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ORIGINAL ARTICLE

Geoenvironmental site investigation using different techniques in a municipal solid waste disposal site in Brazil

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Abstract Different geoenvironmental site investigation techniques to assess contamination from a municipal solid waste disposal site in Brazil are presented here. Superficial geophysical investigation (geoelectrical survey), resistivity piezocone penetration tests (RCPTU), soil samples collected with direct-push samplers and water samples collected from monitoring wells were applied in this study. The application of the geoelectrical method was indispensable to identify the presence and flow direction of contamination plumes (leachate) as well as to indicate the most suitable locations for RCPTU tests and soil and water sampling. Chemical analyses of groundwater samples contributed to a better understanding of the flow of the contaminated plume. The piezocone presented some limitations for tropical soils, since the groundwater level is sometimes deeper than the layer which is impenetrable to the cone, and the soil genesis and unsaturated conditions affect soil behavior. The combined interpretation of geoelectrical measurements and soil and water samplings underpinned the interpretation of RCPTU tests. The interpretation of all the test results indicates that the contamination plume has already overreached the landfill's west-northwest borders. Geoenvironmental laboratory test results suggest that contamination from the solid waste disposal site has been developing gradually, indicating the need for continuous monitoring of the groundwater.

Keywords Site investigation · Tropical soils · Electrical resistivity · Piezocone test · Contamination

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Introduction

Municipal and industrial solid waste disposal sites have been the focus of special attention in recent years since they are a significant source of soil, water and air contamination. Unfortunately, waste is disposed, uncontrolled at many sites, where the restrictions imposed by environmental agencies are disregarded and the rules and techniques for proper landfill management are ignored.

According to the Brazilian Institute for Geography and Statistics (IBGE 2002), Brazil produces about 125,281 tons of municipal solid waste (MSW) per day, 30.5% of which are disposed off in garbage dumps, 22.3% in controlled dumps and 47.1% in sanitary landfills. Although, the selectiveness of garbage disposal has improved in recent years (in 1989, only

10.7% of garbage was discarded in sanitary and/or controlled dumps), 63.6% of Brazilian towns still dispose off their solid waste in dumps.

This scenario indicates the necessity for the development of faster, more practical, direct and inexpensive modern geoenvironmental technologies, designed for the analysis of tropical soils, which can be easily applied in the assessment of contaminated sites. Geoenvironmental site investigations, including laboratory tests, are therefore essential for characterizing and quantifying possible contaminations. All these are fundamental for the selection of the appropriate remediation program which is also crucial for the future reemployment of the land where the landfill is situated.

According to Davies and Campanella (1995), environmental site characterization refers to the superficial and underground representation of a site which approximates actual in situ conditions. This representation is typically developed by both surface and subsurface characterization.

Nowadays, this type of investigation begins with geophysical tests, which are noninvasive tests that allow the identification of the presence and direction of subsurface contaminative flows. Geophysical tests are used in the preliminary mapping phase (McFarlane et al. 1983; Davis and Annan 1989; Beres and Haeni 1991; Lanz et al. 1994; Heitfeld and Heitfeld 1997; Sauck et al. 1998; Green et al. 1999; Atekwana et al. 2000; Bernstone et al. 2000; Aristodemou and Thomas-Betts 2000; Sauck 2000; Stanton and Schrader 2001; Karlik and Kaya 2001; Orlando and Marchesi 2001; Dawson et al. 2002; Soupios et al. 2005a, b, c, 2006), providing the necessary information upon which to base invasive investigation methods such as standard penetration tests (SPT), monitoring wells and cone penetration tests (CPT) (Rhoades and van Schilfgaarde 1976; Cherry et al. 1983; Campanella and Weemees 1990; Strutynsky et al. 1992; Burns and Mayne 1998; Fukue et al. 1998, 2001; Daniel et al. 2003; Opydke et al. 2006).

The piezocone technology, especially the resistivity piezocone test (RCPTU) together with direct-push soil, water and gas samplers is an interesting approach for invasive tests. Because resistivity piezocone test research in Brazil is still incipient, this tool requires many investigations to evaluate its performance in tropical and unsaturated soils, rendering this a highly challenging enterprise due to the country's enormous size and the existence of different soil types.

Estimates of pollutant transport parameters based on laboratory tests such as column, diffusion and batch equilibrium tests, are also important in the more detailed phases of geoenvironmental investigations (Freeze and Cherry 1979; Rowe et al. 1988; Barone et al. 1989; Shackelford et al. 1989; Shackelford and Daniel 1991; Yong et al. 1992; Shackelford 1993; Yong 2001; Du and Hayashi 2004). These tests, which enable to assess the soil's capacity to retain different chemical compounds, only began to be conducted in Brazil a few years ago (Boscov 1997; Boscov et al. 1999; Ritter et al. 1999; Leite and Paraguassu 2002).

The proposal to use different techniques to evaluate contamination from a municipal solid waste disposal site was applied in Bauru, state of São Paulo in Brazil. Geoelectrical and piezocone tests (CPTU and RCPTU) were carried out. Soil and water samples were collected using direct-push samplers and monitoring wells, supported the interpretation of data obtained by indirect tests. Geoenvironmental laboratory tests were also carried out to evaluate the detaining of various heavy metals in the local soil.

Geoenvironmental site characterization

Definition

Environmental, or geoenvironmental site characterization is a relatively new term for geotechnical engineers. So, there are several interpretations of what an geoenvironmental site characterization program is. Davies and Campanella (1995) define it as the field of study that links geological, geotechnical and environmental engineering, and the corresponding sciences, to form an area of interest that includes all environmental concerns within natural or processed geological media. The detection and assessment of groundwater contamination caused by waste disposal is an excellent example where geoenvironmental site characterization is necessary.

A geoenvironmental site characterization requires stratigraphy, geotechnical, hydrogeological and some specific environmental parameters. Combining geophysical and geotechnical in situ techniques is the best way to achieve all the required information (Campanella et al. 1994).

To obtain information about the soil conditions below the surface, some form of subsurface exploration is required. Methods of observing the soils below the surface, obtaining samples, and determining physical properties of the soils and rock include test pits, trenching (particularly for locating faults and slide planes), boring, and cone penetration tests.

Geophysical methods

Geophysical methods are indirect site investigation techniques and predominantly non-intrusive. The main advantage of superficial geophysical methods is the possibility to investigate large areas at a low cost.

The direct result of a geophysical survey is a map of the distribution in space or time of some physical property such as electrical conductivity. The map is only one piece in a puzzle, but it serves as a guide in the first phase of a subsurface investigation (Greenhouse et al. 1995).

Geophysical tests, particularly electrical methods, can be used to study different geoenvironmental characteristics. The following geological, geotechnical, hydrogeological and environmental characteristics can be assessed using different geophysical methods: (a) rock depth, (b) discontinuities, (c) changes on the soil texture, (d) groundwater level, (e) groundwater flow, (f) presence and three-dimensional distribution of the waste, (g) contaminated soil, (h) contaminated groundwater and plume shape. All characteristics are indispensable in a good geoenvironmental site characterization.

Electrical resistivity tomography (ERT) is potentially an appropriate subsurface imaging tool for landfill site characterization, due to its ability to distinguish permeable sand and gravel from clays. However, engineers want more accurate identification of interface depth than what standard ERT inversions supply. So, the use of reference geoelectrical models based on RCPT can be investigated. The use of RCPT data can potentially guide the inversion algorithm towards improved solutions (Catt et al. 2005).

Penetrometer methods

Stratigraphics specializes in penetrometer exploration services for geoenvironmental and geotechnical studies. The penetrometer method is minimally intrusive, using a high capacity hydraulic ram mounted on a heavy truck to push small, 4.3 cm diameter probes directly into the ground, without drilling a borehole.

The modern site characterization approach is based on the piezocone penetration test (CPTU). The standard piezocone measurements can be used as a tool for logging soils. Empirical and semi-theoretical correlations are available to estimate mechanical properties of the soils. The measurements of excess pore water pressure, which are generated during penetration and their subsequent dissipation provided insight into the soil type and its hydraulic parameters (Campanella et al. 1994).

