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ORIGINAL ARTICLE

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Electromagnetic methods to characterize the Savoia di Lucania waste dump (Southern Italy)

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Abstract The aim of this work is the joint application and integration of non-invasive geoelectrical methods for studying the landfill of Savoia di Lucania (Southern Italy). This landfill for its engineering features and small dimensions (70 m × 30 m × 6 m) represents an optimal test site to assess a geophysical survey protocol for municipal solid waste landfills investigation and monitoring. The landfill of Savoia di Lucania has been built with a reinforced concrete material and coated with a high-density polyethylene (HDPE) liner. Three electrical resistivity tomographies (ERT), two self-potential (SP) map surveys and one induced polarization (IP) section have been performed, both in the surrounding area and inside the waste landfill. The geophysical investigations have well defined some buried boundaries of the landfill basin and localized the leachate accumulation zones inside the dumpsite. Comparison of our results with other engineering and geological investigations could be the key for evaluating the integrity of the HDPE liner. Finally, the joint use of the ERT, IP and SP methods seems to be a promising tool for studying and designing new monitoring systems able to perform a time-lapse analysis of waste landfill geometry and integrity.

Keywords Electrical resistivity tomography · Self-potential · Induced polarization · Landfill

Introduction

Waste dumps play an important role in the environmental sciences, and the increasing demand for larger space for domestic and industrial wastes makes them a necessary part of the human cycle of activities. The main problem, related to the presence of a waste dump, is the leakage of contaminant fluids into the subsoil and groundwater due to the possible break-up of the covered liner. Therefore, it is crucial to understand the interactions of a waste disposal with the surrounding environment (Bernstone et al. 2000).

The risks of the municipal waste dumps generate a significant interest in environmental agencies. However, to check dumpsite-tight problems in the time, it is necessary to have more information about the subsurface within a short time and in a continuous way. Therefore, geophysics could play a key role in a monitoring system on waste landfill. In the last years, geophysical techniques became a valuable diagnostic tool for environmental problems owing to their cost-effective, non-intrusive approach and fast acquisition time. Moreover, in order to improve the reliability of the geophysical information, the use of several geophysical techniques in the same investigation area is a necessary practice in environmental problems (Steeples 2001).

Of the several geophysical methods used in waste landfill studies, the electromagnetic methods are the most popular owing to their ability to detect variations in fluid content, chemical composition and temperature in the subsurface. Electrical resistivity tomography (ERT), self-potential (SP) and induced polarization (IP) are part of them. The ERT consists in measuring the resistivity values (ohm m) of the subsoil computed from the electrical field associated with the injection of current at the ground surface. The IP measures the voltage decay between two potential electrodes after the current has been turned off and the physical parameter is the chargeability (mV/V). The SP is a passive method and measures the natural electrical potential distribution (mV) at the ground surface with non-polarizable electrodes.

These geophysical methods are widely used in the study of different environmental and engineering problems. The ERT gave information about structural geological geometries such as fault planes in tectonically active areas (Caputo et al. 2003; Colella et al. 2004), landslide bodies (Lapenna et al. 2003) and archaeological buried features (Rizzo et al. 2005). The SP method is usually used to characterize subsurface fluid flow (Revil et al. 2002; Lapenna et al. 2003; Perrone et al. 2004) and recently to define the distribution of heads during pumping test (Rizzo et al. 2004). Environmental applications of IP are numerous and a promising application is hence the detection of organic contaminants (Slater and Lesmes 2002). To limit the involvement of IP data acquisition, the use of stainless steel electrodes and conventional ERT cables has been proposed by Leroux and Dahlin (2001, 2002, 2003). The authors assert that good results are possible if the measurements are acquired in low noise sites, the acquisition sequence is performed to limit the charge-up effect and when possible, the charge-up correction is implemented.

The previous electromagnetic methods have been applied in waste landfill mapping of internal landfill structures (Bernstone et al. 2000; Splajt et al. 2003) to distinguish several types of refuse in chemical waste disposals (Aristodemou and Thomas-Betts 2000; Prezzi et al. 2005), to define the geometry of waste disposal, as well as to detect possible leakages related to some low-resistivity plumes in the underlying gravel and sand (Karlik and Ali Kaya 2001; Bratus et al. 2002). Recently, self-potential method (SP) has been used to map the redox potential distribution and to define the redox front of a contaminant plume (Naudet et al. 2004).

