Resistivity-IP for landfill applications

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Resistivity-IP mapping for landfill applications

With case studies from South Africa and Sweden, Torleif Dahlin,[1*] Håkan Rosqvist[2] and Virginie Leroux[1] show how resistivity and time-domain induced polarization investigations can be combined to make a powerful tool for delineating the extent of buried waste as well as mapping contaminant leakage.

Solid waste landfills constitute integral parts of the soil hydrological system and pose a serious pollution threat to both groundwater and downstream surface water. There is therefore a need to understand and quantify the hydraulic behaviour of solid waste landfills. In a landfill, high concentrations of materials such as heavy metals, nutrients, and organic substances lead to a risk of pollution to the surrounding environment. The pollutant load to the environment depends on the quantity and quality of the water that percolates through the landfill and reaches the surroundings. Leakage from municipal solid waste deposits is generally associated with high ion concentrations and hence very low resistivities. This makes geoelectrical imaging techniques particularly interesting for mapping the three dimensional extent of contamination around landfills (Bernstone and Dahlin, 1999).

A number of problems frequently occur in connection with landfill surveys, and they tend to be interlinked and complex. There are often several issues that need to be resolved concerning old, buried, and poorly documented landfills due to environmental protection demands. For example, the extent and depths of the waste buried in old landfills are often unknown, and the extension and status of soil covers at landfills are often uncertain. Geological formations, soil layers, and bedrocks, underlying landfills are often contaminated as a result of leakage of contaminants from the waste, and the landfill often poses a severe threat to groundwater resources around landfills. The combination of resistivity and time-domain induced polarization (IP) has been shown to be a powerful tool to obtain an overview of landfills (Iliceto and Morelli, 1999; Carlson et al., 2001; Leroux et al., 2007). Furthermore, Dahlin et al. (2007) have shown that 3D inversion of 2D datasets can increase the resolution of the resistivity survey.

Geophysical investigations are often required in order to gain sufficient understanding, since drilling and sampling alone are not enough for a complete picture. Examples include tracing and monitoring of contaminant spreading with associated risk of groundwater contamination, and assessment of soil stability in order to reclaim soils that have become enclosed in urban areas. Landfill mining is another application requiring identification of the buried materials.

Landfills present specific difficulties to the surveyor: they are usually very heterogeneous in three dimensions and documentation is often poor, inadequate, or outdated. Due to biodegradation, their geometry and properties may have changed significantly compared to the original state. Drilling and sampling is costly and can only be used to a limited extent. Geoelectrical methods are suitable because electrical properties are strongly related to water content, salinity, and porosity. IP in particular has been used successfully for distinguishing buried waste from its surroundings. The origin of the higher polarizability often observed in refuse, however, is still disputed. Most likely, this is partly due to metal content (e.g. Angoran et al., 1974; Slater et al., 2006) but there are some indications that the presence of biodegradable organic matter is also significant (see Carlson and Mayerle, 2009). This paper describes and compares the results of resistivity and IP measurements at sites in Sweden and South Africa.

Method description

In the field examples presented here, combined resistivity-IP data were collected as 2D geoelectrical imaging with the ABEM Lund Imaging System (Dahlin, 1996). The system features multi-channel measurements (seven simultaneous potential readings for each pair of current electrodes for the version used here) and makes it possible to collect datasets with very high data density e.g., with multiple gradient array which was used for the results presented here.

The IP data were recorded in time-domain by integrating the decay signals after current turn-off, and in 10 time-windows of 100 ms each, starting 10 ms after current turn-off.

The acquired data were inverted using Res2dinv and Res3dinv with the robust inversion constrain (L1-norm). The L1-norm option allows for large contrasts in the models and is more robust against noise in the data (Loke et al., 2003), this latter feature is most important for the IP data which is much more sensitive to noise. The inverted models were plotted as vertical sections and 3D visualizations of the distribution of resistivity and chargeability of the ground.

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Furthermore, the results were also plotted as normalized chargeability, which is expected to show the surface conductance of the ground (Slater and Lesmes, 2002).

