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ORIGINAL ARTICLE

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3D behaviour of contamination in landfill sites using 2D resistivity/IP imaging: case studies in Portugal

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Abstract Aiming at defining a valid spatial contamination model, resistivity and induced polarization (IP) measurements were used to investigate contamination plumes in the vicinity of two municipal landfills (Ovar and Ílhavo). Previous geophysical surveys and underground water samples confirmed the contamination. However 2D resistivity/IP surveys enabled in obtaining a more accurate spatial model. The Ovar survey consisted of two profiles with nine Wenner soundings each; the Ílhavo survey was carried out along two individual lines using a Wenner standard pseudo-section. In both situations, negative IP values were found associated with positive IP values, which can be explained mainly by 2D or 3D geometric effects caused by the presence of the conductive plumes. The data were modelled using a 2D inversion program (RES2DINV) and the resulting resistivity and chargeability distributions were displayed as pseudo-sections. The resistivity and chargeability pseudo-sections define the contamination plumes and the sedimentary structure. These case studies illustrate the advantages of 2D resistivity/IP surveys for the mapping of shape and dimension of contamination associated with landfills.

Keywords Contamination plume · Landfill · Resistivity · Chargeability · 2D inversion · Aveiro · Portugal

Introduction

Groundwater resources are very important for public water supply. Many of the environmental problems are directly or indirectly related to the location of groundwater and its protection from contamination sources of various kinds (Sharma 1997).

It is well known that groundwater contamination can easily occur and carry on for a long time, because recovery is slow and difficult. The problems associated with municipal, abandoned or non-controlled landfills are of general concern, especially because of the interactions between the hazardous contents of the leachates derived from them and the groundwater.

In view of the large number of poorly documented landfills, fast and inexpensive methods to investigate the shallow subsurface are becoming increasingly important. Non-invasive surface geophysical techniques are increasingly used for landfill characterization, particularly where intrusive methods are hazardous and pose significant risks to health and safety.

Physical properties of many rocks are significantly altered by the presence of water in pores and fissures, the degree of alteration varying with the nature and content of the contaminants present; this makes it possible to locate water-bearing structures and to investigate the quality of water using appropriate geophysical techniques (Sharma 1997).

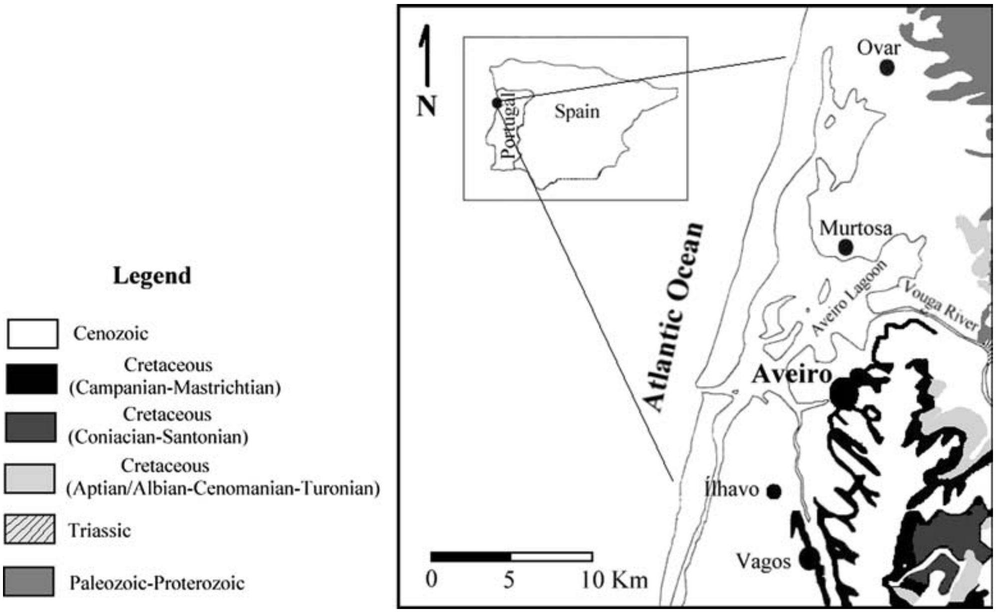


Fig. 1 Location and geological setting

Geophysical methods, including the measures of soil electrical properties, have been particularly applied (Benson et al. 1997; Sauck et al. 1998; Pokar and Loke 1998; Sauck 2000; Atekwana et al. 2000; Porsani et al. 2004), because the electrical conductivity of contaminated formations tends to be higher than that of uncontaminated formations, as the dissolved salts due to pollutants diminish the electrical resistivity of the formations containing them.