In this work ERT, IP and SP surveys have been jointly carried out to define the buried boundaries of the landfill basin and to localize the leachate accumulation zone and moreover, for contributing to detect the integrity of HDPE liner. The latest problem could be the cause of contaminant fluid leakages into the groundwater, producing a serious risk for the aquifer and human health. Leakage from municipal solid waste deposits is generally associated with high ion concentrations and hence very high conductivity (Bernstone et al. 2000).

Methods and Field data acquisition

The geophysical survey of the municipal waste dump of Savoia di Lucania (Basilicata, Italy) has been based on the use of electrical resistivity (ERT), induced polarization (IP) tomographies and self-potential (SP) technique. Three ERT and one IP sections have been carried out in December 2004 and January 2005 (Fig. 2). In order to monitor the eventual variation of the natural/artificial electric field inside and outside the waste dump, related to contaminant phenomena, several SP measurements have been acquired in two different periods (June 2004 and January 2005).

The geoelectrical surveys (ERT and IP) have been acquired using the Syscal R2 georesistivimeter equipped with a multi-electrode switch system with 32 channels. The acquired data have been elaborated using the RES2DINV inversion software (Loke 2003). The used inversion approach consists of applying the 2D inversion routine by Loke and Barker (1996), which is a Gauss–Newton least squares method based on the finite-difference model of the subsurface. The latter is obtained by optimizing the 2D resistivity model trying to reduce in an iterative process the difference between the measured apparent resistivities and the calculated apparent resistivities, obtained from inverted resistivity model. The difference between calculated and measured pseudosections at each step and at the end of the inversion process is represented by RMS in percent terms. Moreover, to define better the boundaries of the waste landfill a robust inversion approach has been applied. This option attempts to minimize the absolute changes in the resistivity values, producing models with sharp interfaces, such as the buried boundaries of the waste dump.

The SP method consists of measuring at the earth surface the natural electric field developed in the subsurface by some polarization mechanisms occurring at depth. In the case of the polluted area two main phenomena could produce the SP signals: groundwater flow (Fournier 1989; Birch 1998; Revil et al. 2002; Rizzo et al. 2004) and oxidoreduction reactions (Nyquist and Corry 2002; Naudet et al. 2004). Two SP maps have been carried out in the investigated area in different periods (June 2004 and January 2005). The equipment used to obtain the SP map includes two non-polarizing electrodes ($Pb/PbCl2$ ‘‘Petiau electrodes’’), a high-input impedance millivoltmeter (10^8 ohm internal impedance) and an electric steel cable. The SP measurements have been acquired using Base-Station technique, which consists of fixing an electrode to a reference station while the second one is moved at each measurement stations. The distance used between each following station was 5 m. In order to have uniform ground contact conditions for all electrodes, we dug small holes (10 cm deep) filled with a salty bentonite mud. All the SP data (117 SP data for June 2004 and 95 SP data for January 2005) have the same base reference station taken upstream of the landfill.

The Savoia di Lucania waste dump: field survey and results

The municipal waste dump of Savoia di Lucania (Basilicata, Italy) is a little basin, sized 70 m × 30 m and 6 m deep (from engineering project data), anomalously placed onto a previously canalized natural stream (Fig. 1). The basin structure has been built using reinforced concrete and coated with a high-density polyethylene (HDPE) liner. The small size makes possible the planning of several geophysical experiments at different times. The bedrock is composed of siliceous rocks (Scisti Silicei Formation), which are highly fractured. As a result, great electrical resistivity variations, related to the presence of water in the fractures, in agreement with Archie's Law, are expected.

Three ERT and one IP section were carried out across the landfill in December 2004 and January 2005 (profiles A–A′, B–B′ and C–C′ in Fig. 2). The results of the ERT A–A′ with topographic corrections are shown in Fig. 3. The tomography was acquired using dipole–dipole configuration with electrode spacing of 5, 10 and 15 m to investigate in depths up to 20 m. This configuration was used to obtain both ERT and IP surveys. In accordance to Leroux and Dahlin (2001, 2002, 2003), the dipole–dipole array induces any charge effect on the potential electrodes making possible acquired IP data with the same cables of the ERT survey. In order to acquire resistivity and chargeability data, we chose a current injection time of 1,000 ms. In this setting, the used georesistivimeter obtains three IP windows to compute the weighted apparent average chargeability.

