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Published in:
European Journal of Engineering and Environmental Geophysics

1997

European Journal of Environmental and Engineering Geophysics, **2**, 121-136 (1997)

DC RESISTIVITY MAPPING OF OLD LANDFILLS: TWO CASE STUDIES

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(Received January 1, 1997; revised version accepted June 3, 1997)

ABSTRACT

Geophysical investigations were carried out on two old waste disposal sites, Lernacken and Lackalänga, both situated in the province of Scania in southern Sweden. The objectives of the surveys were to map the internal structure and to delineate the extent of deposited waste, as well as to gain information about the local geology. The methods used were 2D DC resistivity, frequency domain electromagnetics (FDEM) and magnetics. The resistivity data sets were interpreted with 2D smoothness constrained inversion, and the FDEM and the magnetic data sets were contoured. The objectives were successfully met, including delineation of sludge ponds, a coastal saltwater front and geological structures, and identification of the positions of buried metal objects. In addition, at Lernacken leakage plumes were identified by the resistivity survey. The slingram EM equipment was rapid, whereas the 2D DC resistivity surveys provided valuable depth information that allowed the construction of quasi 3D models of the ground. The in-phase component in slingram measurements was especially good at localising individual metal objects, but the total field magnetic measurements also worked well.

KEY WORDS: environmental geophysics, resistivity, magnetics, frequency domain electromagnetics, inversion, landfill, waste, leakage plume, metal detection.

INTRODUCTION

The application of geophysical methods in environmental investigations, whether contaminants are limited in extent, or are moving as a contaminant plume, has been analysed for many years. The numerous situations where geophysical surveys are of interest have been discussed by e.g. Mazac et al. (1987), Jewell et al. (1993) and Allen et al. (1994). Morris (1996) and Ferguson et al. (1996) have published recent case studies related to environmental geophysical surveys. During the last five years there has been considerable development of the DC resistivity technique. Improvements in acquisition systems and interpretation techniques provide possibilities to collect large data sets in a short time, and to create accurate models of the resistivity distribution in the ground. This paper describes two geophysical surveys where the internal structure and the extent of deposited waste were determined. Three different geophysical techniques were used: DC resistivity, FDEM/slingram (frequency domain electromagnetics) and magnetics. The methods were selected by their sensitivity to galvanic resistivity, electromagnetic induction and magnetisation respectively.

The first case study comes from Lernacken, situated outside the city of Malmö (Fig. 1a). The area was investigated in connection with large construction works, and the targets were waste ponds containing hazardous waste. The area was mapped with geophysical methods in September 1995.