The addition of IP data to the more traditional resistivity data helps to differentiate between clay and sand containing salt water, both of which respond as low-resistivity layers, because saline waters (because of high ionic conductivity) typically show a poor IP response while clayey layers show high chargeability, which allows discrimination between these two formations (Sharma 1997).

Ovar and Ílhavo landfills have been the disposal sites of urban solid waste for a long time. The negative environmental impacts caused by wastes deposition are manifested in the landfills, adjacent zones, namely, in the groundwater, because these structures are located above permeable and porous formations, which aid in contamination scattering (Belmiro et al. 1999). The fact that these landfills are located in the vicinity of groundwater used for domestic consumption, urged the investigation of possible groundwater contamination.

Geological and hydrogeological settings

The study areas are located in the Aveiro region (Fig. 1), which corresponds to the northern sector of the Portuguese Occidental Meso-Cenozoic sedimentary basin.

In both areas local geology consists mainly of Quaternary sedimentary units composed of alluvium, sand dune, eolian sands, organic mud and gravel formations of the Pleistocene, which disconformably overlie older Cretaceous/Paleozoic sediments. The upper part of the Cretaceous formations consist of clays and clayey formations, known as Vagos Clays. The Paleozoic formations consists of schists and greywackes. The Quaternary formations contain on top a free aquifer of the Holocene separated by mud layers from a lower and semi-confined aquifer associated with Pleistocene formations of the lower Quaternary (Teixeira and Zbyszewski 1976; Barbosa 1981; Silva 1990; Matias 2000). The mud layers constitute a non-homogeneous aquitard, which does not isolate the lower aquifer and therefore contamination can reach the lower structure. These freshwater aquifers are recharged by direct infiltration of surface water.

Previous investigations

In the Ovar landfill, the first investigation project took place in 1991 (Matias et al. 1994) and involved conventional site characterization techniques, including EM (Geonics EM34) and DC resistivity soundings followed by drilling to sample underground water in low-resistivity areas. The results allowed to conclude that: (1) both the groundwater flow and free aquifer contamination in the landfill area extend westwards to the Atlantic Ocean; (2) both the aquitard and semi-confined aquifers are contaminated.

These studies enabled local authourities to raise the necessary funding for future monitoring of the area and also for the landfill sealing in 1998.