Waterval waste deposit, South Africa

At the Waterval landfill site, landfilling was started in 1928 by wet-tipping in water-filled clay pits. At first the landfilling was practised as open dumping; however, from the late 1960s the open dumping was followed by a proper sanitary landfilling operation. In 1978 the landfill was finally closed (Blight, 1995). The landfill is situated in a valley drained by a small stream, which for parts of its lengths runs through a culvert under the raised part of the landfill. The floor of the valley is composed of silty clays and sandy clays formed by the in situ weathering of the country rock (Blight, 1995). The landfill is placed on top of a geological contact zone, so faulting and rock with different geophysical properties should be expected (Rosqvist et al., 2004).

There are shallow alluvial deposits of clay along the course of the stream, and weathered bedrock along the line of the stream occurs at a depth of 5–6 m below the natural ground surface. In Blight (1995), the mean permeability of the alluvial and residual clays was estimated to 16 m/y. It was concluded that a pollution front is advancing from the toe of the landfill and it was estimated that the leachate front has progressed no more than 40 m in over 65 years. The leachate is believed to originate from the refuse dumped in the water-filled clay pits (Rosqvist et al., 2004).

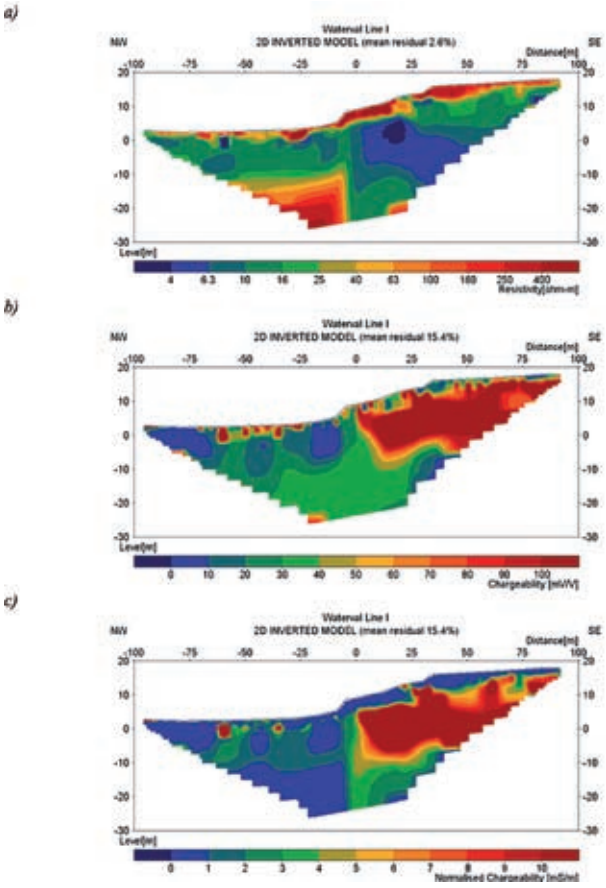

Figure 1 *2D inverted models from Line I at Waterval waste deposit; (a) resistivity, (b) IP, (c) normalized IP.*

A drilling campaign was performed in order to take disturbed soil samples and groundwater samples for laboratory evaluation to provide further data for the interpretation of the results of the geoelectrical measurements. In the drilling campaign six shallow auger boreholes were drilled for sampling of soil and groundwater. The drilling points were selected on the basis of the geoelectrical results in order to support the geological interpretation, and to verify possible correlation between low resistivity anomalies and leachate water contamination (Rosqvist et al., 2004).