Site characterization including contaminant plume delineation can be accurately performed using rapid penetrometer methods. Temporary groundwater monitoring wells can then be economically installed at optimal locations using a minimum of expensive borehole drilling. The combination of minimally intrusive penetrometer methods and large diameter borehole drilling is less expensive and less disruptive to site activities than use of drilling methods alone.

Sometimes, instruments other than the basic standard CPT probe are used, including: piezometric cone penetration tests with soil electrical conductivity measurements (CPTU-EC or RCPTU) which provide simultaneous measurements allowing geotechnical, hydrogeological and qualitative geochemical evaluation of site characteristics. Soil electrical conductivity and temperature are continuously measured using a high resolution (2.5 cm) electrode array and thermal sensor mounted on the penetrometer. Soil electrical conductivity depends primarily on the soil pore fluids and soil clay content. Unsaturated soils and soils saturated with many LNAPL (light non-aqueous phase liquids) and DNAPL (dense non-aqueous phase liquid) compounds exhibit very low electrical conductivity (EC). Dissolved inorganic compounds, such as those contained in brines and landfill leachates, significantly increase soil electrical conductivity.

The CPT, CPTU and RCPTU graphical data presentations (sounding logs) are produced immediately as the penetrometer test progresses. Layering and saturation are visibly obvious, as are relative strength and consistency. Soil EC anomalies, possibly associated with contamination, are also obvious. A series of penetrometer sounding logs can be used to characterize subsurface site conditions with ease and accuracy.

In addition to penetrometers with sensors, penetrometer samplers are used to sample groundwater, soil and soil gas. Direct samples confirming indirect measurements are quickly, reliably and economically obtained. The modern piezocone technology for geoenvironmental site characterization incorporated special samplers for this purpose (Lunne et al. 1997). Samples are used to confirm indirect testing data or to measure a specific contamination. Liquid and gas samplers are pushed to a selected depth based on interpretation of an adjacent CPTU test. A variety of soil samplers from the direct-push technology are also available. CPTU test can also govern the depths from where to recover soil samples and the equipment that pushes the cone can be used to push in the sampler. Monitoring wells are still a very interesting option for a long-term liquid sampling and geophysical and CPTU tests can be used to select the best location to install them.

Site description

The city of Bauru, located in the center of the state of São Paulo in southeastern Brazil (Fig. 1), has a population of about 320,000. The study area is a MSW disposal site located northwest of the city, which receives 207.2 tons/day of urban wastes. This site can be considered as a controlled dump because it is a planned landfill that incorporates some of the features of a sanitary landfill such as: siting with respect to hydrogeological suitability, grading, compaction of the wastes, leachate control, partial gas management, regular (not usually daily) cover, access control, basic record-keeping, and controlled waste picking.

The site's geology is characterized by sandstone from the Marília Formation, covered by alluvial sandy soils or colluvial clayey sands. Underneath these layers are residual soils from sandstone. The hydraulic conductivity of these soils was found to vary from 10^{-7} to 10^{-6} m/s. The depth of the groundwater level is about 5 m below the base of the landfill. In order to protect the subsurface and the shallow groundwater table from leakages from the landfill, four 20-cm-thick layers were compacted using local soil with water content 3% above the optimum water content, and compacted to around 95% of the Standard Proctor maximum dry density. The upper surface of these layers was coated twice with diluted asphalt emulsion to seal and protect the bottom of the landfill. This procedure was used because it was inexpensive and acceptable for controlled dumps in Brazil when the landfill was established.

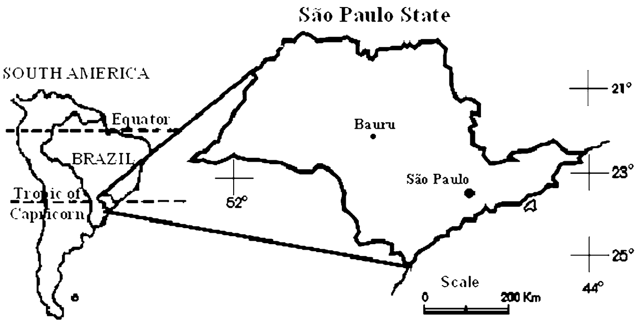


Fig. 1 A general map of South America with a detailed map showing the location of the city of Bauru, state of São Paulo in Brazil

Site investigation program

Figure 2 shows the location of all the in situ tests carried out at Bauru's MSW disposal site. Disturbed and undisturbed soil samples, (where structural properties of the soil do not represent and represent the in-situ conditions, respectively), were collected from a slope located along 70 m south-west of the landfill. Table 1 presents the average geotechnical parameters determined by the laboratory tests carried out on these samples, those were also used for column and batch equilibrium tests.

Geophysical tests

Geophysical methods are indirect site investigation techniques and are predominantly noninvasive. The main advantage of superficial geophysical methods is that they allow large areas to be investigated at a low cost. For the detection and mapping of contaminant plumes and leakages, electrical methods are the most useful for detecting inorganic plumes. Among the various existing methods, electrical resistivity method is the most widely applied and well known (Greenhouse and Harris 1983; Kean et al. 1987; Bernstone and Dahlin 1998; Green et al. 1999; Svenson et al. 1999; Bernstone et al. 2000; Aristodemou and Thomas-Betts 2000; Meju 2000; Orlando and Marchesi 2001; Dahlin et al. 2002; Porsani et al. 2004; Mota et al. 2004).

The electrical resistivity method encompasses various techniques for the application of field tests, which basically consist of electrical sounding and electrical profiling techniques and include a wide variety of possible electrode configurations, rendering the method highly versatile.

In a vertical electrical sounding (VES), the distance between the current electrodes and the potential electrodes is systematically increased, thereby yielding information on subsurface resistivity from successively greater depths. The variation of resistivity with depth is modeled using forward and inverse modeling computer software.

In a dipole–dipole electrical profiling, two electrodes are separated by a constant spacing called the "a" spacing and are used to inject current into the ground. Two additional electrodes also separated by the "a" spacing are moved along the survey line at distances from the current electrodes that are multiples of the "a" spacing (Johnson 2005).

Figure 2 shows the location of dipole–dipole electrical profiling (C1–C5) and vertical electrical sounding (VES 1–VES 9) lines on which the various geophysical tests were carried out. The electrical

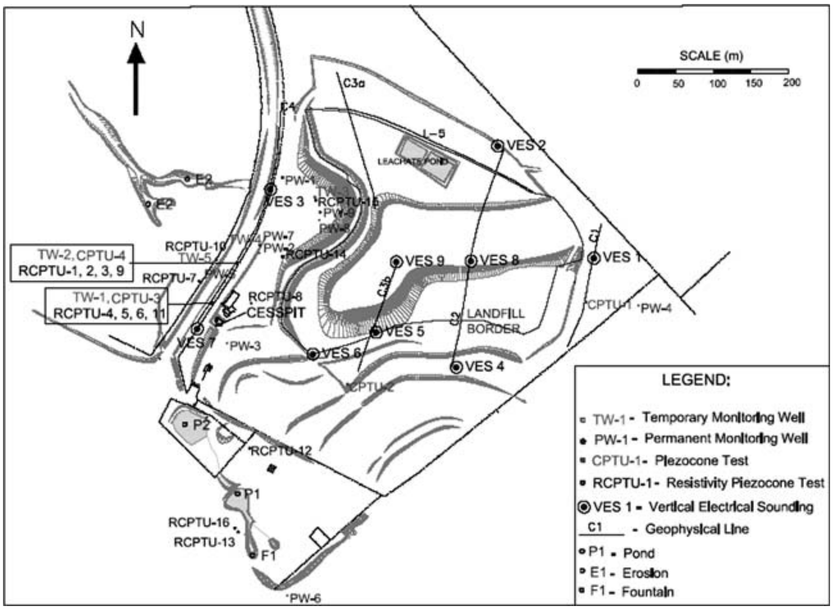


Fig. 2 Location of the tests carried out at Bauru's MSW disposal site

Table 1 Average geotechnical soil properties of the samples collected around Bauru's MSW disposal site

w (%)	γ_n (kN/m^3)	G_s	γ_d (kN/m3)	e	S_r (%)	n (%)	Sand (%)	Silt (%)	Clay (%)	w_L (%)	w_P (%)	$\rho_{d\ max}$ (g/cm^3)	w_{op} (%)	k_v (m/s)
6	16	2.7	15	0.8	19	45	73	6	21	20	15	1.9	12	6×10^{-7}

w water content, γ_n natural unit weight, G_s specific gravity, γ_d dry unit weight, e void ratio, S_r degree of saturation, n porosity, w_L liquid limit, w_P plastic limit, $\rho_{d\ max}$ maximum dry density, w_{op} optimum water content, k_v vertical hydraulic conductivity

profiling lines were laid out with 10 m spacing between the electrodes, while the vertical electrical sounding lines were laid out in a Schlumberger array with a maximum spacing of 150 m. Figure 3 illustrates the field equipment used for the electrical resistivity measurements.

