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DC-resistivity mapping of internal landfill structures: two pre-excavation surveys

C. Bernstone · T. Dahlin · T. Ohlsson · W. Hogland

Abstract Geophysical investigations using 2-D DC resistivity were carried out on old parts of two similar landfills, with waste of different ages. The data sets, which included high data density in both vertical and horizontal directions, were interpreted with 2-D smoothness constrained inversion. The landfills were excavated after the surveying. The objective was to test the capability of the resistivity method as a pre-characterization technique. The objectives were only partially fulfilled. First, the moisture content was the parameter that appeared to exert the dominant control over the resistivity distribution of the landfill. The most important potential information that can be recovered is, therefore, an indication of the waste piles hydraulics. Second, it was neither possible to estimate the amount of recoverable soils, nor to correlate the type of waste with the resistivity models. However, discrete anomalies were identified, and if specific materials are searched for, the resistivity models indicate possible places to search.

Key words Environmental geophysics · Resistivity · Inversion · Landfill mining · Waste · Characterization

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Introduction

Excavations of existing landfills are carried out for a variety of purposes (Hogland and others 1995; Collivignarelli and others 1997). They can, for example, be attractive in areas where waste is deposited in large regional landfills or where economical and environmental considerations necessitate the efficient use of available space. Such excavations free additional volumes for continued deposition in those cases where intermediate daily soil covers can be recovered. In addition, the soil itself can provide valuable material for the construction of new waste cells or for capping. This type of work is commonly associated with the aggregate term “landfill mining”.

Geophysical methods may prove useful for determining waste characteristics prior to excavation. Not only can they be used to locate hazardous waste but they can also be used to estimate the volume of waste and soil and the type and distribution of waste in the waste pile.

Landfill-related geophysical surveys are frequently reported in the literature. Carpenter and others (1990) used a resistivity technique to map the internal landfill structure, the leachate level and the thickness of the cover material, and Kobr and Linhart (1994) combined CVES and VLF in an investigation which provided information on both the waste and the local geology. Cardarelli and Bernabini (1996) used VLF and refraction seismics to obtain the maximum thickness and the geometrical limits of a closed landfill, and Haker and others (1997) used surface wave tests to determine dynamic waste properties. Bernstone and Dahlin (1997) used DC resistivity, magnetometry and slingram to estimate the location of metals in a closed landfill. Geophysical measurements have also been used to identify the condition and function of landfill’s final cover, and to identify fractures and erosion degradation (Bergström 1997; Carpenter and others 1991).

The aim of this study was to examine the capabilities of the 2-D DC resistivity technique, and 2-D inversion data analysis to characterize waste properties in covered landfills. Two landfills in southern Sweden were surveyed, the Filborna and Måsalycke landfill. The landfills were excavated and characterized after the surveys. The excavation work in Filborna was initiated for economic reasons, with limited time and funding available for the classification. In Måsalycke the study was undertaken as part of a scientific project (archaeology and modern waste) and involved only a small area.

Data collection

Electrical properties of geologic and waste material

The physical properties of naturally occurring geological materials can fall within a broad range, as exemplified by the resistivities of geological materials in Fig. 1. However, for a given area and a given material the variation is usually small and variations in measured resistivities can be related to, for example, variations in water content, fractures, or variations of a non-geological origin. However, in landfills the situation is the opposite. The changes in physical properties can be abrupt and vary considerably over small distances. In the case of the resistivity parameter, the variation is related to waste characteristics. This relation means that it may be possible to obtain an overall picture of the amount and characteristics of waste by undertaking geophysical measurements of the landfill cover surface.

Geophysical properties, including resistivity, of in-fill materials are related to the tipping history of the landfill site, because this determines the composition and amount of material deposited. With time the geophysical properties become a function of (1) leachate generation, mobility of leachate, and degree of saturation, (2) gas generation, (3) internal temperatures and their variability, and (4) compaction density and its variability (McCann 1994).

Leachate water

The final cover prevents precipitation from entering the waste and produces leachate water. According to Heibrock and Jessberger (1995) a good estimate of the leachate production is 30% of the annual precipitation, however, up to 45% (SEPA 1993) has been recorded.

Rosqvist and others (1997) have shown that water generally flows in restricted channels and voids in the solid waste media. They also conclude that only a limited fraction of the pore volume available for solute transport participates in the water flow.

The ionic strength of a solution determines its electrical conductivity. Leachate water generally has a high electrical conductivity and saturated zones will therefore have very low resistivities. For example, the mean resistivity of leachate water from 26 Swedish landfills was 2.9 Ωm, with a span between 0.7 and 20 Ωm (SEPA 1990).

Landfill gas

Volatile materials and landfill gases tend to migrate upwards. The effect that this migration has on the waste formation resistivity is difficult to quantify.

Temperature

Exothermal reactions accompany several processes that occur in waste material and the temperatures directly reflect the degree of decomposition in a landfill (Yoshida and others 1997). According to Lanini and others (1997) oxygen diffusion from the atmosphere may be the factor controlling the temperature increase in landfills. This mechanism stops when the refuse is covered with either other refuse or a clay layer. The mobility of ions increases with increasing temperature, as the viscosity of water is lowered (Dahlin 1993). Hence elevated temperatures decrease the resistivity of materials where electrolytic conduction dominates.

Density

The most common form of movement in a landfill can be related to settlement of the waste. This settlement can be due to compaction, waste material collapse, or decomposition and consolidation of the waste (SEPA 1993). During the actual landfill gas production, the bulk density changes need not be significant, as compaction and gas