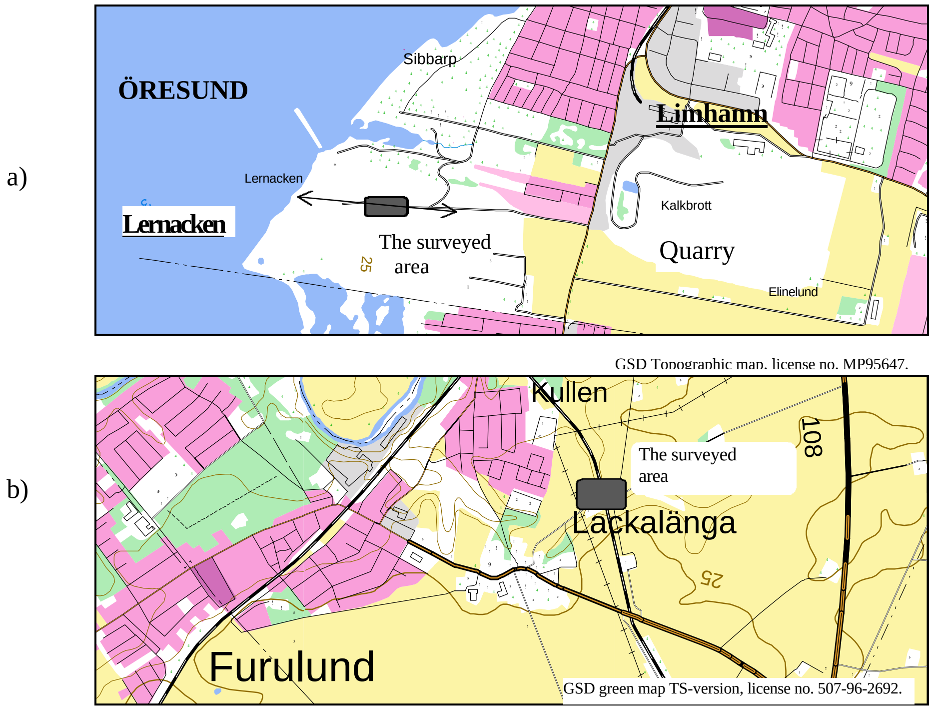

Fig . 1. (a) The Lernacken area, with the survey area and the line of the cross section in Figure 2 indicated. (b) The Lackalänga area with the survey area indicated. Reproduced with approval from LMV 1994.

The surveys led to better knowledge about the spatial extent of the waste, and about the geological setting. Further, it was possible to identify leakage plumes from the ponds. The second case study comes from Lackalänga, 30 km further to the north (Fig. 1b). A geophysical investigation was undertaken to map internal landfill structure prior to a railway track extension (Dahlin and Jepsson 1995). Excavation of the waste, and replacement with competent ground materials, were required prior to the track extension. The aim of the geophysical survey was to identify possible buried metal drums containing hazardous waste within the waste body. Several positions with probable metal content were identified and later confirmed by the excavation work.

METHODS

DC Resistivity

The resistivity data acquisition system used in the surveys was the ABEM Lund Imaging System. It is a further developed version of a multi-electrode system developed at Lund University (Dahlin 1993). The main parts of the system are a resistivity meter

(Terrameter SAS300C), a 4x64 channel relay matrix switching unit (Electrode Selector ES464), a portable PC-type computer, four electrode cables (21 take-outs per cable) and steel electrodes. A separate current amplifier (Booster SAS2000) is optional. The equipment was operated by two people.

The data acquisition of the Lund Imaging System is controlled by software that checks that all the electrodes are connected and properly grounded before measurement start. After adequate grounding is attained the software scans through the measurement protocol. The electrode configuration is user selectable through protocol files. Wenner CVES (continuous vertical electrical sounding) measurements were applied throughout the surveys, but the electrode distances differed. The measurement protocol included 10 different electrode spacings, ranging between 5-120 metres at Lernacken and between 2-48 metres at Lackalänga.

During fieldwork, data quality control and a first interpretation of data were possible by automatic pseudosection plotting. Pseudosections are constructed by contouring the measured apparent resistivities, where the midpoint between the electrodes in a measurement constitutes the length scale and the electrode separation the depth scale. No smoothing of the data is done because of the linear interpolation between the measured values.

At Lernacken the true resistivity structure was interpreted with 2D smoothness constrained inversion. Two-dimensional (2D) structures are assumed in the inversion procedure, i.e. the properties are constant perpendicular to the line of the profile, although the current electrodes are modelled as 3D sources. A finite difference (FD) model of the resistivity distribution in the ground is generated and adjusted to fit the data iteratively. The program was RES2DINV, which uses a quasi-Newton technique to reduce the numerical calculations (Loke and Barker 1996). In the inversion of the data the damping factor can be varied and the vertical-to-horizontal flatness filter ratio adjusted depending on the expected geology, in this case the filter ratio was set to unity. Finally, the interpreted 2D sections were merged into 3D models by triangulation with linear interpolation, and slices from selected depths extracted.

Frequency Domain Electromagnetics (Slingram)

Geonics EM31 is a well known FDEM instrument. Its application in environmental related problems is described by, for example, Jansen et al. (1993), Jordan and Constantini (1995) and Ferguson et al. (1996). The instrument is one-man portable, and has a beam mounted to the control unit to separate the transmitter from the receiver coil. The intercoil spacing is 3.7 metres and the operating frequency 9.8 kHz. The basic function is described by McNeill (1980). The design of the EM31 allows direct readings of the ground conductivity. However, the validity holds only within certain limits, i.e. measurements at low induction numbers. In this case the relation between the magnetic and the electric fields is linear. If the in-phase component is high, the assumption is violated and as a result the measured value will not correspond to the real conductivity of the soil. For vertical dipole measurements the depth penetration in conductive materials is approximately 5 metres (Ferguson et al. 1996).