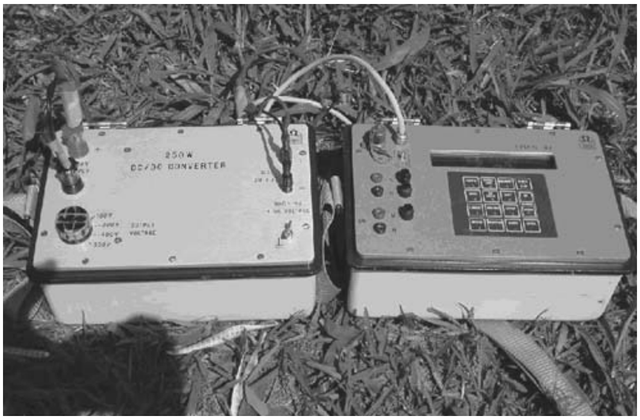


Fig. 3 Iris Syscal R2 equipment used and installed at Bauru's MSW disposal site for electrical resistivity tests

Piezocone technology

The piezocone (CPTU) is a standard instrumented probe (ASTM 1986) with a 60° apex and typical diameter of 35.7 mm (10 cm^2 area) on the end of a series of rods (Fig. 4). It is pushed into the ground at a constant rate of 20 mm/s by a hydraulic pushing source. Standard CPTU measurements of tip resistance (q_c), sleeve friction (f_s) and pore pressure (u_2) are typically recorded at intervals of 25 or 50 mm depth. These three parameters, in various combinations such as friction ratio ($R_f = (f_s/q_c)*100\%$), are used to delineate site stratigraphy using specific charts like the one proposed by Robertson et al. (1986). Empirical and semi-theoretical correlations are available in the literature to estimate the mechanical properties of the soils.

The resistivity module, which can be attached to the piezocone, consists of Wenner, Schlumberger or dipole–dipole electrode arrays. Figure 4 depicts a resistivity Wenner type piezocone with a four-electrode array, with which resistivity measurements are taken with the inner electrodes and the current is applied through outer electrodes. These measurements are digitally recorded at 25 mm intervals, providing essentially continuous in situ data sampling, in addition

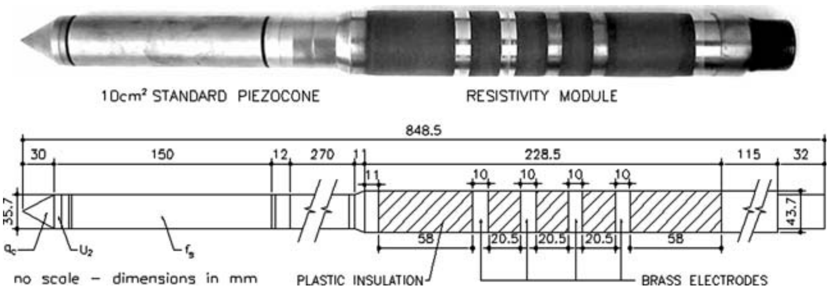


Fig. 4 Schematic representation of a resistivity piezocone probe with 4-electrode array

to all other standard CPTU measurements. Linear calibration factors are developed by immersing the module in water baths of known resistivities and measuring the module output.

Several piezocone trial tests were carried out at Bauru's MSW disposal site on different occasions. On the first occasion (CPTU-1 to CPTU-4), a standard 100 kN CPTU probe with 10 cm^2 cross sectional area was used to measure the tip resistance (q_c), sleeve friction (f_s) and pore pressure (u_2). In the other tests (RCPTU-1 to RCPTU-16) an electrical resistivity module was attached to the CPTU probe to measure the bulk resistivity of the soil (R). The piezocone transmitted the signals captured by the sensors through sound waves. A self-anchoring (Fig. 5), multi-purpose push platform with a hydraulic system of 200 kN capacity was used for pushing CPT probes and groundwater or soil samplers. The pore pressure was measured at the standard position behind the shoulder of the tip (u_2) using a slot filter filled with automotive grease in all the tests, as suggested by Larsson (1995), except for RCPTU-5, in which the traditional porous filter element saturated with glycerine was used.

Soil and water samples were collected using the direct-push system at depths that exhibited alterations in the q_c and R_f values found in some of the sounding profiles. These samples were used in grain size distribution tests, determination of electrical conductivity and pH values.

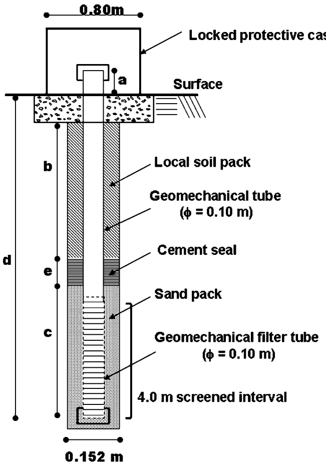
Note that electrical conductivity (EC) is the inverse of resistivity (R), and that the following expression can be applied:

$$\mathrm{EC}\ (\mu\mathrm{S/cm}) = \frac{10{,}000}{R\,(\mathrm{ohm\,m})}. \qquad (1)$$

Monitoring wells

Based on the results of the geophysical tests, nine monitoring wells for water sampling were located and drilled around the study area, in addition to five temporary monitoring wells that had been previously constructed, as shown in Fig. 2. Figures 6, 7, respectively, give a schematic representation of the permanent and temporary monitoring wells built in the area. The permanent monitoring wells were built according to the Brazilian standard (ABNT 1997, with the characteristics shown in Fig. 6. The temporary wells were built using the same self-anchoring, multi-purpose push platform used for the piezocone tests, which also al-

Fig. 5 Self-anchoring, multi-purpose push platform carrying out piezocone tests at Bauru's MSW disposal site



Well	a (m)	b (m)	c (m)	d (m)	e (m)
1	0.36	2.00	10.00	12.00	0.00
2	0.22	2.00	10.00	12.00	0.00
3	0.07	4.00	10.00	14.00	0.00
4	0.27	28.90	8.00	37.40	0.50
5	0.22	3.30	4.20	8.00	0.50
6	0.21	1.50	4.00	6.00	0.50
7	0.24	5.50	6.00	12.00	0.50
8	0.24	24.50	5.00	18.00	0.50
9	0.22	8.50	5.00	14.0	0.50

Fig. 6 Schematic drawing of the permanent monitoring wells built at Bauru's MSW disposal site

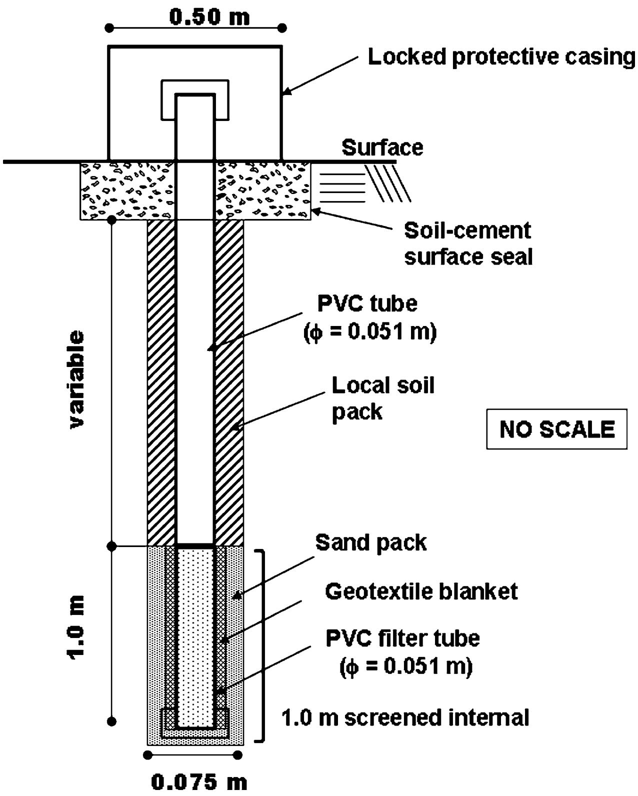


Fig. 7 Schematic drawing of the temporary monitoring wells built at Bauru's MSW disposal site

lowed for the drilling of 75 mm diameter holes down to the groundwater level and the installation of 50.8 mm PVC (polyvinyl chloride) pipes with a 1.0 m filter tube wrapped in geotextiles.