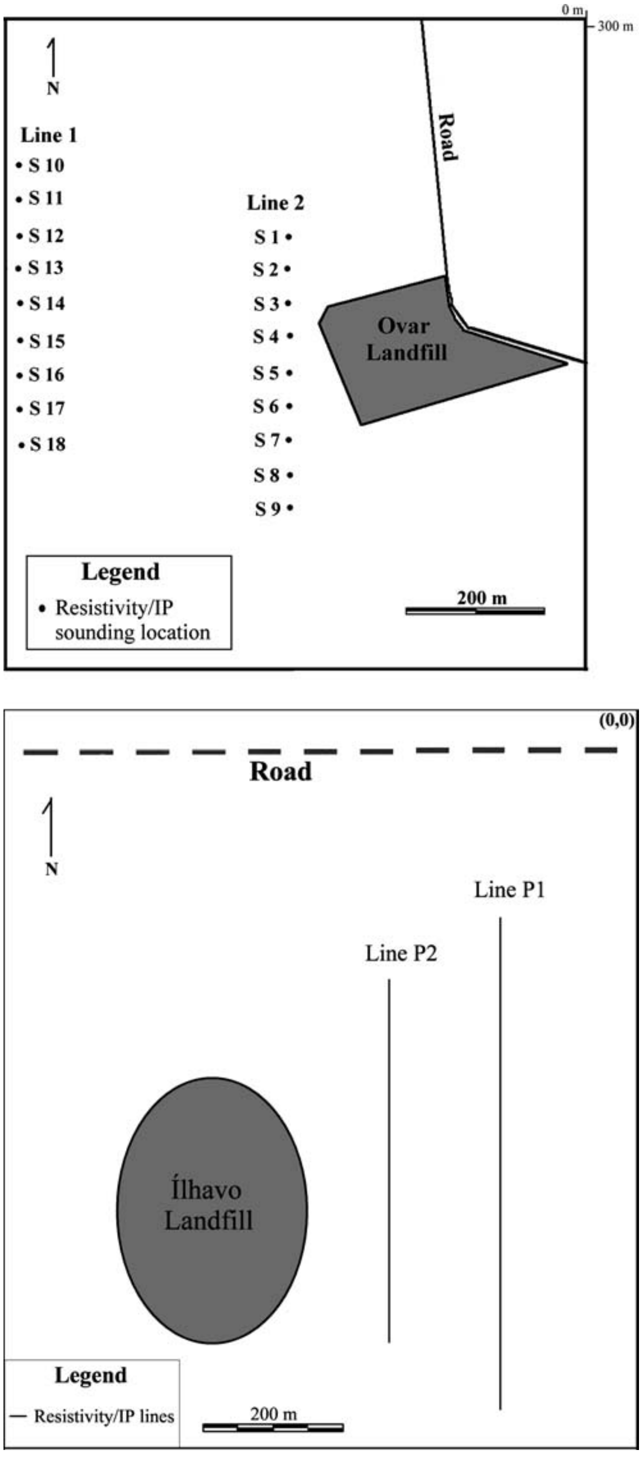


Fig. 2 Location of profiles. **a** Ovar landfill; **b** Ílhavo landfill

In 1999, the landfill area was studied to evaluate contamination evolution. The methodology used in this study was the same as that used in the previous one, in 1991, but including the resistivity/IP profiles (Fig. 2a).

The Ílhavo landfill study was performed after landfill sealing. Previous conventional site characterization techniques included EM soundings (Geonics EM31 and EM34), GPR profiling (antennas of 25 MHz and 100 MHz) and underground water sampling and chemical analysis (Belmiro et al. 1999).

The results confirmed the contamination and allowed to define the plume behaviour. This preliminary study allowed to conclude that: (1) the groundwater flow and the free aquifer and semi-confined aquifer contamination in the landfill area extend eastwards to the Aveiro Lagoon; (2) plume evolution is heading eastward and spreading in the North–South direction. Based on this study, two resistivity/IP profiles were performed in the contaminated area (Fig. 2b).

Field studies

Instrumentation

The resistivity/IP survey was undertaken using a Scintrex generator, which supplied a 2-s square wave to a transmitter circuit. The receiver circuit (IPR-8, Scintrex) allows measuring both chargeability and resistivity. Concerning induced polarization, six integrant channels (M_{61}, ... , M_{66}) operate during a discharge cycle of the decay voltage signal. Raw data was processed to obtain the decay curve from New Mont Standard and mV/V data was obtained for the 1-s reference. Current settings of 60–200 mA for Ílhavo and 10–90 mA for Ovar were used, with a time interval for chargeabilities of 0.2 s.

Survey design

The Ovar survey consisted of two lines (1 and 2) with nine Wenner soundings each, 50 m apart and with a maximum inter-electrode spacing of 64 m. The distance between the profiles was 400 m.

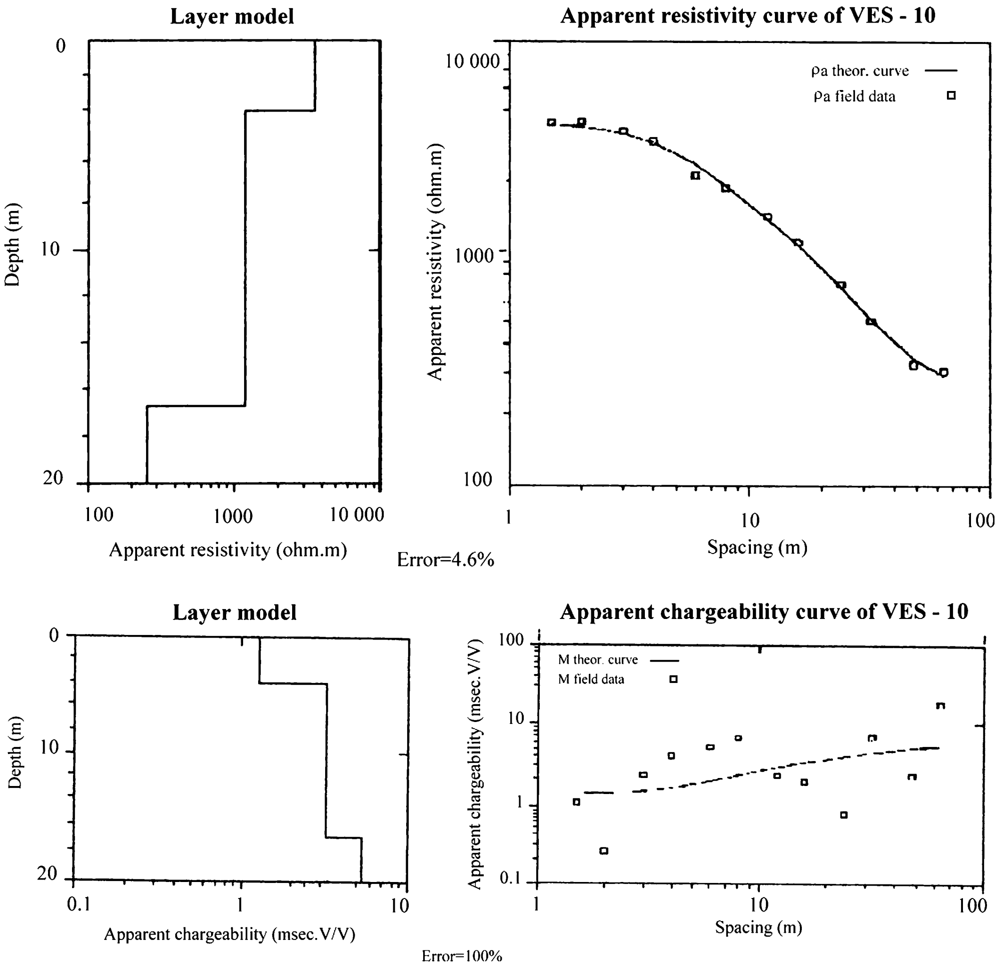
The Ílhavo survey was carried out using a Wenner standard pseudo-section. Thus, measurements were carried out along two individual lines (P_1 and P_2) with unit electrode spacing of 10 m. The ‘‘a’’ spacing (Wenner spacing) used was 10, 20, 30, 40 and 50 m. The distance between the lines was 170 m.