In the sections in Figure 1, the landfill body is located from the relative distance at approximately 0 m and up. In Figure 1a, the red and yellow parts (high resistivity) near the surface are interpreted as well-drained coarse grained soils, like sand and gravel. The red and yellow parts at greater depths (approximately 10 m) are interpreted to be the bedrock which also was confirmed by the drilling survey. The parts with intermediate resistivity in the sections are interpreted as soils with intermediate grain size or fractured/weathered rock depending on the relative position. The resistivity section clearly suggests that there is a fault zone in the bedrock around distance 0 m, which fits well with the geology. The blue and dark blue parts (low resistivity) at depths of approximately 3–10 m below the ground surface may be interpreted as waste (in the landfill body) and soil in the unsaturated zone and in the groundwater zone. The dark blue zones in the landfill body and outside the landfill body may be interpreted as waste or soil containing lechate water from the landfill. A very distinct low resistive anomaly is evident around -60 m in Figure 1a, which corresponds to the position of the culvert. Low resistive zones outside the landfill could be interpreted as clayey soil and/or a mixture of clayey soil and soil contaminated by leachate. In the resistivity sections, the boundaries of the landfill cannot be clearly identified.

The chargeability (IP effect) is very strong in the waste deposit (Figure 1b), with values reaching hundreds of mV/V. The normalized chargeability plot (Figure 1c) gives a slightly different image with a cleaner appearance with respect to high chargeability anomalies. The upper limitation and lateral extent of the waste body appears to be well defined. It was not possible to reach the top of the covered landfill with the heavy drilling rig that was available, but it was evident from site inspection that the thickness and character of the covering material varied and that, for example, metal waste was exposed at the surface in places. Apart from the main waste body, smaller anomalies with high normalized chargeability are visible at distance -35 m and -60 m, where that

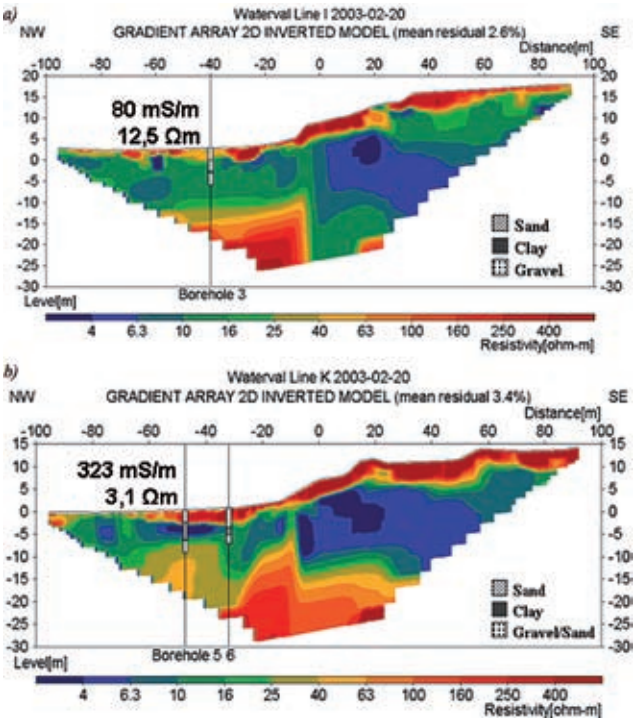

Figure 2 *2D inverted from Waterval waste deposit with drilling and water conductivity results superimposed, (a) Line I, (b) Line K. Groundwater conductivity in earlier investigations were in the range 38–84 mS/m.*

latter coincides with the culvert. Parts of the soil zone exhibit somewhat elevated normalized chargeability, which may be related to variation in soil composition. Also the interpreted fault zone at 0 m is associated with elevated normalized chargeability, possibly due to weathering and mineralization in the zone.

It is assumed that the groundwater flow beyond the toe of the landfill follows the bottom of the valley and thus, the direction of the small stream, which for parts of its length through the landfill site area runs through a culvert. In the resistivity sections in Figure 2, the culvert can be recognized as a zone of low resistivity from the surface to a depth of 5–10 m, at the relative distances of -60 m (line I) and -75 m (line K) m, respectively.

The picture obtained by the resistivity measurements is supported by the conductivity measured in the groundwater samples taken. For example, for borehole 5 on line K (Figure 2b) low resistivity coincided with high water conductivity (323 ms/m). Borehole 3 on line I (Figure 2a), on the other hand, was sited where there was no low resistive anomaly, and here the water conductivity (80 mS/m) was in the range of previously reported background levels (38–84 mS/m).