Laboratory tests

Due to the several variables that affect the results of field tests to assess contamination, column and batch equilibrium tests were carried out to evaluate the retention of several heavy metals in the soil in the surrounding area of the Bauru's MSW disposal site. Leachate collected from the landfill's recirculation cell and a synthetic solution composed of about 10 mg/L of Ni, Zn, Cd and Pb were used as percolation fluids. The concentrations of these four metals were enhanced in the leachate by adding nitrates of these metals to improve the quality of the chemical analyses, since the concentrations measured in the leachate were close to the detection limit of the atomic emission spectrometer (ICP-OES—inductively coupled plasma optical emission spectrometer) used in this research.

The column tests were carried out with a Tri-Flex 2 permeameter (Fig. 8). Prior to the actual column tests, permeability and column tests were conducted with a 100 mg/L saline solution to check the soil's reaction to low and high electrical conductivity fluids and to different confining pressures. Permeability tests were carried out till a fluid volume equal to two pore volumes of the soil sample had percolated through the soil to guarantee the stabilization of the degree of saturation and therefore of the hydraulic conductivity. The column tests with percolation of the metal solutions and the leachate with added metal nitrates were carried out at a confining pressure of 30 kPa and with hydraulic gradients of 11.6 and 13.0, respectively.

Batch equilibrium tests were carried out following appropriate guidelines (ASTM 2001), with soil-solution ratio 1:4 (25 g of dry soil sieved through a 40 mesh to 100 mL of solution). The equilibrium time was determined by preliminary tests for 168 h (1 week) for all studied metals, both for the synthetic solution and the leachate. Figure 9 shows the orbital shaker, i.e. the device used for shaking the flasks containing the suspensions at a rotation rate of 60 rpm. After equilibrium, the suspensions were filtered and nitric acid was added. The flasks containing leachate were also centrifuged and filtered again. The filtrates were stored in a refrigerator at 5°C till the chemical analysis.

Results were expressed as the adsorption degree as a function of the equilibrium concentration. The adsorption degree (S) is defined by the following equation:

$$S = \frac{(C_0 - C_e) \cdot V}{M}. \qquad (2)$$

C_0 = initial concentration of the solution, C_e = equilibrium concentration, V = volume of the solution in the flask, M = dry soil mass.

Test results and discussion

Geophysical tests

The vertical electrical soundings VES 8 and VES 9 were performed within solid waste landfill to study the relation between wastes and natural soil. Based on these soundings, the geoelectrical layers characterized by low resistivity (10.2 to 18.8 ohm m) were interpreted as waste and as leachate-saturated waste. The bottom of the landfill was found to vary in depth from 16 to 20 m and was characterized by resistivity values of 28.9–29.9 ohm m (Fig. 10).

Vertical electrical soundings were performed outside the solid waste landfill provided information about the position of the groundwater level, which varied

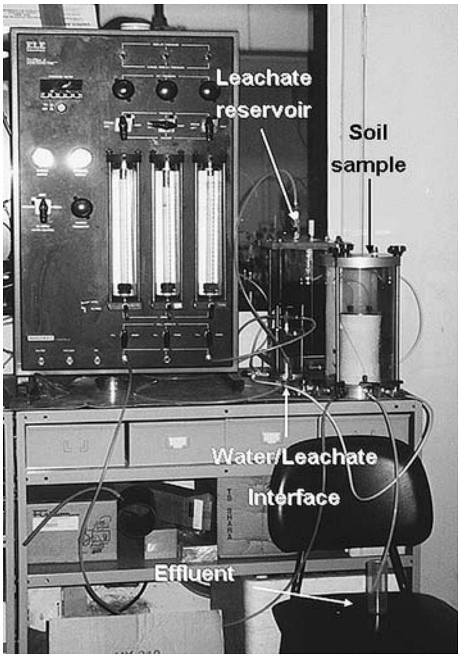
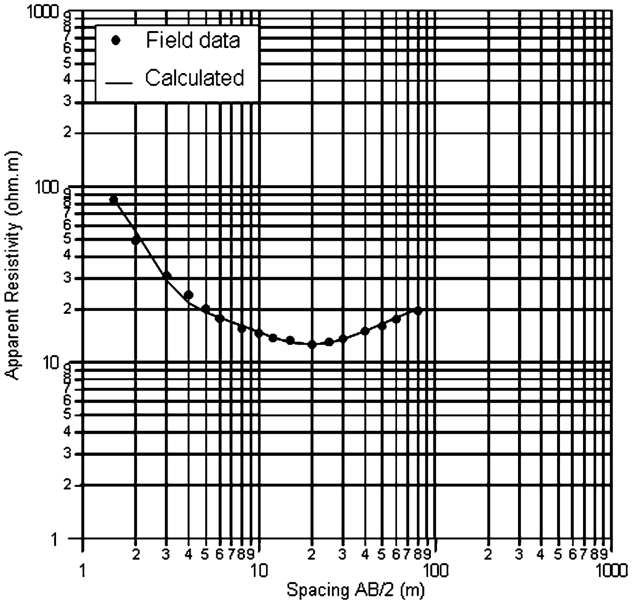


Fig. 8 General view of the Tri-Flex permeameter prepared for the leachate percolation column test

Fig. 9 Orbital shaker used in the batch equilibrium tests

from 12 m (upstream) to 8 m (downstream) depth. The results of these soundings revealed a considerable heterogeneity of the interpreted models, above all, with respect to the more superficial layers. This electrical heterogeneity reflects the mixture of materials that characterize the superficial soil in the area, with alternating layers of fine sand, clayey silt, colluvial soil, and colluvium composed of clayey sand.



GEOELETRIC MODEL – VES 8

Layer	Thick	Resistivity	Interpretation
1	0.73 m	166 ohm.m	Landfill covering material
2	4.05 m	18.8 ohm.m	Waste
3	16.4 m	10.4 ohm.m	Waste + leachate
4		28.9 ohm.m	Landfill bottom

Fitting error = 4.8%

Fig. 10 Interpretation of VES 8, located in the solid waste landfill at the study site (Lago 2004)

Five dipole–dipole electrical profiling trials, C1–C5, were carried out at the study area. C2 and C3 profiles crossed the solid waste landfill, C1 and C4 profiles were acquired upstream and downstream of the site, respectively and C5 profile located north of the landfill as is shown in Fig. 2. Lines C2 and C3 served to identify solid wastes and anomalous resistivity zones. Lines C4 and C5 were carried out to check for possible contamination outside the solid waste landfill. The data were modelled using the modelling software RES2Dinv (Loke 1998) and the polygon modeling software RESIXIP2Di (Interpex 1996), generating 2D models that allowed for a detailed analysis of the relationships between the natural materials and the solid wastes. Figures 11, 12 depict the results obtained from lines C2 and C4, respectively.

The resistivity sections of Line C2 revealed that resistivity values exceeding 40 ohm m should be interpreted as corresponding to zones of natural soils. The most conductive zone (2–40 ohm m) occurred between the distances of 50 and 250 m, which characterized the solid waste landfill.