In both landfills, the survey profiles have a general North–South orientation and are perpendicular to the expected contamination plume.

Numerical inversion

The resistivity and IP field data were modelled using the 2D finite difference inversion program RES2DINV

Fig. 3 Results of VES-10 Ovar line 1. Left: the layer model obtained from 1D inversion; Right: field data and the theoretical curve deduced from the layer model



(Loke 2000). This program attempts to achieve convergence between the observed apparent resistivity and chargeability values and those from a model obtained using the Gauss–Newton smoothness constrained least squares method. The inversions of the resistivity and IP data sets were done separately. The obtained resistivity model was used for the inversion of the IP data. In both cases, the inversion was carried out to the point at which the difference between consecutive RMS errors was less than 5%. A 0.25 vertical–horizontal flatness filter ratio and large rectangular inversion blocks were used to improve the generation of quasi-horizontal sedimentary models.

Several IP measurements were found to be negative. The negative IP can be due to geometrical effects of the depolarization transient field, which results from the position of the bodies or polarizable layers in relation to the ground surface where the measurements are carried out (Bertin and Loeb 1976; Nabighian and Elliot 1976; Hallof and Pelton 1980). However, negative IP effects can also be found in horizontal multilayered situations where the lowest layer is more conductive than the layer immediately above it and the uppermost layer is at least somewhat polarizable. In cases of three horizontally geo-material layers, these effects can also occur whenever the geoelectric section is of the K type ($\rho_1 < \rho_2 > \rho_3$) or Q type ($\rho_1 > \rho_2 > \rho_3$). The negative IP effects can be due to electromagnetic coupling.

In these surveys, the occurrence of negative IP values is due to 2D or 3D geometric effects (Loke, personal communication, 2000) caused by the presence of the conductive plumes. In the Ovar landfill, the negative IP values can also be due to the fact that the geoelectric section is of the type Q (Fig. 3).

The field data shows that positive values are more frequent than negative ones and that negative values are more likely with larger electrode spacing, concretely, whenever the current reaches the conductive regions (plumes). The plumes position and shape are seen in the signal of chargeability values. However, these negative values can also result from electromagnetic coupling, though in the field works the reels were placed perpendicularly and the distance between wires was increased in order to reduce this effect.