The Mark II from Apex Parametric Ltd. is another dipole-dipole electromagnetic instrument, with 1.5 metres intercoil spacing and 5 kHz operating frequency. It is a minimum coupled instrument (coil axes 55° from horizontal) with a high lateral resolution. The depth penetration is maximum 26 metres in non-conductive environments (Apex 1976), otherwise less. Both the in-phase and the quadrature component are registered for later interpretation. Because of the attenuation of the electromagnetic signal in the ground, the value measured by a FDEM instrument is a weighted average of the coverage, and the value is said to be apparent.

The survey at Lernacken included the EM31. The line separation was 10 metres. In cases of sudden change the station separation was 5 metres, otherwise it was 10 metres. The conductivity data set was transformed to apparent resistivities and contoured. The survey at Lackalänga included the Mark II. The line separation was 4.5-5 metres, and measurements were taken at every 2 metres. Both the in-phase and quadrature components were contoured.

Magnetometry

The GSM8, from GEM Systems, is a gamma proton magnetometer with 1 nanoTesla resolution and accuracy. The use of proton magnetometers in landfill surveying is dealt with by Cochran and Dalton (1995). They discuss the influence of the grid dimensions on target detection, and compare a conventional magnetometer with a multi-sensor system and a high resolution metal detector. The resolution of individual objects is better with the two latter instruments, but with a small grid dimension a total field magnetometer works well. The principle of instrument handling and data interpretation is described by Breiner (1973).

The data analysis was qualitative. Numerical analysis can provide quantification of the anomalies. However, an attempt to model the results with a 2D indirect modelling program failed due to the lack of knowledge of magnetic susceptibility and remanent magnetisation of the buried objects. A number of models with metal objects spread over the bottom of the valley all fit the field data. With an understanding of individual simple anomaly functions, and given some reasonable assumptions regarding the geology and buried object, a qualitative but satisfactory interpretation can usually be made (Breiner 1973).

The magnetic method was also included in the survey at Lackalänga. Recording of the total magnetic field was taken at 2 metres intervals. Because the area was covered in 2 hours a base station was not considered necessary. The intensity of the Earth’s field is around 49.5 μT in the area, and the inclination is 69°.

CASE HISTORIES

Case 1: Mapping of sludge ponds at Lernacken, Malmö

Background and site description

Due to the deposition of filling materials over the last 80 years, the Lernacken area has extended out into the sea by several hundred metres. Although few early records about the disposed material exist, the materials are mostly lime quarry waste and excavated topsoils. In the 1960s several 1-4 metres deep ponds were dug in the fillings for deposition of sludge waste. After closure in 1987 the waste was covered with glacial till. Sludge from gutter wells, grease and oil from separators, and waste from processing industries make up the waste body (VBB Viak 1992a). Soil analyses have revealed very high levels of organic contaminants and heavy-metals concentrated to the pits, with levels quickly decreasing in the underlying soils. No leakage collection system exists, and chemical analyses have revealed considerably raised levels of several substances. Some examples are listed in Table 1.

Table 1. The levels of some chemical substances in the groundwater (Brorsson and Lerjefors 1996). Two samples come from the soil aquifer, and one from the rock aquifer (see Figure 3 for location). The last two columns represent back ground values (if available) typically found in the region.

Substance	Sampled boreholes			Back ground levels[1]	
	Rb7901 soil aquifer [mg/l]	Bp16C soil aquifer [mg/l]	Bp16D rock aquifer [mg/l]	Fictive 1 soil aquifer [mg/l]	Fictive 2 rock aquifer [mg/l]
Chloride	1100	2200	660	36	46.1
Sodium	26	1100	1100	101.9	180.6
Ammonium	44	0.08	0.08	0.02	0.18
COD[2]	12	7.9	7.9		
Aromatics	1.2	< 0.6	< 0.6		
Phenol	$260 \cdot 10^{-3}$	-	$4400 \cdot 10^{-3}$		
Lead	$97 \cdot 10^{-3}$	$< 1 \cdot 10^{-3}$	$38 \cdot 10^{-3}$	$< 0.5 \cdot 10^{-3}$	$< 0.5 \cdot 10^{-3}$
Chromium	$130 \cdot 10^{-3}$	$30 \cdot 10^{-3}$	$10 \cdot 10^{-3}$		

1. The ”fictive wells” represent average values of several wells in the region.
2. Chemical Oxygen Demand.

Geology and hydrogeology

The upper bedrock in the region is a Tertiary limestone overlain by a sheet of glacial till, which follows the slightly undulating limestone relief. The transition to harder limestone is often diffuse, passing through a layer of eroded limestone. The Quarternary cover varies between 2-15 metres and is composed mainly of clay tills and stratified interglacial sediments. Locally, especially in the uppermost part, coarser material forms relatively permeable bodies (VBB-Viak 1992b), see Figure 2.