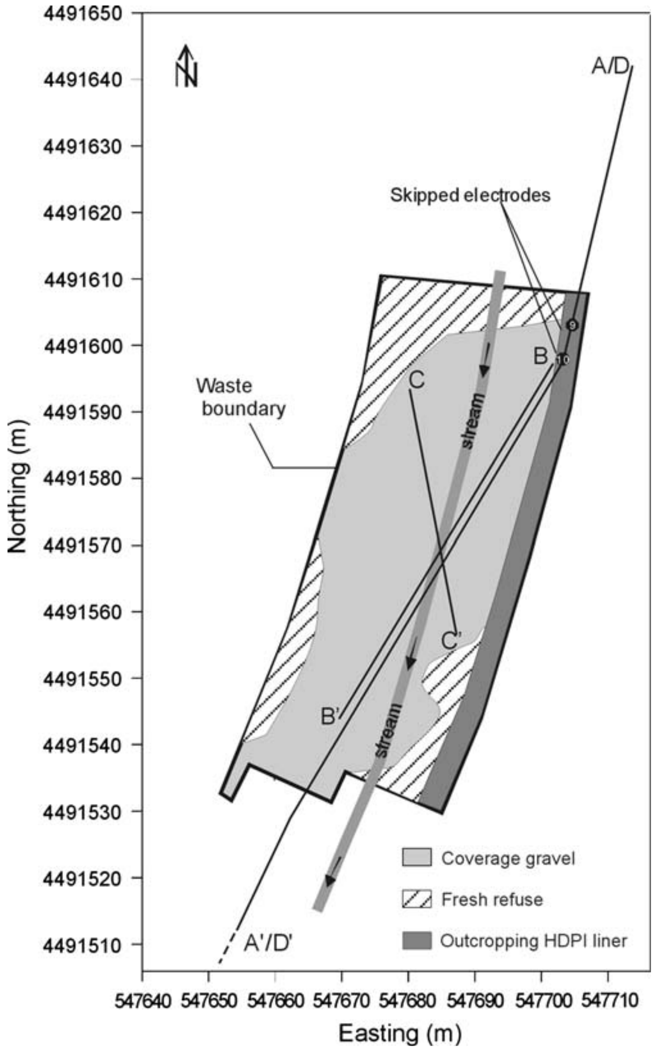


Fig. 2 Sketch map of waste site with active method arrays. A–A′ and D–D′: ERT and IP trace of dipole–dipole array, respectively; B–B′ and C–C′: Wenner–Schlumberger arrays. *Grey stripe* highlights the trace of the canalized stream

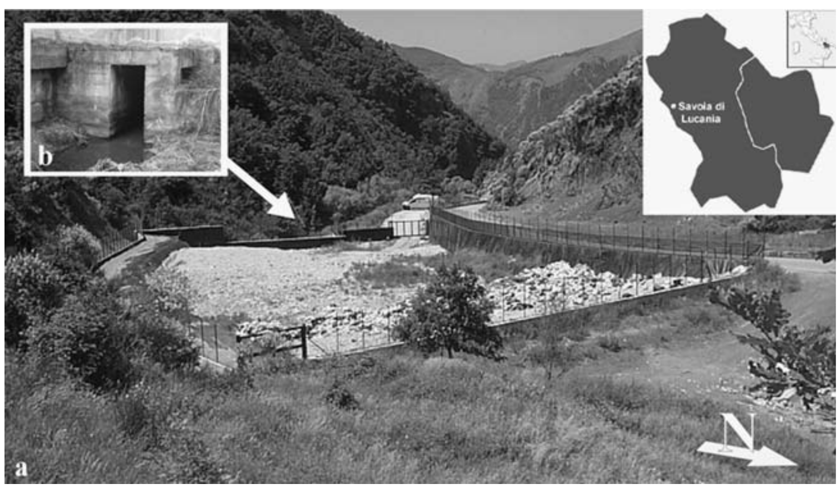


Fig. 1 **a** Waste site of Savoia di Lucania (Basilicata region, Southern Italy); **b** downstream end of the buried concrete channel below the waste basin

In order to have resistivity and chargeability values both inside and outside the landfill, the profile was 155 m long with several electrodes outside the waste area. Although the switch system allows using 32 stainless steel electrodes, the electrodes nos. 9 and 10 have been skipped because of the outcropping liner (Fig. 2).