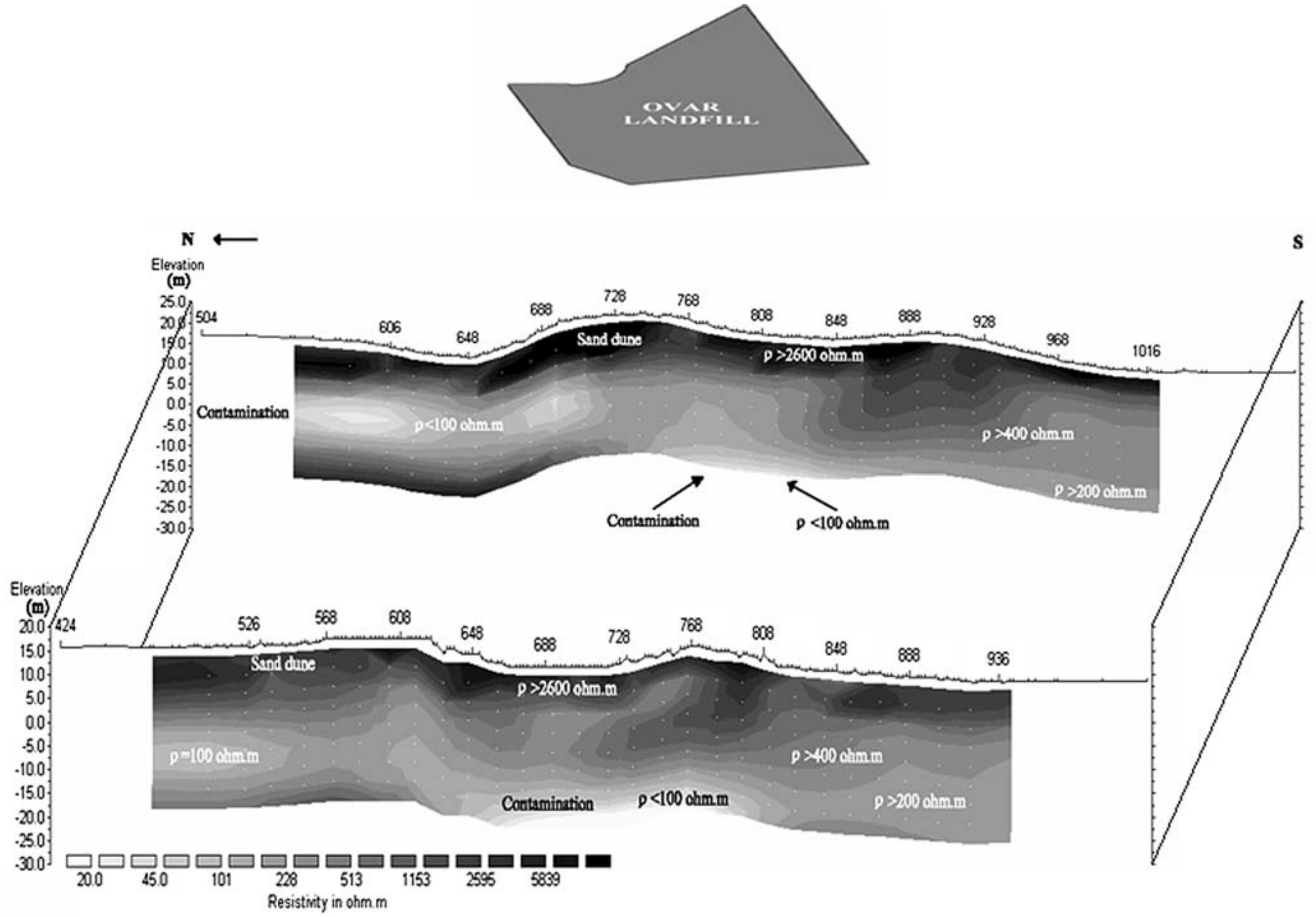


Fig. 4 Resistivity model for the Ovar landfill with contaminated areas

In both surveys the M_{63} apparent chargeability data were used. The 2D IP modelling procedure included all positive and negative values, though the chargeability models were not displaying negative values to facilitate their interpretation.

Concerning the Ovar landfill, first, the 1D inversion of the electrical soundings was done with an inversion program allowing for a distortion in the IP curves where such negative effects occur (Nabigham and Elliot 1976). Figure 3 depicts an example of one of the 1D inversions. According to Loke (personal communication, 2000), the 2D model simulation shows very strong lateral variations, and so it can be expected that the 1D IP solutions are probably not very accurate in this survey area. Therefore, the inversion based on pseudo-sections was carried out using the field conventional 1D data sets. The inversion of the chargeability and resistivity field data was done using the non-conventional arrays (mixed array) option. Only 63 of the 108 performed measurements were used, because just “a” = 8 spacing data were considered. In the inversion data, the unit electrode spacing was 8 m.

In the Ílhavo landfill survey, a total of 530 individual apparent resistivity/IP measurements were performed. The same number of sampled data points was used in the resistivity and IP models in order to get the 2D inversions. For the Ovar landfill, RMS errors of 5.9 % and 12.6 % for resistivity and 3.0 % and 2.9 % for chargeability were obtained after five iterations. For Ílhavo, RMS errors of 11.7 % and 17.9 % for resistivity and 9.0 % and 8.8 % for chargeability were obtained after five iterations.

Results and discussion

The resistivity and chargeability models (Figs. 4, 5, 6 and 7) reveal horizontal layering, which is in accordance with regional geology. The resistivity pseudo-sections show a more resistive shallow layer ($\rho > 2600$ ohm m) that corresponds to dry sand dune. The resistivity decreases with depth, which is related with the presence of a saturated zone.