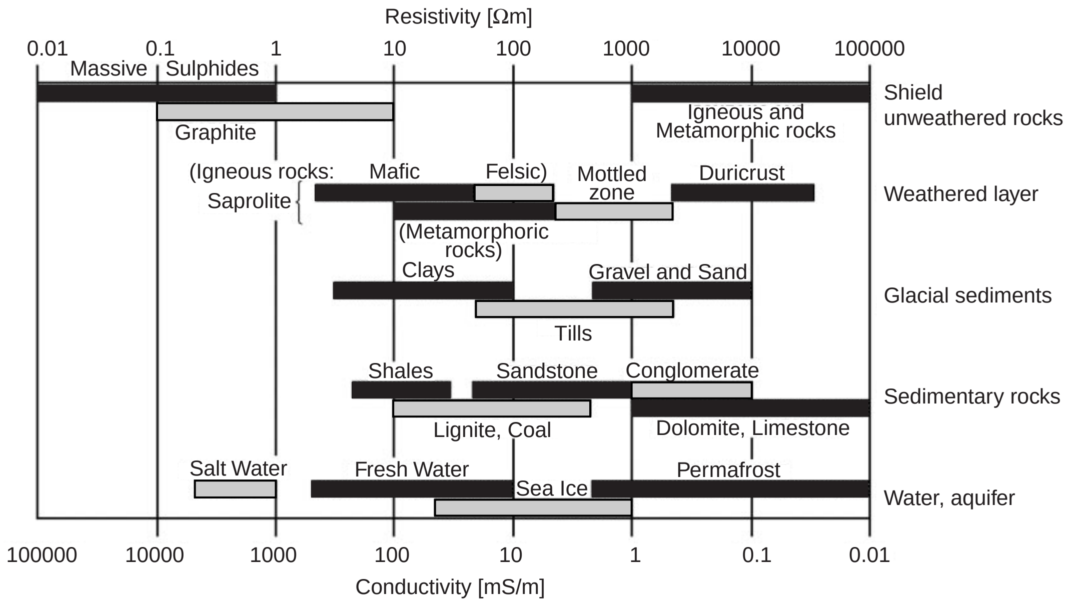


Fig. 1
The resistivity (reciprocal of electrical conductivity) range of some geological materials (Palacky 1987)

production influence bulk density in opposite ways (Mares and others 1993). A single DC-resistivity survey is not a very efficient way to gather information on this parameter.

Waste

The resistivity of typical bulk waste materials is 15–30 Ωm if saturated, otherwise, 30–70 Ωm (McCann 1994). However, some materials, if accumulated, may produce resistivity anomalies:

1. Metals (white goods, car bodies and steel drums) give low resistivities.
2. Ash from incineration plants gives very low resistivities (Bernstone and others 1997).
3. Gardening waste (tree-cuttings, textiles, kitchen waste and many organic materials) should give low resistivities if they are capable of holding moisture.
4. Chemicals (especially if strong electrolytes) and processing waste in general give low resistivities. Organic chemicals, for example hydrocarbons such as xylene ($\approx 7 \times 10^{16}$ Ωm) typically have very high resistivities.
5. Plastics, rubber and certain kinds of building refuse (demolition rubble) should give high resistivities.
6. Waste in plastic bags (which is preserved) and compacted newspaper should act as relatively good insulators and thus give high resistivities.

Even though the above list can be made longer, the examples exemplify the foundation for interpreting a landfill resistivity data set.

2-D Resistivity surveying

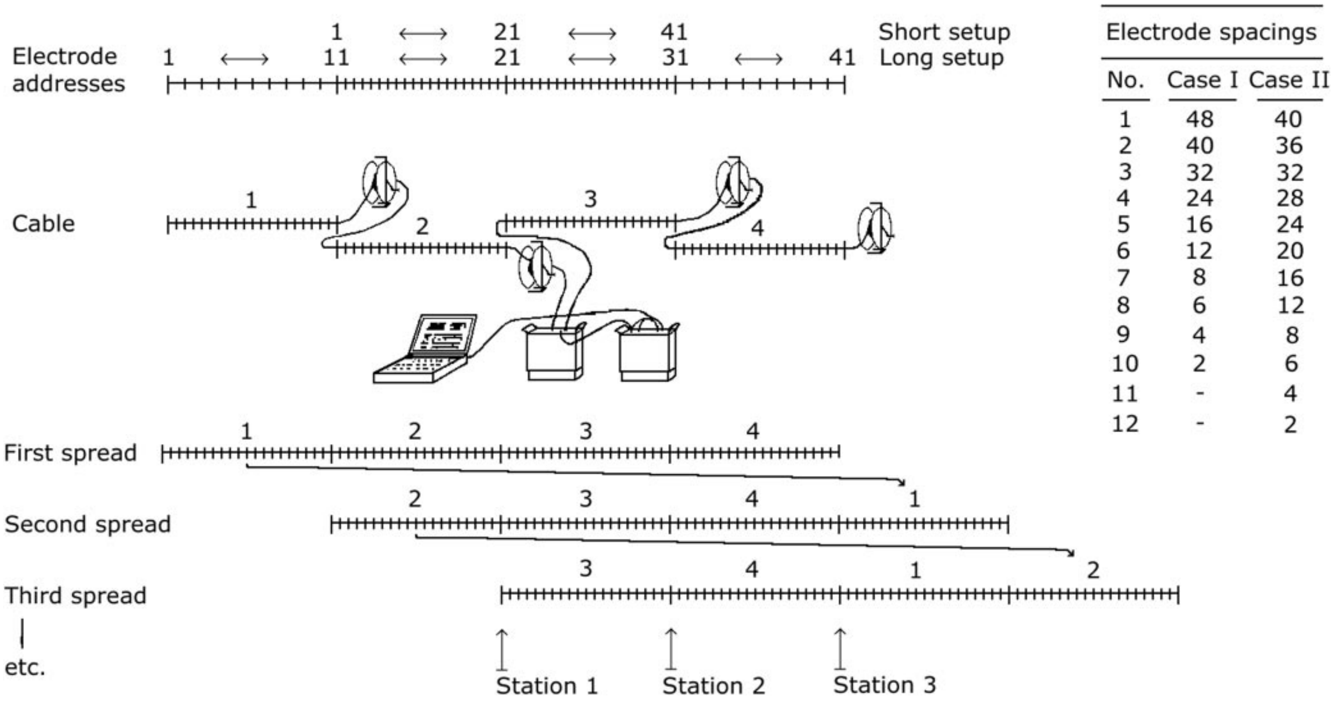
The resistivity method is based on the measurement of the potential distribution arising when an electric current is transmitted through a body via two electrodes. The CVES principle (continuous vertical electric sounding) of handling electrode arrays combines electrical sounding and electrical profiling. The result is resistivity values, which are measured both along a line and at different depths. Automatic acquisition systems based on CVES make it possible to collect dense data sets, which give a comprehensive description of the ground in two dimensions (2-D).

The resistivity data acquisition system used in this survey was the ABEM Lund Imaging System (Dahlin 1996). In recent years, the system has been used extensively in environmental and engineering investigations (Dahlin 1996; Bauman and others 1997; Bernstone and Dahlin 1997), and has proved to work reliably under difficult land and weather conditions.

The main parts of the system (Fig. 2) are a resistivity meter, a 4×64 channel relay matrix switching unit, a portable PC-type computer, four electrode cables (21 take-outs per cable) and steel electrodes. A separate current amplifier is optional. The system supports measurements according to a roll-along principle (Fig. 2).