In the resistivity sections of Line C4, the presence of unsaturated soils and of the saturated zone was detected. These sections indicated that the unsaturated superficial soils are characterized by resistivity values exceeding 100 ohm m. Also, inside the saturated zone, lower resistivities (8–12 ohm m) were

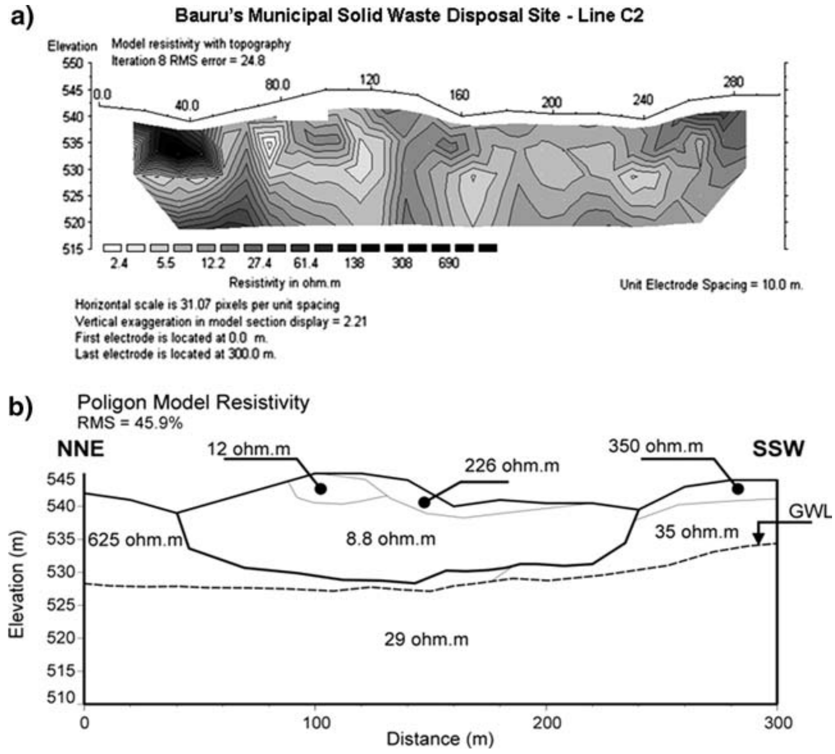


Fig. 11 Results of Line C2. **a** RES2Dinv resistivity model; **b** RESIXIP2Di model

found in the positions between 120 and 150 m and 200 and 250 m, suggesting probable groundwater contamination.

Detection of the plume and delineation of its shape is very important information for geoenvironmental site characterization. All the data obtained by

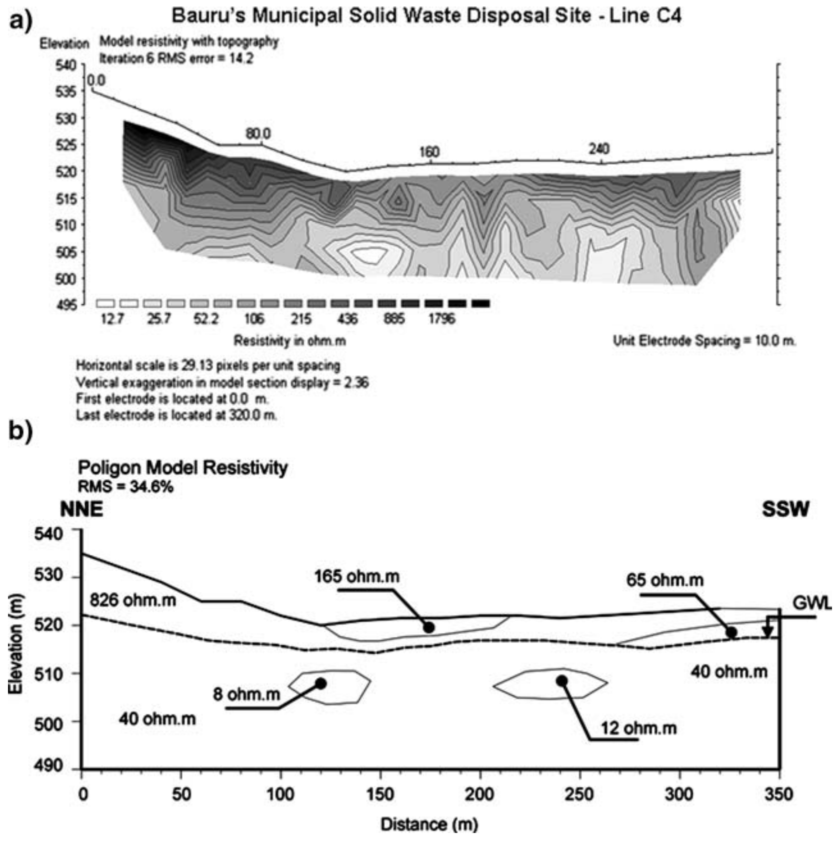


Fig. 12 Results of Line C4. **a** RES2Dinv resistivity model; **b** RES IXIP2Di model

geoelectrical profiling can be used to generate apparent resistivity maps at different depths and these data can be used to assess the horizontal direction of the contamination plume. Figure 13 shows a map of the 15 m theoretical depth, where an anomaly with low resistivity is visible in the landfill area.

Based on the results obtained from the geophysical tests, it was recommended that the RCPTU soundings, the monitoring wells and the soil and water samplings be carried out mainly in several specific positions along Line C4 as well as northeast of the landfill, since low values of resistivity within the saturated zone were identified at these locations, suggesting the presence of contaminants.

Piezocone technology

The profiles obtained with the piezocone test were interpreted using Robertson et al. (1986) classification chart to identify the soil behavior type (SBT) at the study site. As has been found in other researches with tropical soils (Giacheti et al. 2003), the results shown in Figs. 14, 15 indicate that the identification of the stratigraphical profile from piezocone soundings, based on this classification chart, also presents limitations for this area, since it identifies soils with distinct behaviors, but does not permit their textural classification. However, a combined analysis of the q_c and R_f records led to the identification of the layers with distinct behaviors where soil samples were retrivied using direct-push samplers.

The CPTU-1 sounding was carried out east of the landfill to try to obtain a reference resistivity profile of the uncontaminated ground. However, the resistance to cone penetration was greater than the capacity of the self-anchoring, multi-purpose push platform to reach the groundwater level.

The RCPTU-14 and RCPTU-15 soundings, whose results are shown in Fig. 14, were carried out close to the solid waste landfill, followed by water and soil samplings to check contamination of the area. Two sets of RCPTU soundings were carried out close to the temporary monitoring wells in the west, where Line C4 indicated greater contrasts in the resistivity values. Figure 15 shows the results of the CPTU-4 and RCPTU-1, RCPTU-2, RCPTU-3 and RCPTU-9 tests.

All the RCPTU tests that reached groundwater revealed an abrupt drop in resistivity and this information was useful to help identify the groundwater level. The resistivity profiles shown in Fig. 15 for the saturated zone indicate that they are affected by soil texture and mineralogy. Resistivity was higher in sandy layers than in clayey layers. The influence of soil type on the resistivity values of the RCPTU-14 and RCPTU-15 tests were not so clear, since the resistivity value found in the RCPTU-14 test was around 50 ohm m while that of the RCPTU-15 test was measured around 20 ohm m (Fig. 14). It indicates migration of the contamination plume through the sandy layer, based on water sampling using a direct-push sampler at depths of 8.0 to 9.0 m, since it presented low electrical resistivity, which is indicative of the presence

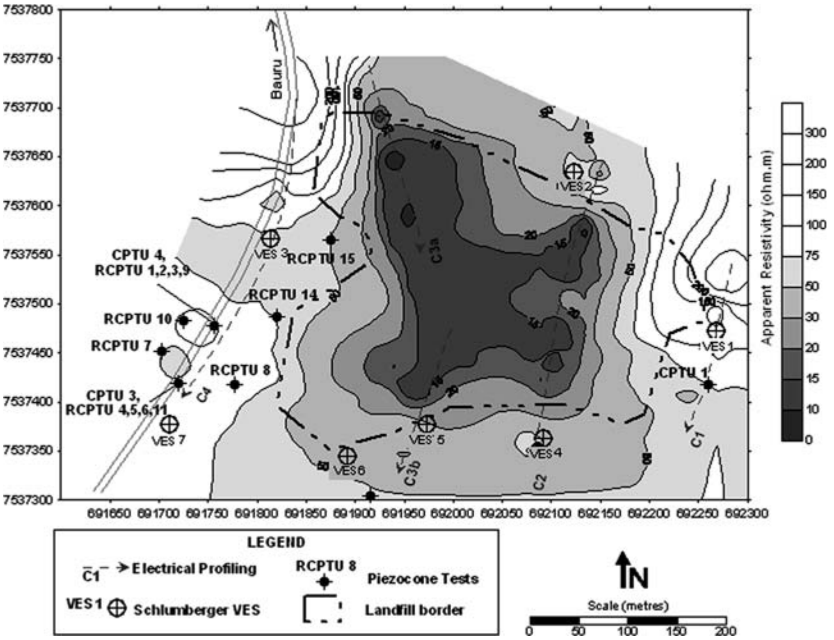


Fig. 13 Map of the apparent resistivity at 15 m theoretical depth at the Bauru's MSW disposal site. Low values (<75 ohm m) indicate that the contamination is reaching the saturated zone