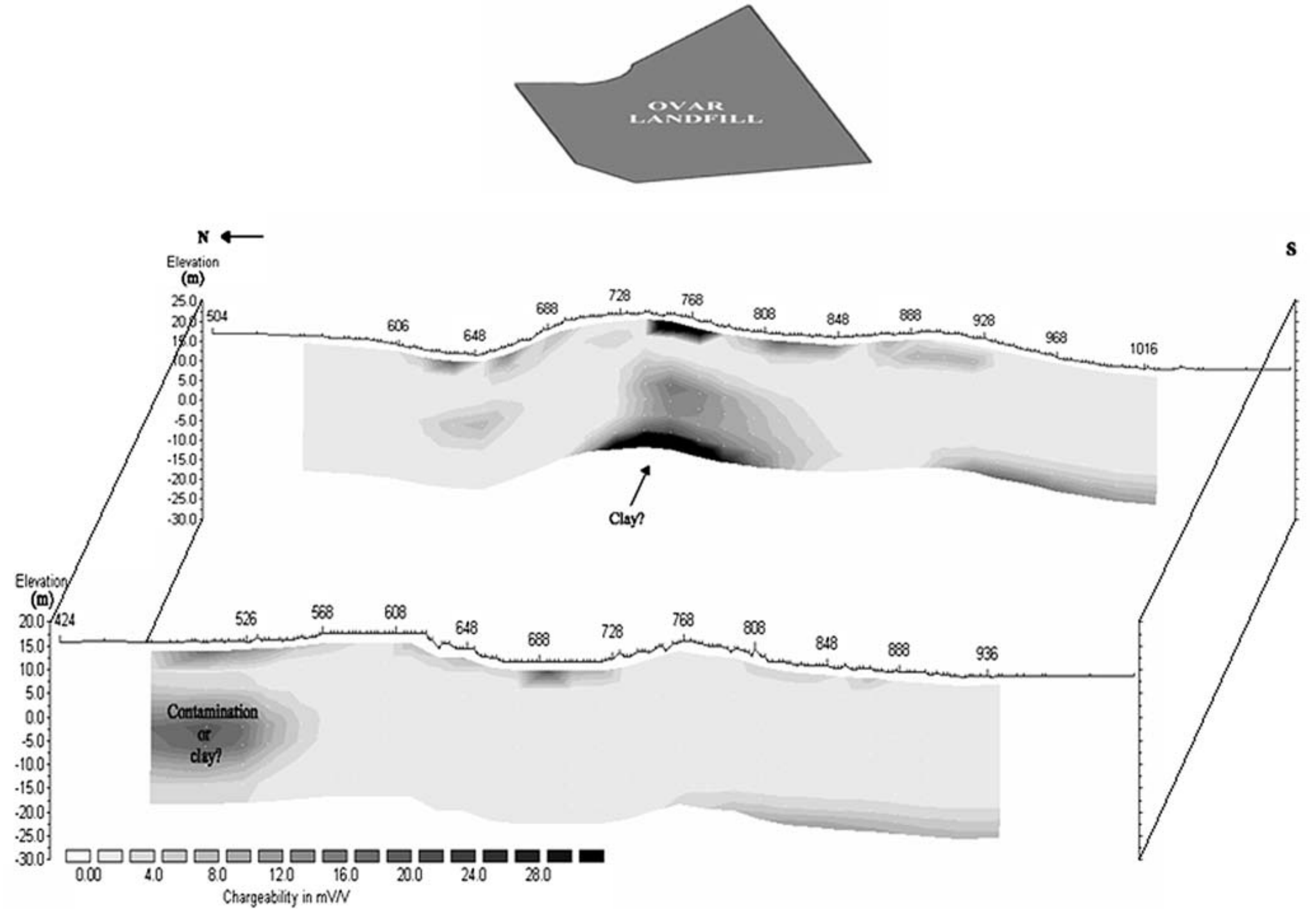


Fig. 5 Chargeability model for the Ovar landfill

In the Ovar resistivity model (Fig. 4) the conductive zones are visible laterally and limited in depth ($\rho < 100$ ohm m), being associated with the known polluted area as well. However, line 1, which is more distant from the landfill, shows lower resistivity values compared with line 2 (Fig. 4), which is closer to the focus (Fig. 2a). This fact can be related to a likely salt intrusion in line 1, owing to its lower distance to the sea (500 m) compared with line 2 (900 m). The topography can disturb resistivity values as well, because a valley exists in line 1. The resistivity model also shows a high apparent resistivity contrast between the areas considered as contaminated and uncontaminated. The contaminated area depth ($\approx$15 m) shows that contamination reaches the lower semi-confined aquifer.