Recent evaluation of inverse modelling has pointed out the importance of dense data sampling in the quest to resolve complex ground structures (Dahlin and Loke 1997). In our survey in Filborna, the measurement protocol utilized ten different electrode spacings (2–48 m). The protocol files in Måsalycke were extended to cover 12 elec-

Fig. 2
The principle of roll-along measurements using the Lund Imaging System (Dahlin 1996). Each mark on the cables indicate an electrode position. The first of the three spreads corresponds to the first base measurement in a survey. In the second and third spread additional measurements are linked to base data. The table list the electrode separations (in meters) in two case studies



Electrode spacings

No.	Case I	Case II
1	48	40
2	40	36
3	32	32
4	24	28
5	16	24
6	12	20
7	8	16
8	6	12
9	4	8
10	2	6
11	-	4
12	-	2

trode spacings, in spite of the extensive time required in the field. The equipment was operated by two people and the Wenner electrode configuration was used throughout the surveys.

Data analysis

General aspects

Quality control and preliminary interpretation of a CVES data set is accomplished through automatic pseudosection plotting. Such plotting can be useful for a preliminary qualitative interpretation, but in complex environments, as is the case in landfill surveys, it may be difficult to obtain an accurate understanding of the structure behind the section.

Inversion

Inversion of resistivity data is the procedure of constructing an image of the estimated true subsurface resistivity distribution, given the respective observed data sets. The RES2DINV software was used in our study (version 3.2). This two dimensional (2-D) inversion routine applies the Gauss-Newton least squares method. It is based on the generation of a finite-difference (FD) model of the subsurface. The model resistivities of the FD grid are automatically adjusted through an iterative process, so that the model response converges towards the measured data (Loke and Barker 1996). A measure of the model fit of a created resistivity model is given by the mean residual value. This value constitutes a comparison between the measured apparent resistivities and the apparent resistivities of the model response from the inverted resistivity model.

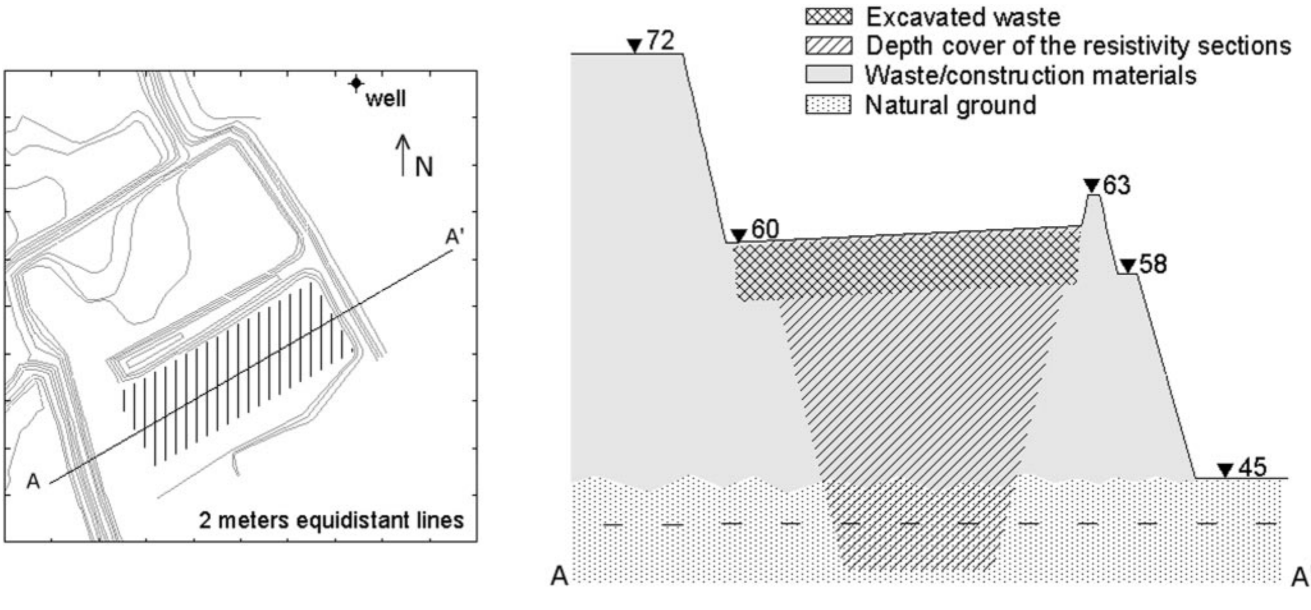
Case histories

The Filborna Landfill

General

This 46-year-old landfill, which is today operated by the Northwest Scania Solid Waste Company, is situated to the northeast of Helsingborg in southern Sweden. The investigation was carried out on an area of 10-year-old waste, which is disposed 15 m above the natural ground (Fig. 3). There is no gas extraction.
In 1994 an area of 8500 m^2 was excavated during a cell upgrade program. The work was described by Hogland and others (1995). Positive results led the operator to continue to work on an adjoining waste cell and by March 1997 an external contractor was engaged. A 2-D DC-resistivity survey preceded the new excavations, with the purpose of performing a pre-characterization of the waste volume which could be compared to the true content. Six parallel CVES profiles 140 m long, reaching a depth of 25 m were measured in January 1996 (Fig. 4). At the time of the survey the leachate production was low (but high during the excavation work). The existing soil cover was incomplete, bare of vegetation and the surface was frozen.
The cell contained both industrial and municipal waste in two waste pallets. The total thickness was approximately 4.5 m, and included an intermediate soil cover (Fig. 3). Further below lies 12 m of older waste followed by quaternary till. Because of an elevated groundwater level in the landfill compared to the natural ground (no effective

Fig. 3
A sketch of the waste cell (**a**) and a cross section (**b**). The *hatched area* in **a** corresponds to the block diagram of Fig. 4, and in **b** the depth cover of the resistivity survey is indicated