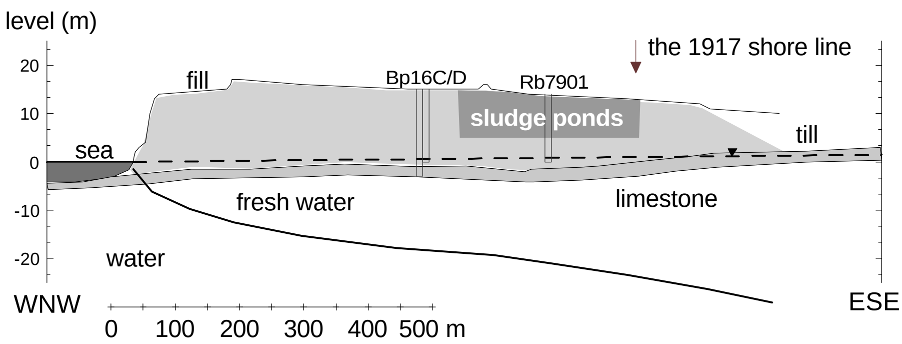

Fig. 2. Cross section through Lernacken and the sludge pond area. The boreholes from Table 1 are indicated.

The overall groundwater flow has a west north-west direction towards the sea (Brorsson & Lerjefors 1996). The glacial till is considered to separate the soil and limestone aquifer, of which the latter is regionally important. Topography and the barrier of the till cause the build-up of hydraulic pressure in the limestone aquifer, and hence groundwater to some extent passes through the till into the soil aquifer. However, locally there is downward directed transport as well, because of the built-up high hydraulic pressures. In this way it is possible for contaminated leachate water to reach deeper strata.

Results and interpretation

Electromagnetics

The apparent resistivities from the FDEM survey are contoured in Figure 3a. Several low resistivity zones are clearly distinguishable and the zones correspond to the pond locations, based on the results of the soil analysis (Fig. 3b).

The measured volume of influence only incorporates saturated soils to a small extent, since the groundwater level lies at a depth where the contribution to registered conductivities is small, as inferred by the EM31 cumulative response function.