IP inversion (Fig. 5) shows high chargeability values near the landfill (line 2), interpreted as an increment in the clay formation contents; on the other hand, line 1, further away from the landfill, shows lower IP values that must correspond to sandy formations or to the influence of possible salt intrusion. However, both sections show higher chargeability values to the right and deeper areas of the chargeability inversion distribution that could be related to local stratigraphy.

In the Ílhavo resistivity model (Fig. 6) it is possible to distinguish, below the water table (at about 3.8 m of depth), two levels of low resistivity (<45 ohm m), which were identified as, contaminated sand. This is in accordance with the high conductivity of the water sampled ion into the S4 borehole (>1999 μS/cm) located at 700 m in line P1 and with the georadar results and hydrogeological model proposed for the region (Belmiro et al. 1999) that reveal an eastward evolution of the contamination plume and a North–South in-depth dispersion.

Distributions of inverted resistivity and IP values show a good correlation with local boreholes (S3 and S10). Dark points on the logs correspond to mud formations and light points to sands. In general mud formations show lower resistivity than sand formations. This is not the case for the inverted sections owing to the contamination of the sand layers, in the studied region.

In the contaminated sand areas, the chargeability model (Fig. 7) shows high chargeability values, which

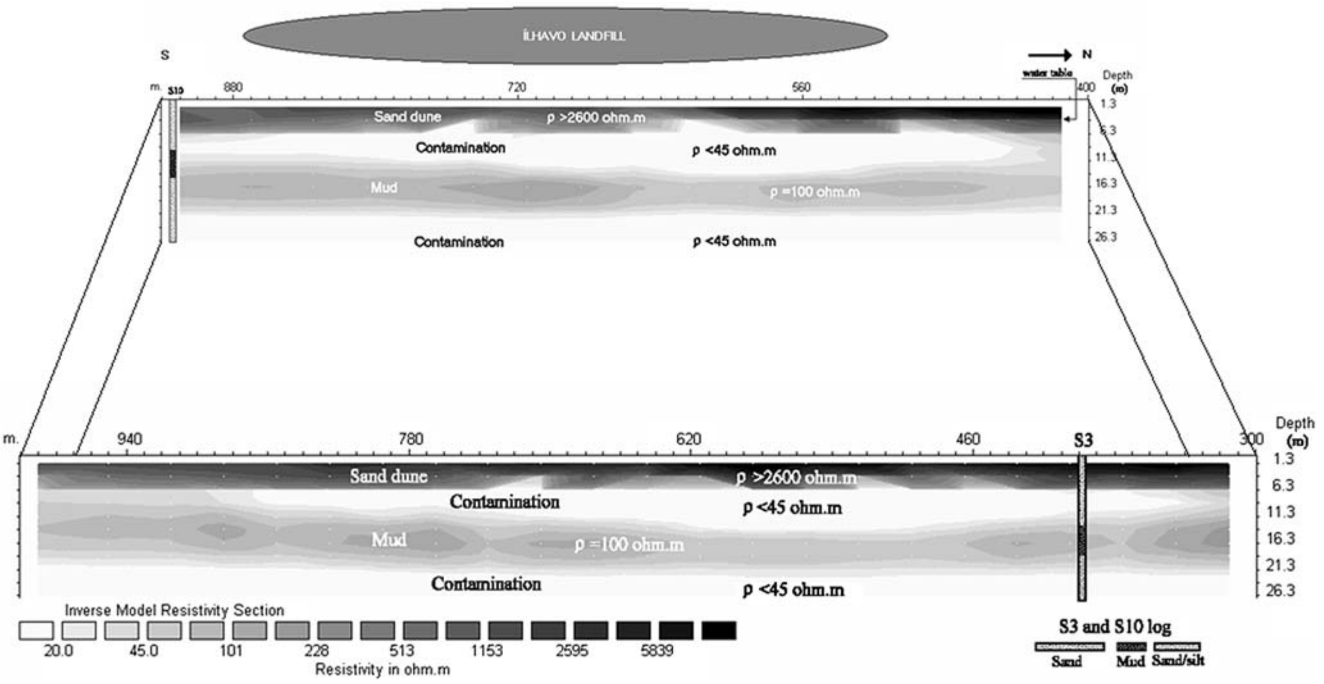


Fig. 6 Resistivity model for the Ílhavo landfill with contaminated areas and interpreted from borehole logs (S3 and S10) and local geology

can be related with contamination. Therefore, in this case IP data is very important to identify the mud layer in the overall sand sequence.