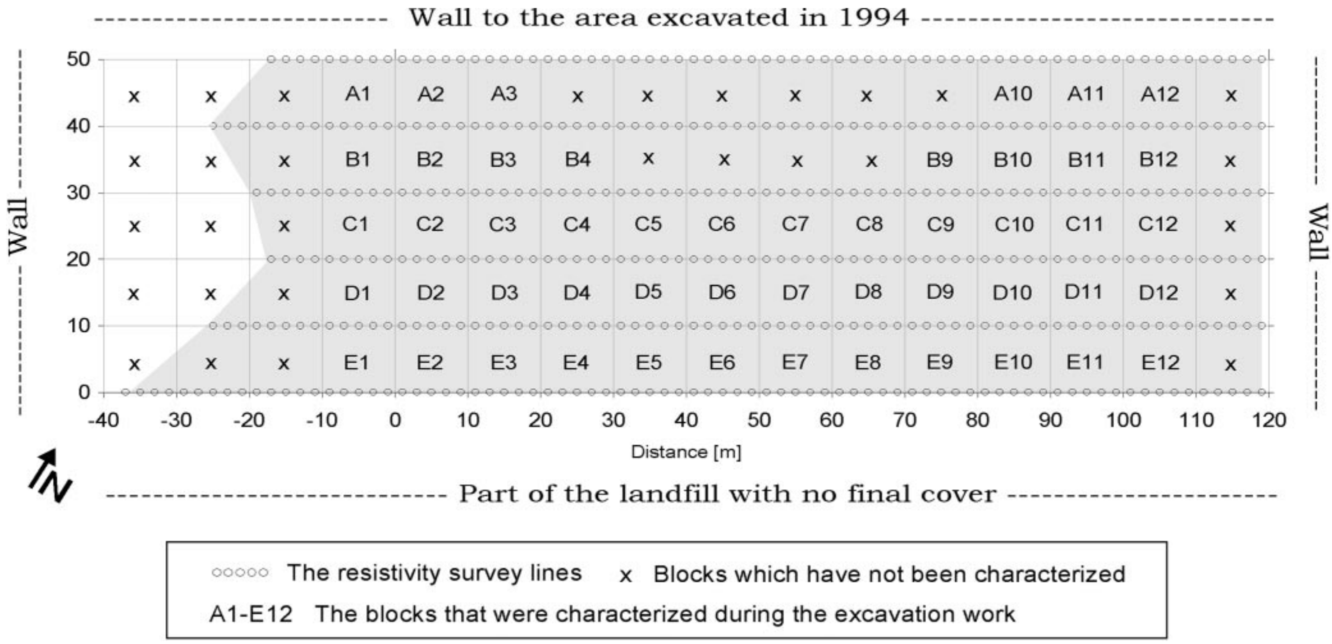


Fig. 4
An overview of the area investigated at the Filborna landfill, with *survey lines* indicated. Cells A4-9 and B5-8 were not characterized

Table 1
The pre-defined waste types used for the characterization

Classification scheme		
1 Soil/stones	4 Gardening refuse	7 Paper
2 Municipal waste	5 Chemical refuse	8 Plastic
3 Building refuse	6 Metal	9 Wood

Table 2
The electric conductivity of leachate water samples

Waste Block	Pump station[a]	B7	C5	C6	C7	C8
Conductivity [mS/m]	340	1370	1650	1280	1080	950

[a] Measured at a leachate water collection pipe

drainage system exist in this part of the landfill) a lateral flow of leachate water in the northeast direction was expected.

Waste characterization

The waste, in blocks of 10 × 10 m, was roughly characterized in parallel with the excavation progress of the 8000 m^2 area (Fig. 4). Each block was given two keys from a classification scheme (Table 1) with pre-defined waste types listed: (1) the dominating waste type and (2) the second dominating waste type. This information, including the moisture content, was obtained through visual inspection of the excavation walls. The electrical conductivity was measured in five leachate water samples (Table 2). Several blocks were not included at the start of the excavation work.

In the 1994 excavation, the temperature was registered at two depth intervals, 0–5 and 5–8 m, at 17 °C and 18–20 °C, respectively. These values are, except for the soil cover, assumed to be valid in the present study.

Data presentation and interpretation

The waste block characterization is presented in Fig. 6, where the dominating material type was given a value of 1 (black) and the second most common material, a value of 0.5 (gray). If two materials shared the latter group, each of them was given a value of 0.25. It is thus possible to compare the resistivity variation visually in both horizontal and vertical directions with the accommodated waste property variations. Clearly the waste cell is dominated by co-disposed soil and mineral wool waste (mineral wool has a low moisture content even if exposed to moisture). Plastic and wood are also present.

Leachate water was found in the characterization work in connection to the cell walls in NNW and ENE (dark colors in Fig. 6d). Both these walls drain partly towards the cell, that is, the precipitation is diverted into the cell where it infiltrates the wall footings. Since no draining system exists the net precipitation over the 8000 m^2 soil cover directly infiltrates the waste body.

An example of the interpreted 2-D resistivity sections is shown in Fig. 5. The individual inverted sections were merged into a 3-D model by triangulation with linear interpolation and slices from selected depths were then extracted (Fig. 7a–e). The mean model fit of the resistivity profiles is 8.9%. Because the area has lateral deviations from the 2-D assumption (3-D effects), as well as highly

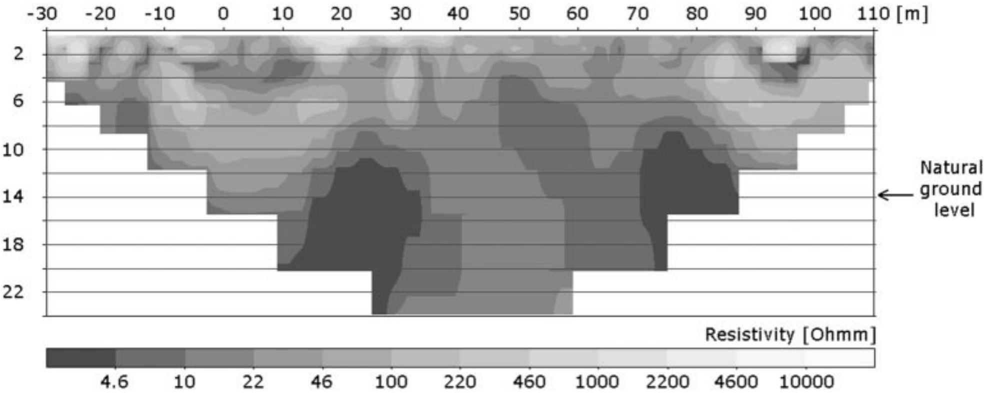


Fig. 5
An example of a 2-D inverted resistivity profile (survey line 50)

contrasting material properties, this fit value can be considered reasonable.

At shallow depths the overall variation of the resistivities is large (460 to >10 000 Ωm). The high resistivities at 0.5 m (Fig. 6a) are probably due to the shallow frost present during measurement. It is also clear that the soil cap is less affected by the frost close to the cell walls (<100 Ωm). At 1.5 m depth the resistivity variation is even greater. To some extent high resistivities coincide with places dominated by soil. At greater depths, 2.8 m and below, the resistivity plots are dominated by low resistivities (<22 Ωm). However, a few marked high resistive areas are visible (220–460 Ωm).