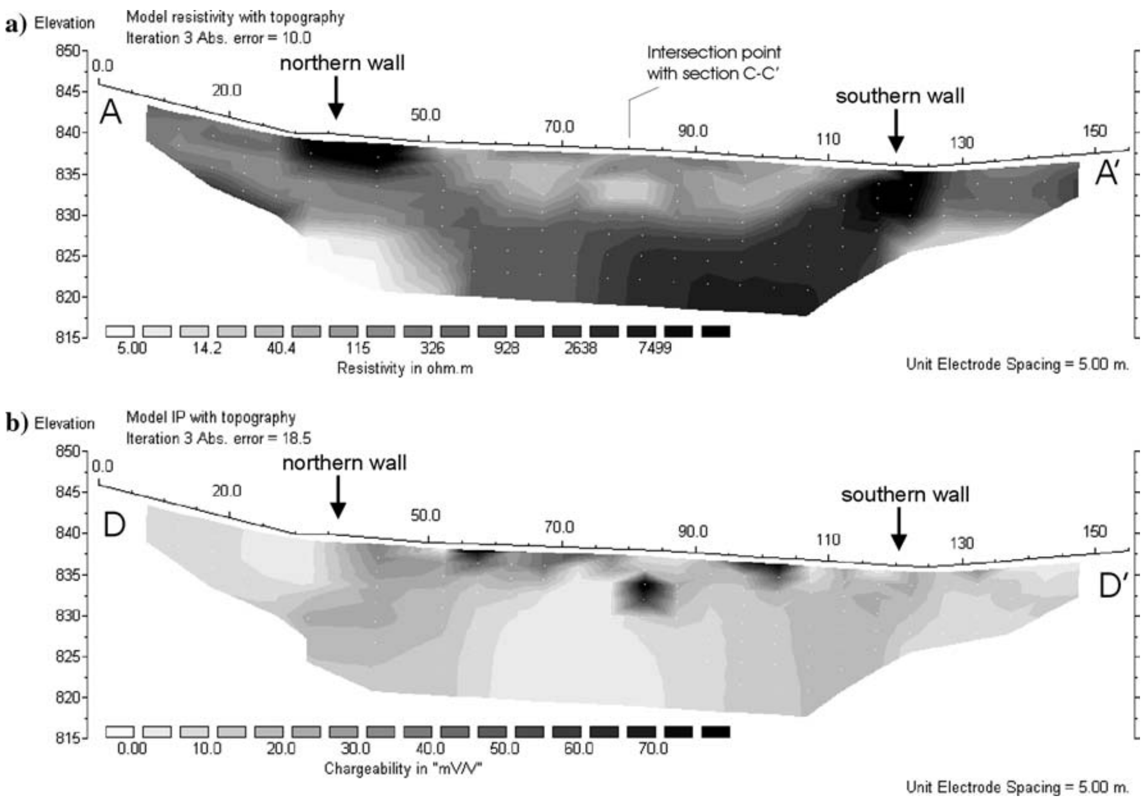
Two shallow Wenner–Schlumberger surveys were carried out inside the landfill detecting the bottom of the basin and obtaining an hires characterization of the refuse. The presence of several cumuli of refuse conditioned the arrangement of these arrays which have been disposed diagonally (Fig. 2). This arrangement allowed obtaining two ERTs with an exploration depth of 6.0 and 10.0 m. Unfortunately, topographical and logistic conditions impeded the carrying out of other ERT and IP arrays with different orientations both inside and outside the basin.

On the ERT A–A′ (Fig. 3a), the lateral and deep boundaries of the waste landfill are well detected by a high-resistivity strip (> 300 ohm m) between 35 and 120 m with maximum depth of 6 m. Below the northern and southern wall, at 30–50 m and at 120–130 m, respectively, two very high resistive zones (> 5,000 ohm m) are localized. They could be related to the buried concrete plateaus, which support the upper structures, and the buried drainage rock. The electrical resistivity values along the northern deep sloping boundary of the basin are lower than the ones along the other limits. This effect could be associated to lack of measured data in that zone due to skipped electrodes (nos. 9 and 10).

Inside the waste landfill from 50 to 115 m, where heterogeneous garbages and leachate accumulations are situated, resistivity values are < 100 ohm m, with a nucleus < 20 ohm m. The conductivity area could be associated with leachate accumulation zone that, according to bibliography, usually has a resistivity span between 1 and 20 ohm m (Bernstone et al. 2000; Aristodemou and Thomas-Betts 2000; Naudet et al. 2004).