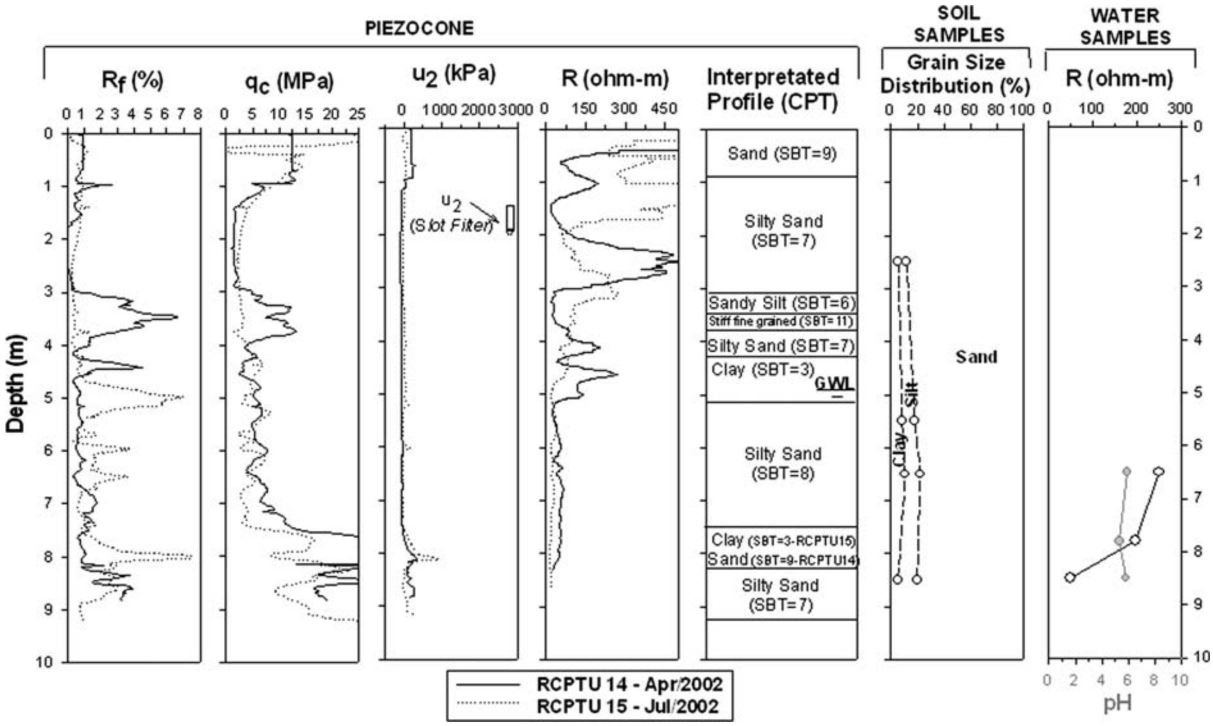


Fig. 14 Resistivity piezocone test results, grain size distribution and groundwater analyses for the study site, adjacent to the edge of the solid waste landfill

of contaminants dissolved in the water. In this particular case, soil and water sampling is required to underpin the interpretation of the resistivity piezocone test.

Table 2 compares the bulk resistivity values measured in the RCPTU tests against those obtained from the water samples collected from the temporary monitoring wells in the same period as the tests. These data

Fig. 15 Resistivity piezocone test results and grain size distribution from samples collected downstream from the solid waste landfill at the study site

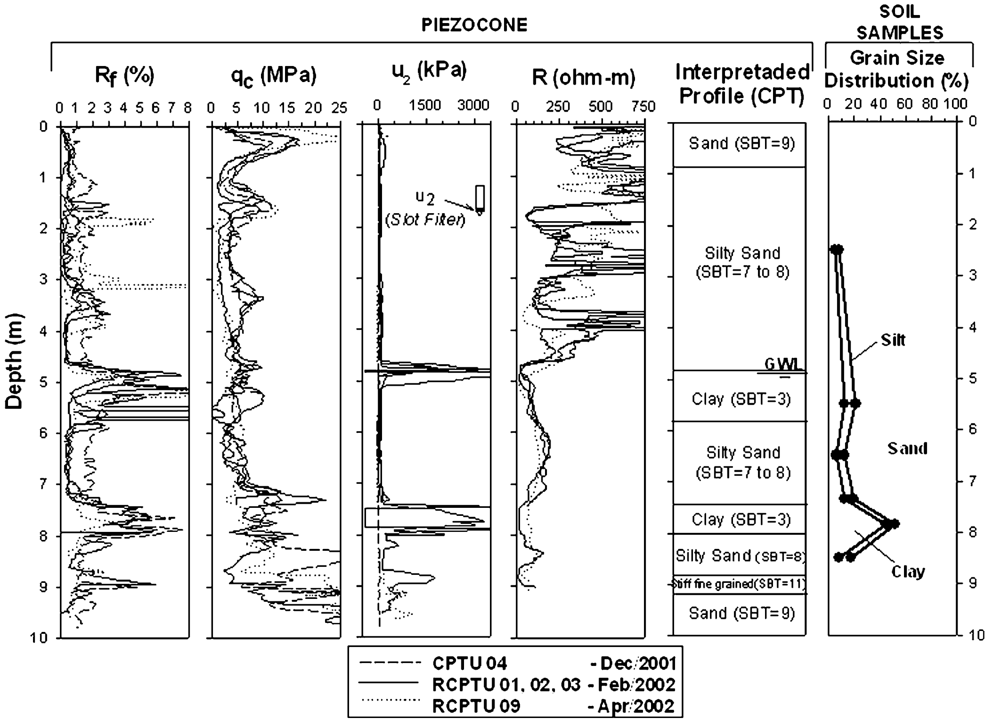


Table 2 Estimate of the soil formation factor (FF) for water samples collected in the same period the RCPTU tests were carried out

Depth (m)	Well/test	R (ohm m)	FF	Interpretated layer
7.0	PT-1 (Feb/2002)	26.3	1.83	Silty sand
	RCPTU 4, 6	48.2		
6.0	PT-2 (Feb/2002)	69.4	2.24	Silty sand
	RCPTU 1, 2, 3	155.4		
7.0	PT-3 (Jul/2002)	18.8	1.55	Silty sand
	RCPTU-15	29.1		

allowed for estimates to be made of the soil's formation factor (FF), given by the following expression (Archie 1942)

$$FF = \frac{\rho_b}{\rho_f} = a \cdot n^{-m} \cdot S_r^{-s}. \qquad (3)$$

where FF = formation factor, ρ_b = bulk resistivity of the soil; ρ_f =fluid resistivity; a, m, s = factors that depend on the soil's mineralogy; n = porosity; S_r = degree of saturation.

The interpretation of the resistivity values in the unsaturated zone (Figs. 14, 15) indicates that this parameter is strongly affected by the degree of saturation of the soil mass, which is in accordance with Archie's law. Figure 15 shows the differences between the resistivity values at 1.5–2.0 m depth for the RCPTU-9 test and all the other tests (RCPTU-1, 2 and 3), which were carried out in the rainy season. On the other hand, RCPTU-15 was carried out in a drier season than RCPTU-14 and the resistivity values up to 2.0 m depth were higher. Resistivity values at depths of more than 2.0 m were highly variable in the unsaturated zone and could not be interpreted.