In general, areas with the lowest resistivities (<22 Ωm) have an irregular pattern and are found close to the NNW cell wall and as isolated spots in other parts. In the former case this correspond to the areas where leachate water was found (Fig. 6d and Fig. 7). This explanation probably applies to the other very low resistive areas as well.

No obvious relationship can be discerned between the resistivity plots and the waste characterization. Even though some local agreements exists, they cannot be considered valid over the whole area. This could be due to the measurement density since the resistivity plots are based upon more comprehensive data than the waste characterization. Furthermore, the moisture content has a high impact on the resistivity, which can mask the effect of surrounding individual waste material. The resistivity plots do not enhance the possibility to estimate the cover soil volume.

Two low resistivity areas, at depths not included in the characterization work, dominate the flanks of Fig. 5. The most likely explanation for these two areas are accumulations of conductive leachate water. The resolution at depth is limited. However, the low resistivities may well continue below the original ground surface level, which would indicate downward migration of leachate water into the original ground. This interpretation is supported by the high conductivity of groundwater samples taken from adjacent wells.

The Måsalycke Landfill

General

The landfill, which is operated by ÖKRAB, is situated 2 km to the south of the Scanian village of Sankt Olof. It has been in operation since 1975. This study relates to 17–23-year-old waste disposed up to approximately 10 m above natural ground level (Fig. 8a). The landfill contained mixed waste in several waste pallets. No gas extraction system exists. The existing soil cover was thin (<1 m) and sparsely vegetated.

A 2-D DC-resistivity survey preceded the excavation work in order to pre-characterize the waste volume and compare this with the true content. The cell contained both industrial and municipal waste. One CVES profile of about 110 m long and 25 m deep was measured in August 1997 (Fig. 8b).

A hydrogeological description of Måsalycke was compiled by Berndtsson and others (1985). They concluded that the natural geology consists of a sandstone overlain by a sandy till. The top part of the sandstone is heavily fractured. The regional groundwater gradient is towards the southwest, but the build-up of a high local groundwater level within the landfill leads to high outward directed gradients. It is doubtful whether a complete vertical hydraulic connection exists since only a small volume of leachate collects in the drain pipes underlying the waste pile. Lateral flow is a plausible explanation, where the drained water is collected by intersecting ditches. Several leachate water horizons with limited hydraulic connection may therefore exist.

Characterization procedure

The excavation was done with an Åkerman H14B HD excavator. The test pit was 10 × 10 m in size and situated on the resistivity profile 1 as shown in Fig. 8b. Observations of depth, temperature, methane content and electric conductivity were taken as the excavations progressed. The soil cover was very hard and sparsely vegetated. After the soil cover was removed the waste was transported by truck to a sorting table and a siever. The characterization is summarized in Table 3.

The top 2 m of waste were dominated by plastic of bags and wrappings, metal sheets, rubber, wood, grass, rope,

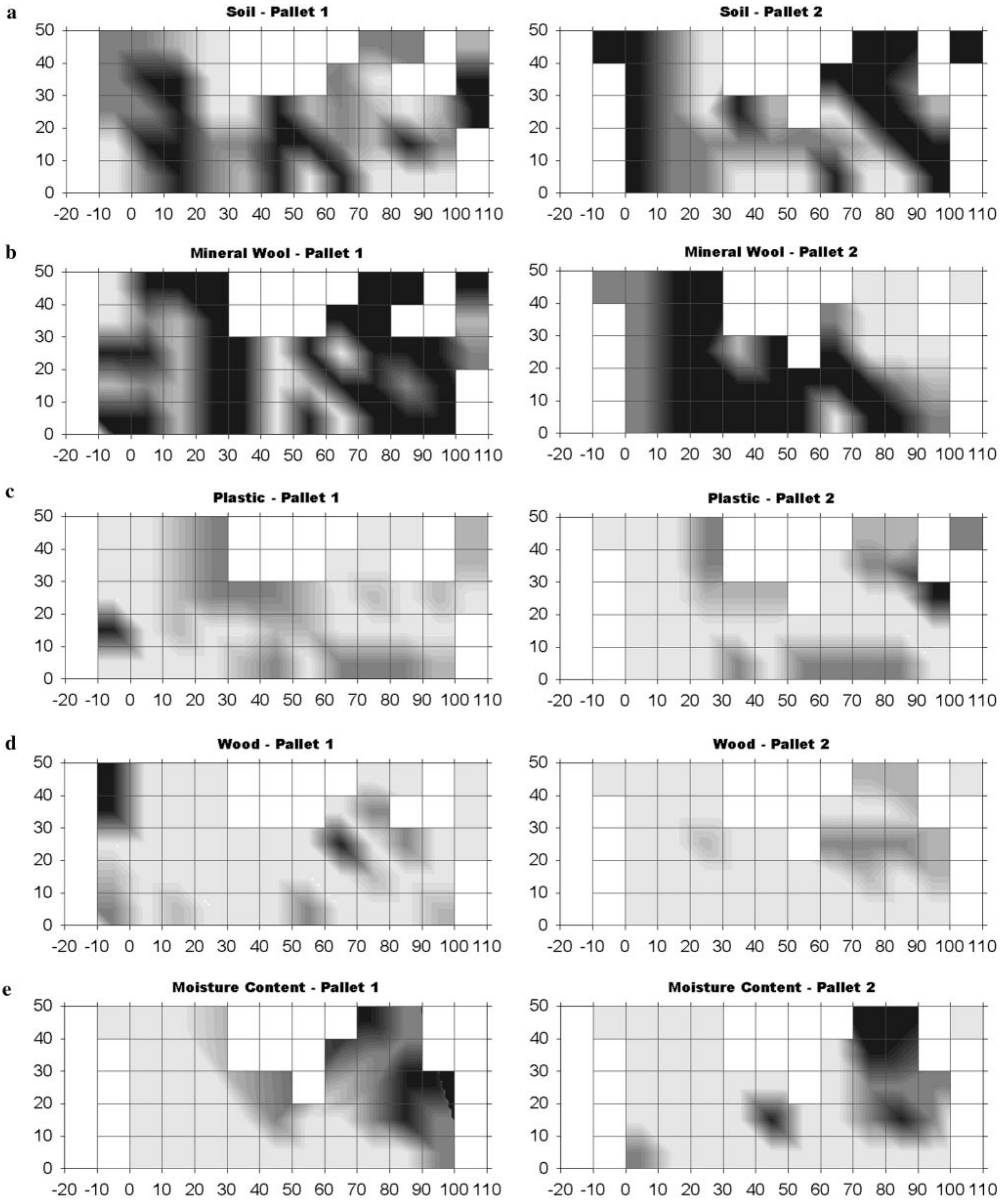


Fig. 6
The result of the waste characterization. *Dark colors* represent material that is abundant; *lighter colors,* materials that are progressively less abundant (interpolation by the triangulation method)

newspaper, tin cups, textile and concrete. The coarse fraction, excluding the cover soil, comprises more than 50% of the volume; 55% of this fraction consists of metal. Below the first intermediate cover (2.6–3.5 m) the waste was comprised of metal pipes, a trawl and building refuse. A second cover lies over a layer of excavated earth