On the surrounding area and below the waste basin, the geological formation of siliceous bedrock outcropping is situated around the investigation area. On the ERT A–A′, outside the landfill, two very low resistivity zones (< 35 ohm m) with minimum values of 4 ohm m are well localized in depth (830 m a.s.l.) below the northern wall. An analogue conductive zone is inferred below the southern wall. On the contrary, since the insulating HDPI liner represents an obstacle for the current lines, below the bottom of the waste basin, high-resistivity values (> 900 ohm m) are well delineated. Therefore, the high-resistivity zone below the deeper boundaries of the waste basin is an artefact. Moreover,

Fig. 3 a ERT A–A′ and **b** IP D–D′ images with topographic correction. The tomographies were obtained using a dipole–dipole array with an electrode spacing of 5 m. The RMS errors are 10 and 18.5%, respectively



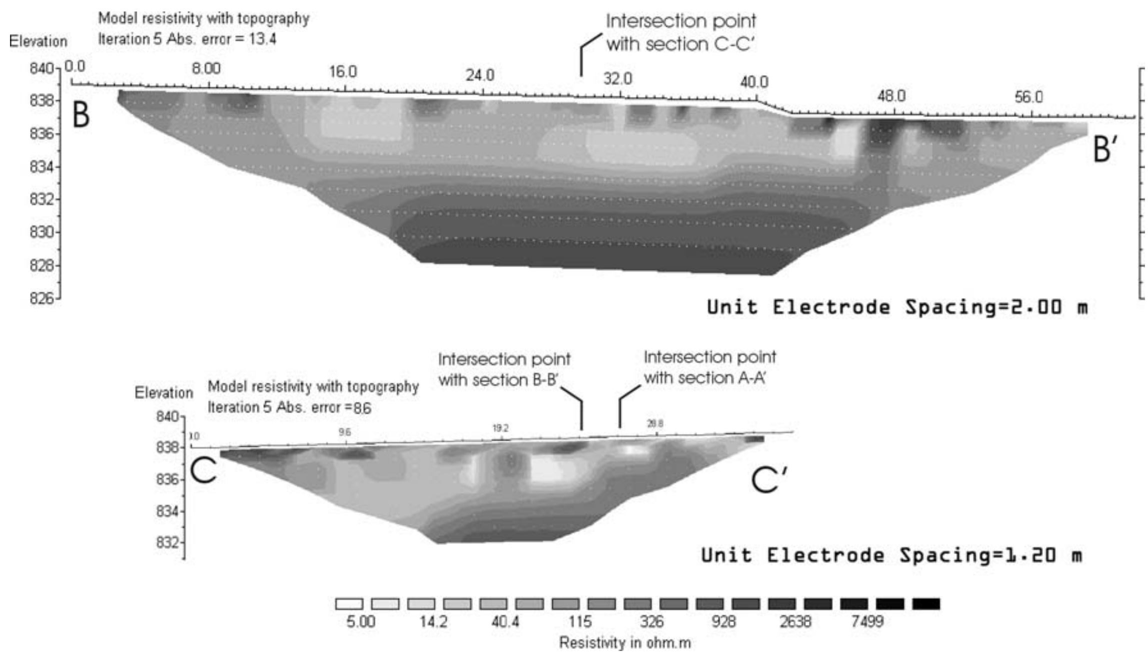
the sensitivity block diagram of RES2DINV software, highlighting the degree to which a change in the resistivity influences the potential measured by the array, shows very low values in this zone (< 0.14; the minimum values to accept the model is 0.2, from M.H. Loke, personal communication). Accordingly, only the low-resistivity zone, localized below the northern and southern walls, depicts a real geological situation.

Figure 3b shows the IP tomography with the topographic correction. Some high-chargeability nuclei (> 50 mV/V) are well localized inside the waste basin that could be associated with some heterogeneous metallic garbage. In particular, the deep high-chargeability nucleus at 77 m is on the boundary of the low-resistive nucleus detected in the resistivity image. Therefore, the anomaly area could be associated to the presence of metallic garbage probably in contact with the leachate.

The ERTs B–B′ and C–C′ are carried out inside the waste basin to obtain a zoom of heterogeneous garbage and leachate accumulations (Fig. 2). The used acquisition technique was Wenner–Schlumberger array type, which provides a good sensitivity in terms of vertical variations of electrical resistivity and allows a good s/n ratio. An electrode spacing of 2 and 1.2 m has been used along the sections B–B′ and C–C′, respectively. The final inversion models with topographic corrections evidence the same pattern of resistivity (Fig. 4). It is possible to delineate an upper part (up to about 6 m deep) with heterogeneous resistivity values, including both several small shallow high-resistive nuclei (> 300 ohm m) and large low-resistive nuclei (< 20 ohm m). The upper part is related to the heterogeneous municipal garbage and the conductive nucleus is associated to leachate accumulations, visible on ERT A–A′ also. The bottom part is characterized by homogenous, very high resistivity area (> 300 ohm m), due to the effect of HDPI liner and reinforced concrete below. Of course, the tomographies carried out inside the landfill cannot delineate the lateral buried boundaries, therefore only the bottom part is well defined.