The resistivity/IP data confirm that contamination extends from the free aquifer to the lower semi-confined aquifer, which can be due to discontinuous muddy levels that allow the hydraulics connection between the two aquifers or rupture of that level. These discontinuities are likely to have been induced by mechanic means when the landfill was deepened.

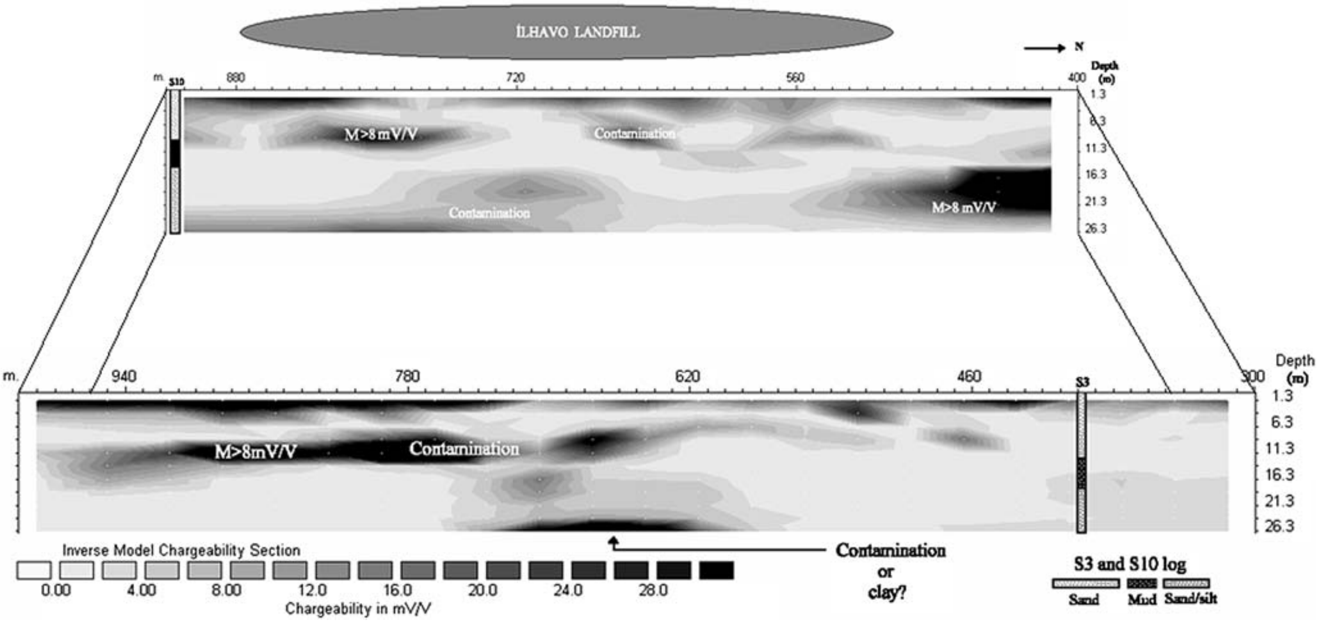


Fig. 7 Chargeability model for the Ílhavo landfill with contaminated areas and interpreted from borehole logs (S3 and S10) and local geology

Conclusions

The occurrence of IP negative values can be due to 2D or 3D geometrical effects related with contaminant plume position and shape. In situations of large electrode spacing, these negative values can also result from electromagnetic coupling.

In both surveys, the resistivity and chargeability pseudo-sections define the contamination plumes and the sedimentary structure.

For Ovar, the results obtained with resistivity/IP methods are in accordance with EM data and physical and chemical properties of water samples (Matias et al. 1999). These show that the contamination of the landfill involving area carries on and evolves westward, in the direction of Atlantic Ocean, as in 1991. Although, with respect to 1991, the resistivity of the contaminated zone diminished from 150–300 ohm m (Ramalho et al. 1998) to resistivity values of less than 100 ohm m. This is in accordance with EM34 and water sample results that show an increase in the conductivity plume in the area adjacent to the landfill between 1991 and 1999 (Matias et al. 1999), revealing an increase in contamination intensity.

For Ílhavo, the geophysical methods used in the first study applied to the landfill area allow to define the behaviour of the contamination plume. The resistivity/IP data are in accordance with EM and georadar data (Belmiro et al. 1999). The resistivity sections show two contamination levels, one corresponding to the free aquifer and another to the semi-confined aquifer, both installed in sands. The plume developed eastward towards the Aveiro Lagoon and laterally in the North–South direction.

The IP data shows which high chargeabilities are associated with contaminated areas and which are associated to zones with high clay formation content. In this kind of sedimentary mud/sand layering, the IP gives a better understanding of the geological structure, and can be a good investigation tool in combination with resistivity and other geophysical methods.

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