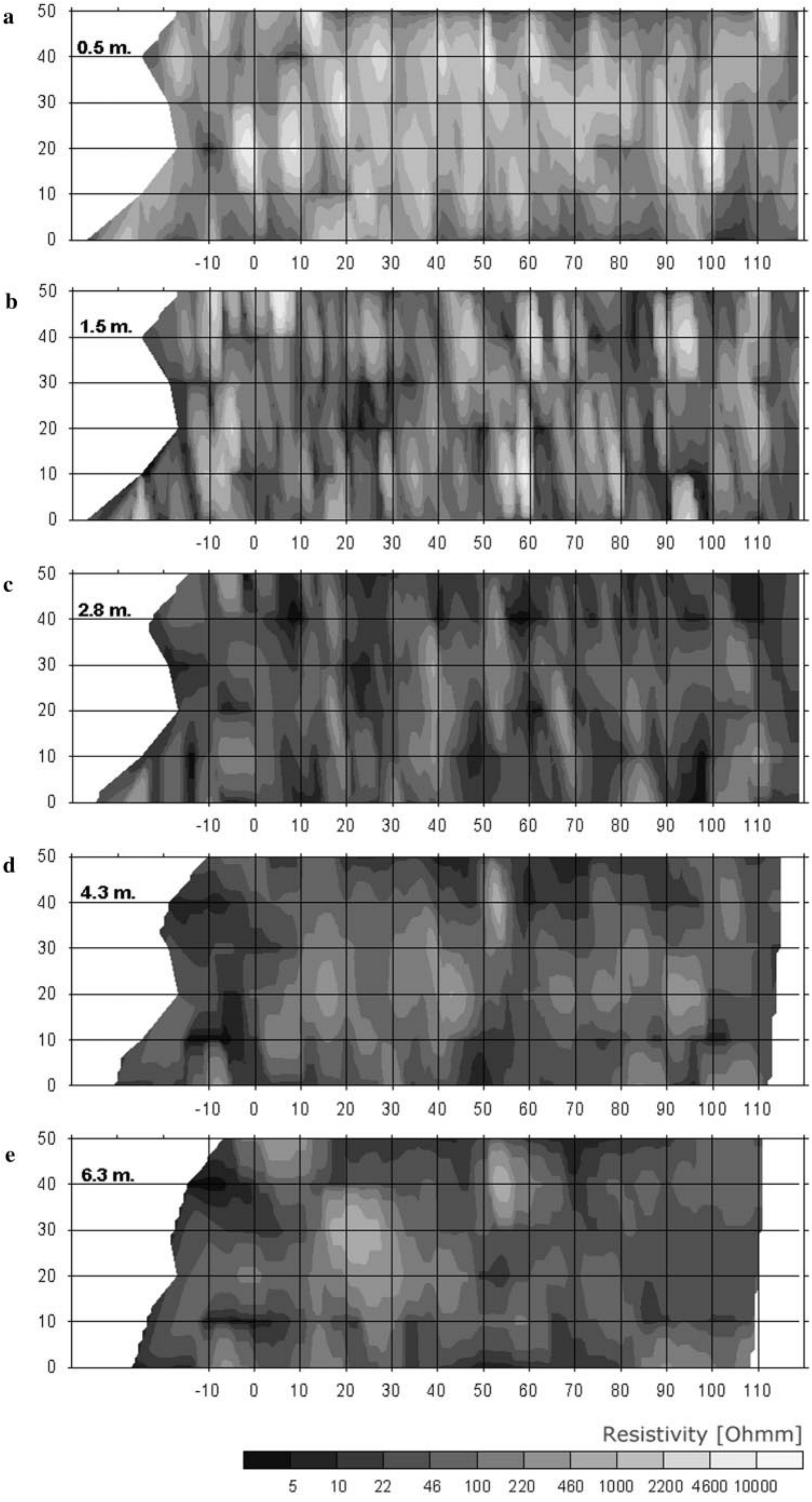


Fig. 7
The resistivity variation in plane **a** 0.5, **b** 1.5, **c** 2.8, **d** 4.3 and **e** 6.3 m below ground surface

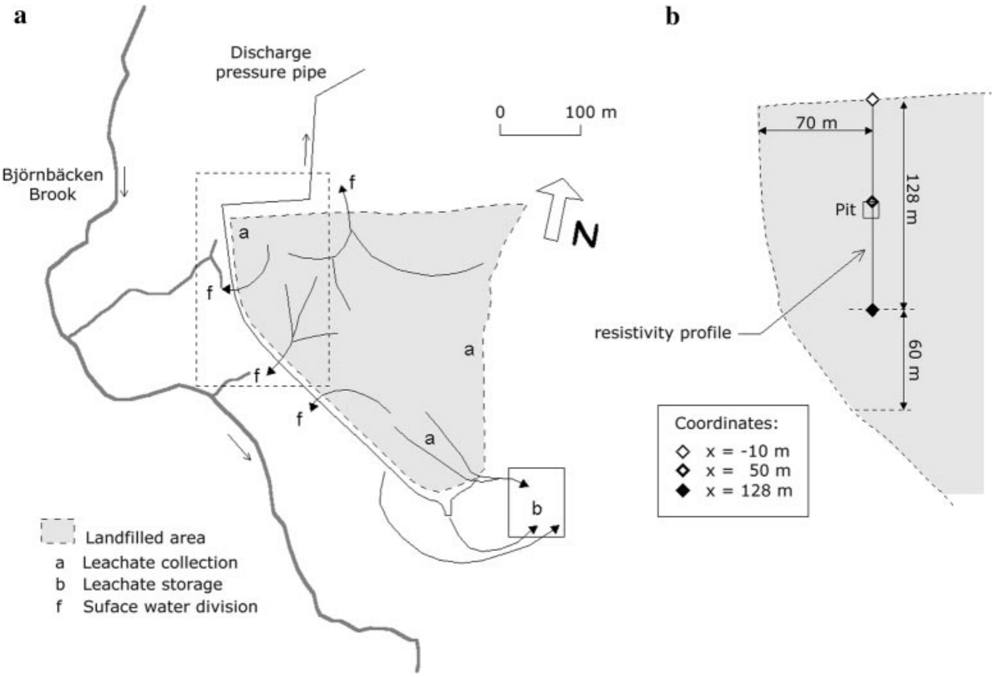


Fig. 8
A schematic map (**a**) of the Måsalycke landfill (modified after Nilsson and Vanek 1992) and (**b**) a detail on the location of the resistivity survey line and the excavation pit