The SP measurements have been carried out using two non-polarizing electrodes (Pb/PbCl2 "Petiau electrodes"), a high-input impedance millivoltmeter (10^8 ohm internal impedance) and an electric steel cable, obtaining two SP data sets in different time. Then, all the SP data have been plotted in a map (Fig. 5) using a kriging interpolation approach with a grid space of 5 m. The first SP map has been acquired in June 2004. It shows a range of potential values from about −56 mV to about 40 mV (Fig. 5a). The very important result was the presence of negative potential values inside the waste dump, whereas positive values are prevalent outside. The negative SP data are well localized in two main parts inside the waste basin: very high negative SP values are placed close to the northern wall; the second negative SP zone is well visible to the south of the dumpsite. The second SP map (Fig. 5b), acquired in January 2005, shows a range of −50 to 48 mV. Although there is a different data coverage than the previous SP map, because of the different locations of the garbage in the open, the two potential data distributions show a similar pattern of SP anomalies.

Fig. 4 ERTs obtained using the Wenner–Schlumberger array with an electrode spacing of 2 m (**a**) and 1.2 m (**b**). RMS errors are 14.9 and 8.6% for B–B′ and C–C′, respectively



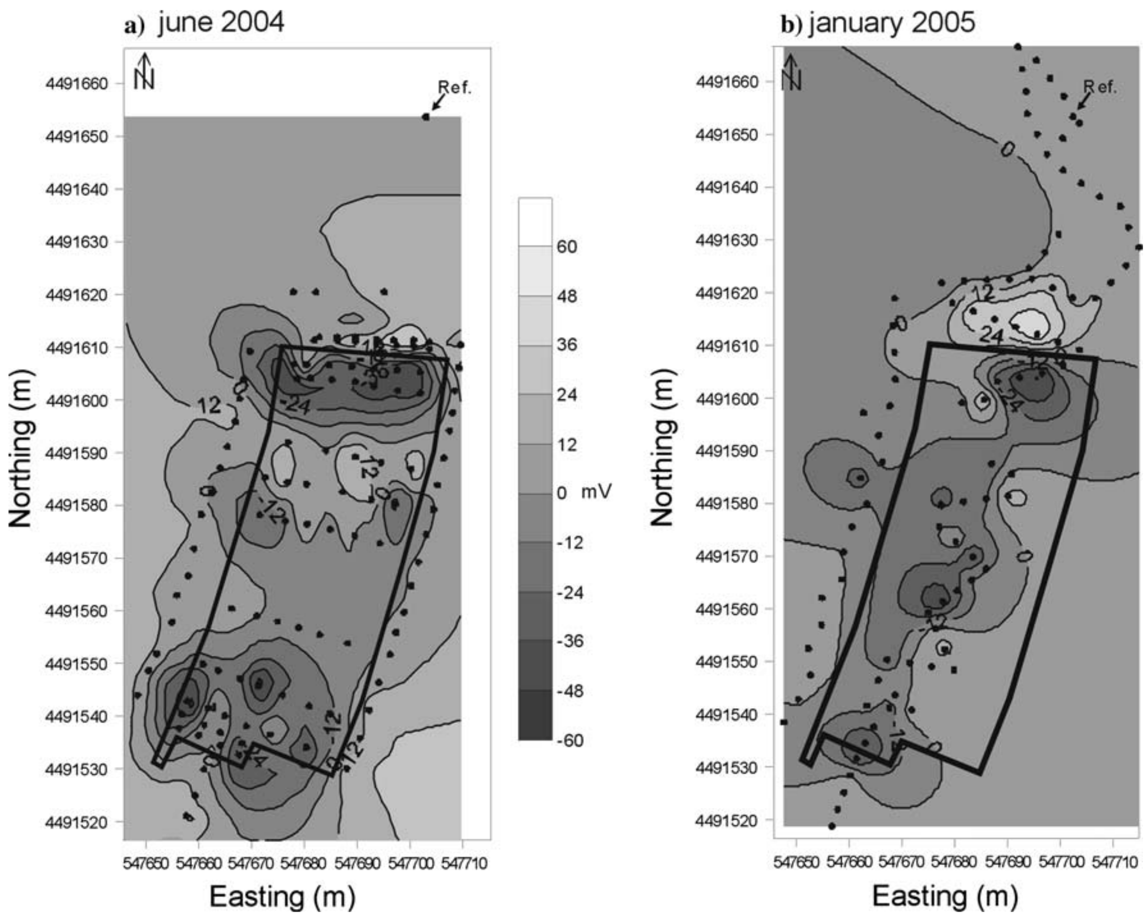


Fig. 5 **a**, **b** SP maps carried out in June 2004 and January 2005, respectively. *Black dots* are the data points. *Ref.* indicates the reference station. *Black line* is the landfill boundary

Comparing all the results obtained, it is possible to observe a negative SP anomaly, localized in the middle of the waste site, just where the high-conductivity zones in ERT A–A′ and B–B′ are placed. In accordance with several authors (Fournier 1989; Revil et al. 2002; Lapenna et al. 2003 and reference therein), the SP positive values could be due to groundwater flow, which creates positive SP anomaly