructive profile, catchment area of gas and similar lengths, the data obtained show a wide variation in the biogas flow. Covering material of the landfill area consists of soil from excavation and opening of waste discharge cells characterized by clay matrix, released on waste and subsequently compressed by steamroller.

Although arranged in horizontal layers with thickness of 5m, the great heterogeneity of the waste in compositional terms, should necessarily lead to settlements differentiated over the time due to factors such as consumption of organic matter or rearrangement of material by seasonal moisture changes due to rain or drought seasons.

Such conditions can cause the generation of fractures in the coating material and the fugitive emission of part of the biogas produced, differential permeability and possible accumulation in specific areas. In this scenario

13 lines of electrical resistivity tomography, grouped into pseudo-3D models, with placement of drains biogas and their respective flow rates were performed (Figure 4).

The results enable a 3D view of the geophysics data and their relations with the flow of biogas and the special arrangement of the drains. The depth reached in models of 2D inversion was 9,1m, maintained in the 3D block.

A preliminary analysis from an aerial view of the 3D block shows an area of high resistivity (141W.m) between the drains 25 and 26, besides another isolated area of high resistivity positioned in the surroundings of drain 27 (Figure 4). An elongated and continuous strip between the drains 25 and 28, limited to the end of lines 1 and 11, is characterized by low resistivity values (24.5W.m), and comprises the area around the drain 28.

The 3D visualization of this product in different special positions allows for greater inferential about the resistivity areas (Figure 5).

For the drain 26, characterized by increased flow in the study area (44.8m^3/h), its catchment area in the vicinity and its continuity until 9m depth are fully characterized by high resistivity values (141W.m).

In contrast, the drain 28 had the lowest flow (29.5m^3/h), crosses depths levels with large variations in resistivity. In the first 2m of depth, there occur high resistivity values (141W.m), which brusquely fall to very low values from 4m depth (0.3W.m).

The drain 27 is characterized by an elevated flow (40.0m^3/h) and similarly to the drain 26 crosses an area of high resistivity values. However, below a depth of 7m there is a reduction in resistivity patterns, which gradually pass from 141W.m to values near 58W.m.

The flow tube 28 presented slightly higher flow than the lowest flow and in similarity to the drain 25, presents large variations in resistivity with the increase in depth. The first 3m depth are characterized by values ranging from 24W.m and 10W.m with gradual reduction in resistivity with increasing depth until values near 1.78W.m.

The joint analysis of the results indicate a strong correlation between high resistivity values and drains with larger flows of biogas, while there is the prevalence of low resistivity values in regions of lower flow drains. The uptake in areas of high resistivity along the entire depth of the drains in depth is another factor that affects the high flow rate. As levels of resistivity below 141W.m occur or become predominant, there occurs a concomitant decrease in the flow of biogas.

In this sense, the areas of high resistivity should characterize zones of accumulation of biogas, which predominance in mass residues in void spaces rather than the accumulation of manure, result in an increased resistivity, attributed to the insulating character of the gases to the passing of electric current.

This principle is adopted in geophysical profiling in studies of hydrocarbons, where physical parameters such as electrical resistivity and spontaneous potential are routinely employed in investigations of exploratory drill holes or for detailing of oilfields, due to the possibility of estimating lithological parameters such as permeability, porosity, grain size, rock types, besides the presence of oil or gas (Asquith & Gibson, 1982).

Conclusion

Measures in the drains describe a wide variation in biogas flow in a relatively small area, possibly due to issues related to settlement by fouling, decomposition of organic matter and accommodation of waste, changes in the pattern of permeability and generation of zones of accumulation of gases.

This latter aspect was subject to evaluation by means of analyzing measurements of electrical resistivity for various levels of depth and laterally among the lines of data acquisition. Biogas is characterized as an electrical insulator due to its physical state, i.e., areas where there is accumulation of biogas, as part of the waste must be characterized by high resistivity values. Measures of biogas flow corroborate this effect, resulting in a correlation between high flow rates and high resistivity values.

In contrast, degradation of organic matter also produces leachate, due to the loss of moisture in the process. In this sense, the intervals of low resistivity may reflect areas of leachate accumulation, characterized by high amounts of dissolved salts. In addition, it should be considered contributions to increased moisture from infiltration of rainfall at certain times.

The high heterogeneity of the waste, with plastic and other high resistivity materials randomly distributed, and the continuous process of accommodation of materials result in constant changes in permeability, with generation of new areas of accumulation of biogas and extinction of others (Metcalfe & Farquhar 1987; Nastev et al. 2001).

The results of this study demonstrate the effectiveness of the DC resistivity in determining areas of accumulation of gases in landfills, besides the possibility of continuous monitoring of biogas capture systems with a history of change of flows. However, the intrinsic complexity to waste disposed in landfills in terms of composition and compaction, are conditions of great influence in electrical resistivity measurements.

Eventual variations related to changes in the permeability and transmissivity of gases can be estimated by measurements of electrical resistivity, whose analysis and comparison with available flowrates, enables the location of new potentially effective points, to drilling and installing drains for collection of biogas. This procedure may help in optimizing the processes of energy production from burning biogas from landfill, besides the possibility of application in the detection of areas of potential occurrence of fugitive emissions, which result in the escape of gases to the atmosphere.

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