mass (4.35–6.0 m). The next 3.5 m were of mixed waste, gardening and demolition refuse and stones. A fine fraction of degraded materials increase with depth, which is not possible to attribute to original materials. The moisture content in the pit varied from 10% close to the ground surface and to 30% at a depth of 9.5 m.

Data presentation and interpretation

The interpreted 2-D resistivity section is shown in Fig. 9. The model fit is 6.4%, which can be considered good. The waste characterization investigation was done between the indicator marks (50–60 m).

The resistivity distribution in the model (Fig. 9) indicates a top layer of laterally varying resistivities (25 to >250 Ωm) which is followed by a transition to a low resistivity layer (>16 Ωm). Both these layers are of varying thickness, although the latter dominates the mid-part of the profile. There is then a transition zone to relatively high resistivities (>100 Ωm) at 18 m depth.
The part of the resistivity profile that corresponds to the excavation pit (Fig. 10) follows the general appearance described above. The differences lies in that there are neither low nor high resistivities in the top layer and that the succeeding low resistivity layer is thick. The top layer resistivity ranges between 63 and 100 Ωm.

Table 3
Observations and measurements during excavation

Depth [m]	Temperature [°C]	Electric conductivity [mS/m]	Methane [%]	General observations and observations in the resistivity survey line
0.5–0.6	22.5	–	0.3	Soil (sand, clay, mixed with waste)
1.5	15	–	0.0	Coarse waste fraction (waste only)
1.75	15	175–250	0.3	Reaching cover layer (#1, clay till 60 cm thick) with water on top, coarse waste in the line
2.4		–	–	Cover layer removed
2.6		–	2.0	Waste mixed with relatively much soil
3.0	13.5	–	2.0	A trawl. Outpouring water. Reaching a cover layer
3.5–4.35		255	2.0	Cover layer (#2) of earth and clay, stones mixed with waste (30–60 cm thick)
4.35–6.0	12	480	–	Excavated earth masses
6.05	9.2	430–680	–	Water trickles into the pit
7.0–8.0	10	–	1.0–2.0	Gardening refuse (stumps, tree branches), demolition refuse, boulders (80 cm diameter), more moisture at increased depth
8.0–9.5	9	580	–	Some water on the pit floor

[a] In some cases the shown value represents the mean of several samples

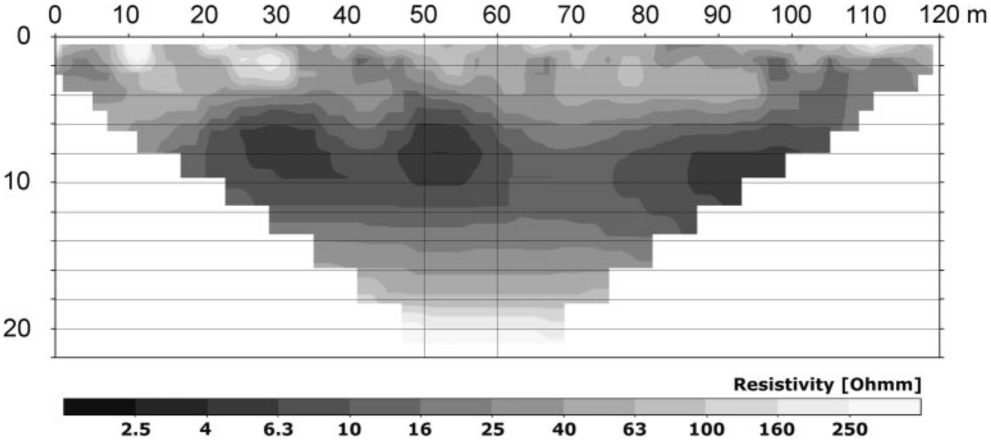


Fig. 9
The 2-D inverted resistivity profile (all distances in meters). The model fit is 6.4%. The excavation and characterization was done between 50 and 60 m

A comparison with the characterization in Table 3 indicates that the top resistivity layer corresponds to the cover of sandy or clayey soil mixed with waste. Neither the top cover nor the first internal cover layer of clay till are resolved.

The transition to lower resistivities, 40 Ωm and below, at 3.5 m corresponds to the start of the second internal cover layer (earth, clay and stones mixed with waste). The cover layer is followed by excavated earth masses down to a depth of 6 m, where 2 Ωm leachate water trickles into the pit. This level agrees well with the start of the very low resistivity area (<6.3 Ωm).

The last 3.5 m of waste (from 6 m down to 9.5 m) lies within the area of very low resistivity. The materials consists of gardening refuse (stumps, tree branches), demolition refuse and boulders. The overall moisture content increases with depth, ending with a puddle at 9.5 m where the excavations stop. The pit floor at 9.5 m deep is composed of earth masses that build up the landfill bottom. It is believed that this base consist of leveled earth, laid down when the foundations were prepared in the mid 1970s. Unfortunately no measurement of the exact depth to the underlying natural sedimentary rock were made.