in the flow direction, where there is an accumulation of positive charges (when the base reference station is taken upstream). Therefore, the SP positive anomaly located outside the waste deposit could be associated to a positive charge accumulation due to the drainage structures below the northern wall that prevent natural groundwater flow. This effect is in accord with Perrone et al. (2004) where deep concrete structure prevented natural groundwater flow producing a local positive SP anomaly. The underlying physics of SP signals produced in contaminated sites is not well understood. Some authors (Nyquist and Corry 2002; Naudet et al. 2004 and reference therein) individuated a negative SP anomaly in contaminated sites, suggesting a consequence of oxidoreductions reactions. Therefore, the negative values inside the waste basin could be related to redox gradients between reduced leachate and oxidized rainwater.

In Fig. 6 there are SP profiles extracted from the collection data acquired in June 2004 and in January 2005 following the section of ERT A–A′ and B–B′. The results show a very different behaviour between the SP data acquired outside and inside the waste basin. The inside SP data are negative with heterogeneous pattern. Comparing the SP profile of January 2005 and ERT A–A′ and C–C′, high negative SP values (−40 mV) are situated just in correspondence with the high-conductive nuclei. Unfortunately, the negative anomaly in this area is not visible in the SP profile of June 2004, probably because of the lack of data. Moreover, close to the confined wall strong negative peaks (up to −60 mV) are visible, but there is no clear correspondence on ERTs. On the contrary, SP data outside the landfill show a drop in potential with positive values < 10 mV. Moreover, several strong positive values (up to 50 mV) are localized outside the northern wall and they could be associated to positive charge accumulation zone due to groundwater flow (just discussed before).