The apparent resistivity values shown in Fig. 13, as well as those determined in the RCPTU tests (Figs. 14, 15), indicate congruence for the saturated zone, since tests RCPTU-4, 5, 6 and 11 showed lower resistivity values than tests RCPTU-1, 2, 3 and 9 (Fig. 15). Note that the former are closer to a patch of apparent resistivity lower than 75 ohm m than are the latter (Mondelli 2004). Note, also, that the resistivity values determined from the piezocone were congruent with the resistivity contrasts presented in the map in Fig. 13, which indicates that the RCPTU-15 test was the one closest to the plume and showed the lowest resistivity values. On the other hand, the RCPTU-14 test, which was carried out slightly farther from the plume, albeit also in a region with traces of contamination, showed higher resistivity values than the RCPTU-15 test.

Monitoring wells

Three campaigns to collect water samples from the permanent monitoring wells were carried out during this study. The first and third campaigns were conducted during the rainy season and the second during the dry season.

Several campaigns to collect water samples from the temporary monitoring wells were carried out during a year, which yielded concentrations of the metals Fe and Pb only in the last campaign. These results were compared with those obtained from the permanent monitoring wells, as shown in Table 3.

Overall, it can be stated that the wells most strongly affected by the contamination plume are PW-1 and TW-3, followed by PW-7, which presented the lowest values of electrical resistivity and the highest values of chlorides, BOD, COD and several heavy metals, confirming the signs of contamination revealed by tests RCPTU-14 and RCPTU-15 conducted west-northwest of the landfill. These signs of contamination close to the landfill were confirmed by the chemical analyses of the water samples shown in Fig. 14.

The results of the analyses of water samples from wells PW-5 and TW-1 confirmed the low resistivity blotch that appeared on the map of apparent resistivity at the 15 m theoretical depth, west of the landfill. The contamination found in these two wells may indicate interference from a cesspit located in their proximity (Fig. 2).

This finding indicates that care must be taken in the interpretation of data from monitoring wells, and that the physical and geological factors of the site must be taken into account, as well as other possible sources of contamination in the area.

Laboratory tests

Figure 16 shows the values of hydraulic conductivity of the soil surrounding Bauru's MSW landfill as a function of the confining pressure for water and for a saline solution. As expected, the hydraulic conductivity decreased as the confining pressure increased. The hydraulic conductivity for the saline solution was approximately threefold higher than for distilled water, which varied from 1×10^{-7} m/s to 6×10^{-7} m/s under the applied confining pressures.

The hydraulic conductivity of the soil around Bauru's MSW disposal site determined in column and falling head tests (10^{-7} m/s) can be considered low for sandy soils, but are above the maximum limit of 10^{-9} m/s for bottom liners, according to most environmental regulations.

Table 3 Average values of the parameters obtained from the chemical analyses carried out for the various campaigns to collect water from the monitoring wells

Well	GWL (m)	*R* (ohm.m)	BOD (mg/L)	COD (mg/L)	Cd (mg/L)	Cr (mg/L)	Fe (mg/L)	N*i* (mg/L)	Pb (mg/L)	Zn (mg/L)	Chloride (mg/L)
PW-1	8.7	17.9	14.3	56.3	–	0.17	24.2	0.09	0.03	0.12	114.0
PW-2	7.3	161.8	7.3	25.7	–	0.14	28.4	0.01	0.02	0.19	3.8
PW-3	10.4	45.6	4.7	15.0	–	0.11	2.30	–	–	0.07	3.7
PW-4	30.7	33.9	1.8	10.0	0.02	0.08	1.25	0.02	0.04	0.15	2.8
PW-5	6.3	17.1	6.7	22.7	0.08	0.11	9.44	0.05	0.06	0.13	15.9
PW-6	2.9	220.8	8.3	34.7	–	0.07	2.05	0.08	0.04	0.13	3.1
PW-7	6.5	27.1	7.7	32.7	–	0.25	50.8	0.05	0.01	0.16	55.2
PW-8	6.9	48.6	5.7	15.7	–	0.08	0.50	–	0.01	0.11	29.9
PW-9	6.6	23.6	3.3	15.0	–	0.09	2.14	0.01	0.03	0.04	59.5
TW-1	7.0	37.9	10.0	22.1	–	–	11.1	–	0.16	–	11.5
TW-2	6.0	73.4	20.7	12.7	–	–	0.03	–	0.08	–	13.0
TW-3	7.0	15.7	40.6	47.5	–	–	62.2	–	0.53	–	93.0
TW-4	7.0	42.4	30.8	20.1	–	–	0.07	–	0.11	–	18.7
TW-5	2.0	142.3	5.3	11.2	–	–	5.55	–	0.15	–	8.4

PW permanent wells, *TW* temporary wells, *GWL* groundwater level, *R* electrical resistivity; *BOD* biological oxygen demand, *COD* chemical oxygen demand

Detection limits: *R* = 100,000 ohm m or *C* = 0.1 µS/cm, *BOD* = 1 mg/L, *COD* = 1 mg/L, *Cd* = 0.0006 mg/L, *Cr* = 0.005 mg/L, *Fe* = 0.005 mg/L, *Ni* = 0.008 mg/L, *Pb* = 0.01 mg/L, *Zn* = 0.002 mg/L, *Chloride* = 0.1 mg/L

Figures 17 and 18 present, respectively, the electrical conductivity of the effluents from the columns percolated with metal solution and with leachate plus metals as a function of the percolated volume. In Fig. 17, note that the conductivity increased rapidly up to 0.25 percolated pore volumes and slowly after that point, tending to reach the solution's initial conductivity (72.9 µS/cm). In theory, this would indicate that the pollutant front reached the other extremity of the test specimen, but the effluent metal concentrations were still practically 0 at almost 3.5 percolated pore volumes. The same behavior was observed in the column test with leachate (Fig. 18), since the breakthrough curves of the metals were just beginning to form when the effluent conductivity reached the value of the influent leachate (15,140 µS/cm), at about 3.5 percolated pore volumes.

In the column tests, the pH of the metal solution, which was 8, dropped to about 5.5 during percolation through the soil. On the other hand, the pH of the effluent from the column tests with leachate dropped from 8 to 4.5 up to a percolated pore volume of 0.7, after which the pH rose to its original level. The same behavior was observed in the batch tests, i.e., the pH of the filtrates of the metal solution was 4.5 while the filtrates from the leachate remained at about 8.5. This indicates that the leachate's pH was less affected by percolation through the soil.

As for the batch equilibrium tests, the sorption isotherms obtained for the metal solution were convex in relation to the axis of the abscissas, indicating that adsorption degree(*S*) increases along with the increase in equilibrium concentration (C_e) (Fig. 19). The sorption isotherms for the leachate were slightly concave in

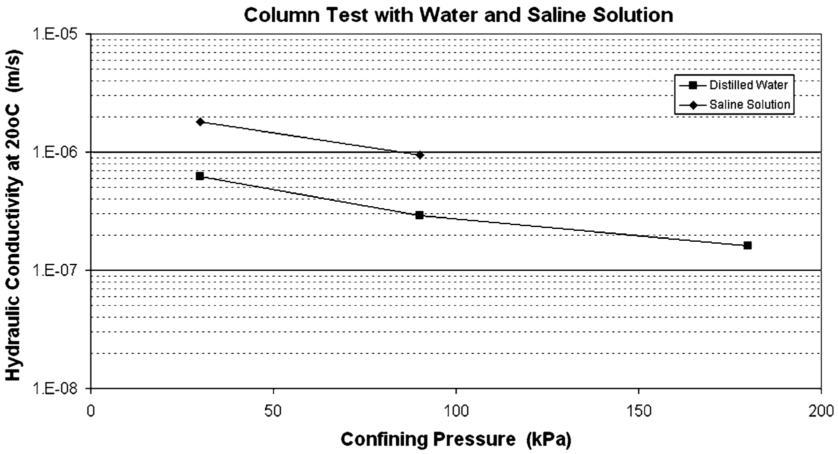


Fig. 16 Hydraulic conductivity as a function of confining pressure for water and saline solution using undisturbed soil samples from the surroundings of Bauru's MSW disposal site