In Blight (1995), it was concluded that the leachate plume had migrated approximately 40 m from the landfill toe. The migration of the leachate plume was confirmed in the resistivity survey; however, to locate the full extent of the plume, additional surveys are needed.

Ekeboda waste deposit, Sweden

The aim of this investigation was to map potential leachate plumes, delimit the extension of the landfill as well as the thickness and quality of the covering layer. Furthermore, the purpose was to compare resistivity and IP surveys as methods for mapping landfills (Johansson et al., 2007).

The Ekeboda landfill has an area of about 20,000 m^2 in a small valley in the municipality of Hörby in southern Sweden. The landfill was in use between 1965 and 1978, with illegal dumping continuing until the mid 1980s. The landfill contains domestic waste, construction, demolition, and industrial waste as well as other hazardous waste such as pesticides and mineral oils. The major part of the waste was burned during the early years, but later on it was deposited. The waste has been deposited on natural ground, comprised of sandy till with underlying bedrock of sandstone or possibly gneissic rock (SGU, 2000). The covering layer consists of various soils, of which no precise record has been kept. At present, the leachate is collected and transported to the local water treatment facility (Johansson et al., 2007).

A combined resistivity-IP survey was carried out at the site. After making two successful perpendicular test lines (see example in Figure 3), a grid of 11 parallel lines were measured with 5 m in-line electrode separation and 10 m spacing between the lines. The parallel lines were merged into one data set that was inverted to create 3D models of the resistivity and chargeability (IP-effect).

When analyzing the inverted sections in Figure 3 it is evident that there is much to gain from a combination of resistivity and IP as tools to investigate old landfills. For example, in the resistivity section of profile 1, low resistivities were found between 90 and 100 m.a.s.l. (Figure 3a) which were interpreted as the wet part of the waste. Higher resistivities were found on top of this, but it is not possible to distinguish the dry part of the waste from the covering layer. The thickness of the covering layer is, on the other hand, quite distinct in the IP section (Figure 3b), where material with very little IP effect is visible in the uppermost layer. The IP section reveals that the covering layer is about 3–5 m thick and that it is thinner towards the outer parts of the landfill. Chargeable material was found by follow-up drilling at depths that correspond well with the waste. Drilling to confirm the results could only identify the upper limit of the waste, whereas the bottom of the waste could not be reached due to difficulties of penetrating through larger metal objects, etc.

When it comes to delimitation of the extent of the waste, the IP sections have some difficulty identifying the bottom of the landfill. This might be explained by the nature of the IP phenomenon and its relation to the resistivity. However, the problem with delimitation of the bottom of the landfill can possibly be reduced by using normalized IP, a parameter that quantifies the magnitude of surface polarization. The normalized IP section appears to clearly delimit the waste

as can be seen in Figure 3c. Using both the resistivity and IP section (Figure 3a and b), it is evident that the covering layer is comprised of material with higher resistivity and lower chargeability towards the outer parts of the landfill. This corresponds to site documentation descriptions of medium grained to coarse grained soil material. In the middle of the model the covering layer consists of material with low resistivity and IP effects that are small compared to the waste. This is interpreted as consisting of more fine-grained soils.

A view of a normalized IP model from 3D inversion of the data from Ekeboda is shown in Figure 4, outlining the possible extent of buried waste at the site.

The results of the resistivity survey do not show an evident leachate contamination from the Ekeboda landfill, but it indicates that there might be a possible leachate plume in a westerly direction, downstream from the landfill. The results of the water sample analyses do not show that there is any strong pollution, which may be explained by the small size of the waste deposit and that deposition stopped many years ago.