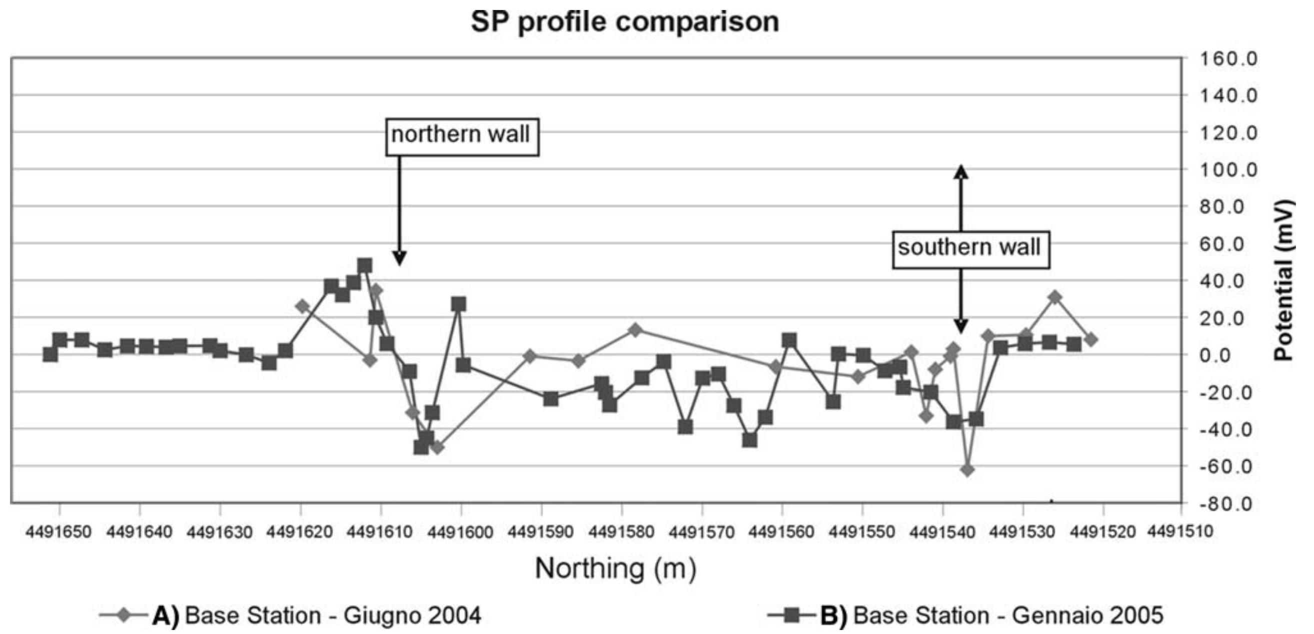
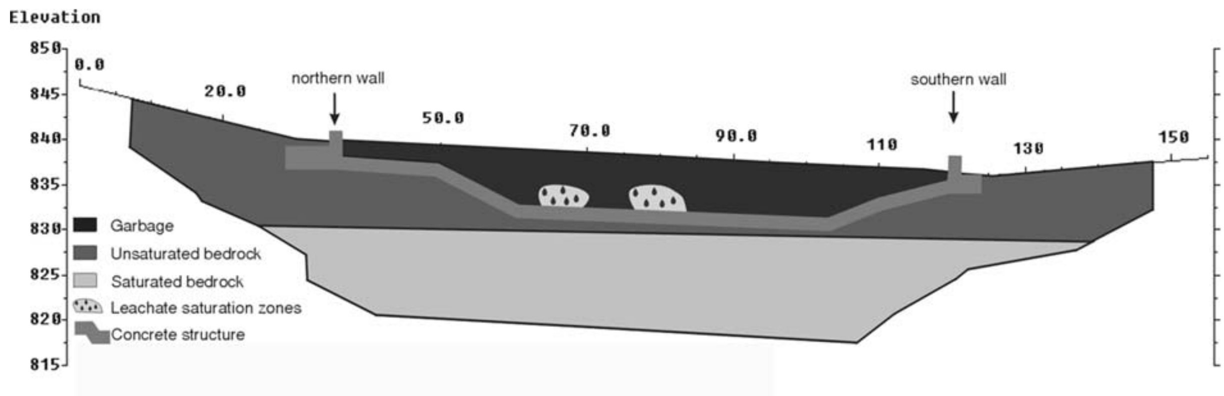


Fig. 6 Two SP profiles extracted from the SP maps in Fig. 5a and b, respectively, along the ERT A–A′ line

Discussion and conclusion

This work represents an application of the electrical resistivity tomography, induced polarization and self-potential methods to waste dump site of Savoia di Lucania (Basilicata, Italy). It has been built with concrete structure on which waterproofing has been obtained using an HDPI liner. The use of ERTs and IP allowed to provide information about the buried shape of the waste basin and to define local leachate accumulations. On the contrary, the applied active methods are not able to investigate below the bottom of the waste dump, because of extremely high electrical resistivity of HDPI liner which prevents current flow across the insulating materials except through any holes or tears. Therefore, the bottom of the waste dump results perfectly continuous deducing that no leakage seems to have occurred. The combined use of ERT and IP methods allows distinguishing between reinforced concrete structure (weak polarization phenomena) and garbage accumulation (strong polarization phenomena). The SP data show a very noticeable separation between negative values, in the waste dump, in agreement with the presence of redox reactions in the leachate (Naudet et al. 2004), and positive, in the surrounding northern area, due to accumulation of positive charges associated to groundwater flow. However, in the next future it is necessary to start quantifying the SP data and to find some correlation with the concentration of polluted zone. Finally, considering all obtained results, an interpreted sketch of dumpsite section along the ERT A–A′ line was drawn (Fig. 7). Moreover, the obtained results suggest that

Fig. 7 Waste basin sketch with surrounding and deep interpretation



cost effectiveness and the low time consumption of the used geophysical methods allow to create a monitoring system to check, in the time, the leachate-tight effective. On the contrary, the main limitation of geophysical data acquired is their qualitative interpretation relative to leachate accumulation zone. Therefore, it is necessary to realize controlled experiments in full-scale model to understand and obtain quantitative information to transfer subsequently in real situations.

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