Fig. 17 Electrical conductivity as a function of percolated pore volume—metal solution—for an undisturbed soil sample from the surroundings of Bauru's MSW disposal site

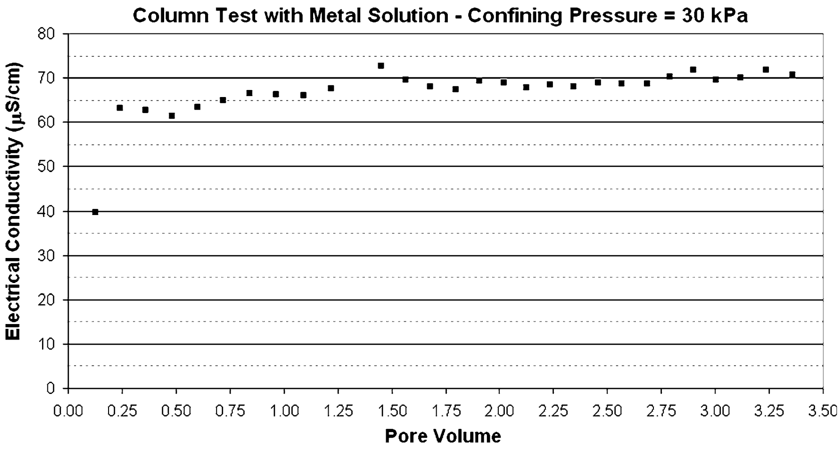
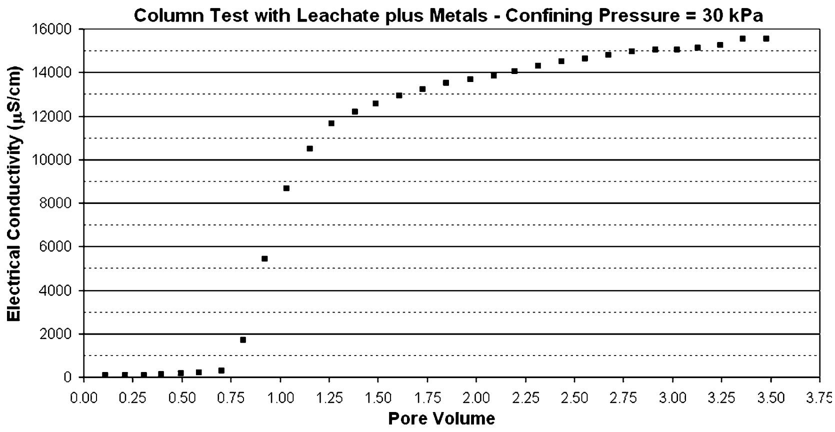


Fig. 18 Electrical conductivity as a function of percolated pore volume—leachate plus metals—for an undisturbed soil sample from the surroundings of Bauru's MSW disposal site



relation to the axis of the abscissas, but presented no visible stabilization of adsorbed solute mass (Fig. 20). In both cases, the linear isotherm was the one that best described the results, presenting a better fit to the testing data.

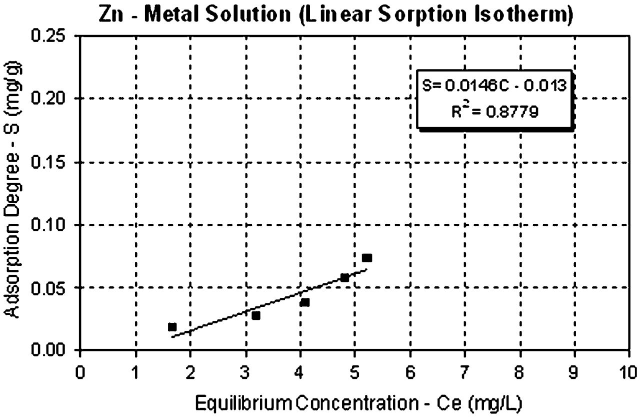


Fig. 19 Linear sorption isotherm of Zn obtained for the metal solution for an undisturbed soil sample from the surroundings of Bauru's MSW disposal site

Table 4 shows values of K_d and R_d obtained in the batch tests, where K_d represents the partition coefficient (the angular coefficient of the linear sorption isotherm) and R_d is the retardation factor given by Eq. 4:

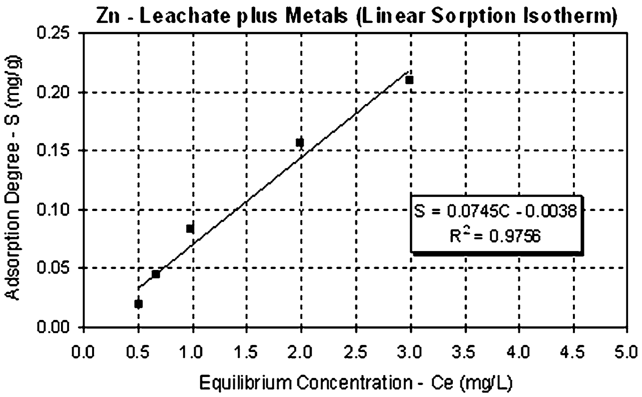


Fig. 20 Linear sorption isotherm of Zn obtained for the leachate plus metals for an undisturbed soil sample from the surroundings of Bauru's MSW disposal site

Table 4 Results of the batch equilibrium tests on soil from the surroundings of Bauru's MSW disposal site (C_0 initial concentration of the solution; R^2 correlation factor)

Parameter	C_0 (mg/L)	K_d (mL/g)	R^2	R_d
Metal solution				
Ni	8.6	31.0	0.7802	104
Zn	6.0	14.6	0.8779	50
Cd	8.4	21.6	0.8964	73
Pb	0.1	–76.4	0.6219	–
Leachate plus metals				
Ni	8.8	7.2	0.7110	25
Zn	5.1	74.5	0.9756	249
Cd	2.6	55.6	0.9489	186
Pb	14.2	298.4	0.9934	996

$$R_d = 1 + \frac{\rho_d}{n} \cdot K_d. \tag{4}$$

where ρ_d = dry density, n= porosity.

A comparison of the K_d and R_d values in Table 4 with the values reported for other soils indicates that this soil has a high retention capacity relative to the studied metals. Ritter (1998) classified the solute as essentially immobile when K_d is higher than 10. On the other hand, R_d values display the same order of magnitude as those obtained by Nascentes (2003) with similar soil and range of tested concentrations. Azevedo et al. (2003) point out that the high R_d values obtained by Nascentes (2003) may have been the result of the low concentrations of metals used in the pollutant solutions. However, the metal concentrations used in this investigation are consistent and even higher than those measured in the leachate from Bauru's MSW landfill (Mondelli 2004), indicating the possibility of a high level of metal retention actually occurring in situ.

Conclusions

The surficial geoelectrical tests allowed for the detection of the shape and direction of the contamination plume and were essential in indicating the locations for the piezocone tests and soil and water samplings in the study area.

The piezocone proved to be a very repeatable test and allowed for the identification of better spots for water sampling. Unfortunately, this technique presented some limitations for tropical soils, since the groundwater level is sometimes deeper than the layer which is impenetrable to the cone. Another important aspect in tropical soils is that soil genesis and unsaturated conditions affect soil behavior; therefore, soil and water sampling are required to support the interpretation of RCPTU tests.

The results of the resistivity piezocone tests (RCPTU) carried out in the area of the Baurús MSW disposal site allowed for the identification of contaminant-saturated zones, which were confirmed through the combined analysis of the results of the geoelectrical tests and the soil and water samples. The combined analysis of all the test campaigns indicates that the contamination plume has already overreached the landfill's west-northwest borders.

The column and batch equilibrium tests indicated that this soil has a good capacity to retain Ni, Zn, Cd and Pb. On the other hand, values of pH solution and electrical conductivity were not much influenced by the percolation through the soil, possibly because of the complex interaction with other constituents of the leachate, such as organic matter and high content of Na, K, Ca and Mg. The association of these observations indicates that the pollution around Bauru's municipal solid waste disposal site may be occurring very slowly, but already shows signs that site remediation need to be adopted.

The consideration of the site's physical and geological features is also fundamental to monitor the evolution of the contamination plume. Periodic campaigns to collect and analyze the water from the monitoring wells are ongoing in order to control the environment's natural characteristics of the site.

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