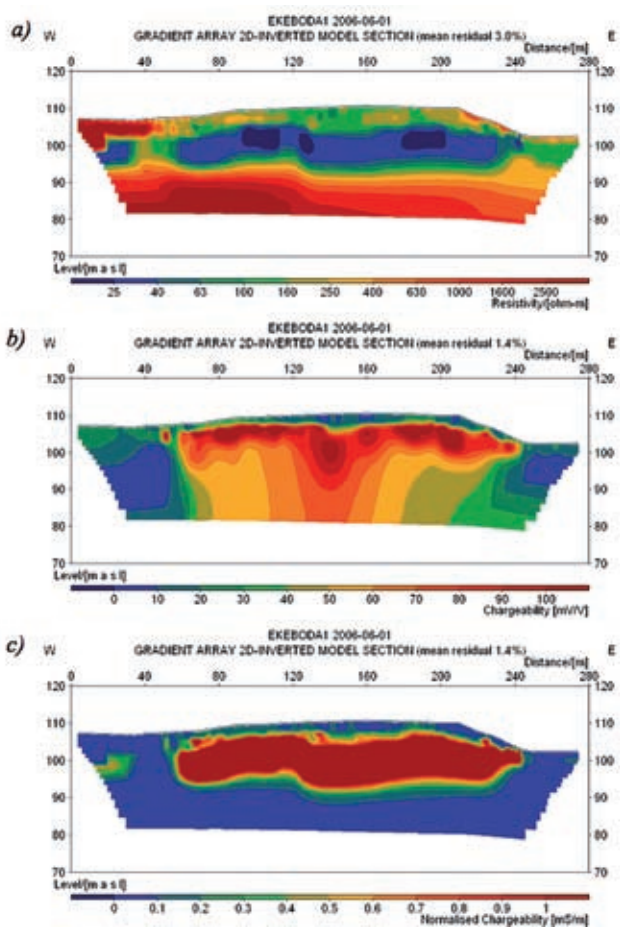

Figure 3 *2D inverted data from (a) the resistivity survey and b) IP-survey along profile 1 at Ekeboda waste deposit. The normalized IP model of the same profile is shown in (c).*

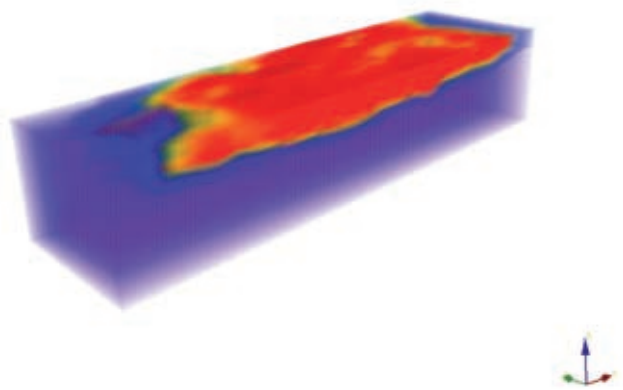

Figure 4 *View of normalized IP model from 3D inversion of data from Ekeboda waste deposit outlining possible extent of buried waste, where red indicates high chargeability and blue low (see Figure 1c for legend). The length of the model is 300 m, and the depth to the bottom of the high chargeability body is slightly less than 20 m.*

Conclusions

Resistivity investigation is well established for detection and mapping of contaminated ground and groundwater. Low resistive zones around the landfills correlate with high ion contents in groundwater samples indicating leachate from the waste. The results from Waterval are a good example of this. Such investigations are often carried out on and in direct connection with buried waste, and in order to plan remediation efforts it is important to know the extent of the waste.

A common problem is that the extent and composition of the buried waste is unknown due to poor or lacking documentation. Resistivity investigation alone often cannot delineate the waste due to large variations in resistivity due to variation in water content. Time domain IP can be used to measure the chargeability of the ground together with resistivity in a time and cost efficient way, provided adequate data acquisition equipment is used. It has been shown at many waste disposal sites that buried waste produces strong IP effects, and thus chargeability can be used to delineate and possibly to some extent characterize the buried waste.

By combining resistivity and IP investigation it is thus possible to delineate the extent of the buried waste as well as mapping contaminant leakage. It is thus a powerful tool in hydrogeological investigations at and around landfill sites.

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