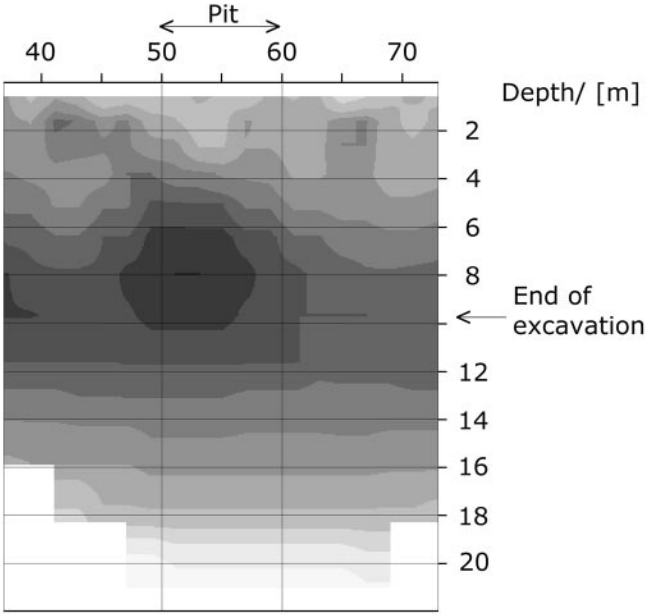


Fig. 10
A close-up of Fig. 9 which corresponds to the excavated pit (same legend)

An extension of the low resistivity area is seen below the end of the waste pile. This extension is probably caused by three reasons, of which the first is related to the geology and the other two to the physical modelling. First, the top part of the sandstone underlying the waste is heavily fractured. Because no effective leachate collection system exists in this old part of the landfill the 2-Ωm leachate water will be transported into the sedimentary rock and mix with the natural groundwater. The transition of resistivities to somewhat higher values at deeper levels probably reflects a decreasing effect of the leachate water in the sandstone aquifer. Second, all smoothness constrained multi-layer or multi-cell inversions result in more or less gradual interfaces, even if the geological boundaries are sharp and distinct. The third fact to consider is that, as a result of the method, the resolution decreases with depth and there is an increasing integration of the stratigraphical properties with depth. In combination, these circumstances lead to effects that can explain why the modelling does not manage to delimit the lower boundary of the low resistivity area.

The approximate 10 °C temperature gradient between the surface and the pit floor leads to a 25% relative resistivity decrease with depth (Dahlin 1993). This gradient means that there is a decreasing resistivity trend superimposed upon the model. Detrending might help to resolve certain features.

It can be concluded that the leachate water has a dramatic influence on the resistivity measurements, even though the moisture content in the waste is low (it varies between 10–30%). The leachate water that exists within the waste material produces a low resultant bulk resistivity. In addition, any material which is capable of holding water, such as sandy soils, will be conductive even if it is not saturated.

A generalization for the whole resistivity profile can be made by extrapolating the trends from the pit interpretations. The top layer demonstrates heterogeneous characteristics, with variations in both thickness and resistivity values. The moisture content is very low in this part ($\approx 10\%$) and therefore the resistivity values are more related to the waste material than in the case below. Its variation in thickness is probably due to a varying water infiltration capability and thus a depression in the saturation level. This reduced infiltration capacity implies the presence of waste materials or soil with low hydraulic conductivities. The isolated low resistivity area at a depth of 2 m at 67 m along the profile could thus be related to fringing leachate water. At a profile position of 90 to 110 m there are indications of a saturated cover layer, with low resistivities starting at the ground surface and continuing with depth. An alternative explanation is the accumulation of metal. At positions of 10 and 30 m there are two narrow areas of high resistivities, which are related to insulating materials, for example, large amounts of plastic or boulders.

The resistivity limit of 16 Ωm and below seems to correspond to the levels where there is an increased moisture content. This relatively continuous layer points out a possibly good horizontal hydraulic connection.

The lowermost resistivities probably reflect the accumulation of leachate water or, if no accumulation has occurred, leachate water with a relatively high electrical conductivity. If the latter is true, then the high values must depend on the degradation process at these points, which in turn must depend on the material present.

The transition to the underlying natural sedimentary rock, in respect of resistivities, is laterally uniform indicating that a "leachate plume" extends vertically from the landfill bottom, at approximately the 10-m level and some 8 m further below.

No estimation of the soil volume can be made because the top cover soil is mixed with a coarse waste fraction.

Discussion and conclusion

The study was limited to old parts of two operational landfills in southern Sweden. Both were constructed in the same manner, although the waste differs in age. The study was initiated because the areas were to be excavated and an excellent opportunity was presented for testing the capability of the resistivity method as a precharacterization technique. The available funds for the actual characterization work were, however, limited.

In summary the following can be stated about the correlation between the resistivity models and the characterization results:

1. The moisture content is the parameter that appears to exert the dominant control over the resistivity distribution of the landfill, as could have been expected. Apart from that, no other obvious relationship was possible to discern from the Filborna study. Several of the resistivity anomalies in Fig. 7 were determined by one or two adjacent measurements only. The plots thus display a strongly heterogeneous picture of the waste resistivity/conductivity.
2. The waste in the Måsalycke study was twice as old as that disposed in Filborna. A very good agreement between the level of free leachate water and the lowermost resistivities was obtained. In addition, the start of low resistivity values correspond to the start of an internal cover layer. The bottom of the waste pile coincides with the start of higher resistivities. However, low resistivities continue below the landfill bottom and indicate that leachate water is transported into the underlying fractured sandstone, finally mixing with the natural groundwater. The cover layer has the heterogeneous character of waste mixed with soil. Thus, the resistivity variations for this layer indicate varying materials and fringing leachate water tables.

In a heterogeneous media, which includes conductive structures, both electrolytic and ohmic conduction exist. However, as pointed out by Li and Oldenburg (1991), the variations in conductive structure alter the flow of electric charges and the final distribution of current is such that the energy loss due to ohmic dissipation is minimized. Physically, this results in current being channeled into regions of high conductivity and deflected away from resistive regions. This deflection means that the electric current in the waste will be strongly controlled by the amount of salinity and the pore electrolytes, but also dependent on the tortuosity of the pore space and the proportion of dispersed conducting waste. There are also other parameters that may place limits on the detection and resolution of deeper targets, e.g., structural dimensions relative to depth and resistivity contrasts (Griffiths and Barker 1993).

It therefore seems that the most important potential information which can be recovered from the surveys is an indication of the hydraulics of the waste piles. This would include leachate water pathways, fringing leachate pockets and the level of saturated waste.

In none of the two cases was it possible to estimate the amount of soil that could be recovered. Moreover, it was not possible to correlate the type of waste against the resistivity models. Discrete anomalies, both of high and low resistivity were identified in the surveys and if specific materials are searched for, the models can suggest possible places to search.

The usefulness of electrical surveys is determined by the reliability of data, the density of the measurements, and the quality of the interpretation (Christensen and Sørensen 1996). Compared to other similar surveys reported on in the literature these two surveys have included increased data density in both lateral and horizontal directions, however, this extra coverage may not be enough. On basis of the results obtained it must be stated that surveys of a limited data cover cannot be interpreted in great detail.

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