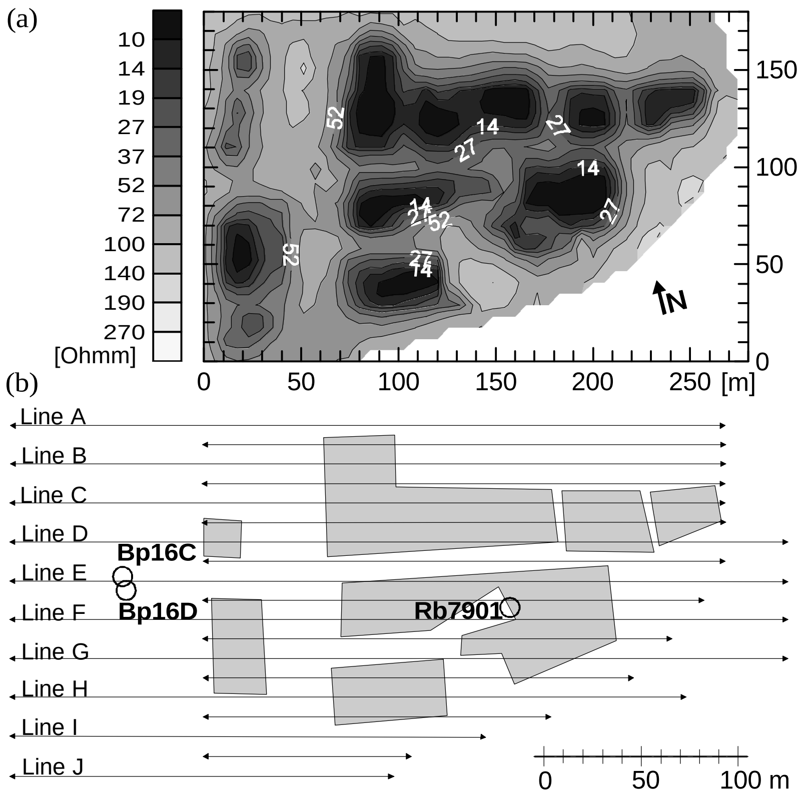

Fig. 3. (a) EM31 apparent resistivities, and (b) the position of the ponds based on soil analysis (Brorsson & Lerjefors 1996), together with the surveyed lines. Labelled lines indicate resistivity, all lines FDEM. The boreholes from Table 1 are also shown.

DC Resistivity

Selected inverted resistivity profiles together with pertaining pseudosections are shown in Figure 4. In total, 10 parallel resistivity profiles were inverted (Fig. 5), where the mean model fit is 8.9%. Because the area has lateral deviations from the 2D assumption (3D effects), and highly contrasting material properties, this fit value can be considered reasonable.

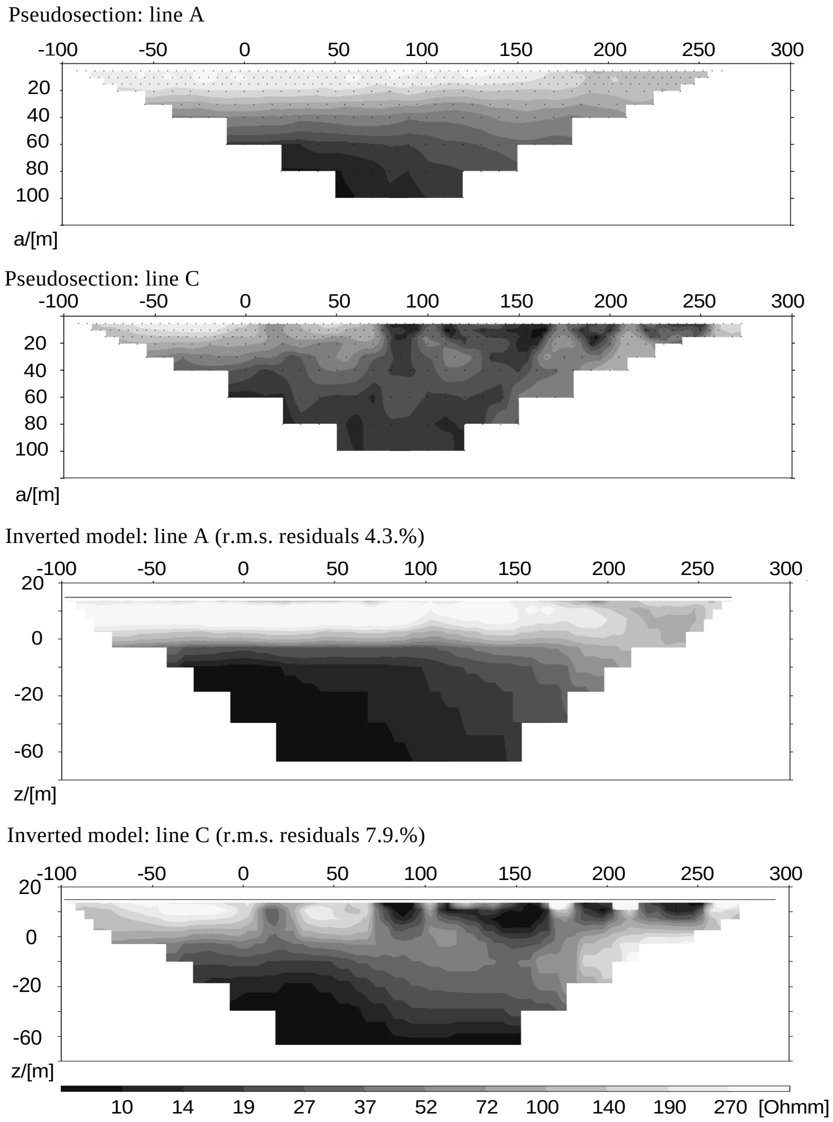

Fig. 4. Pseudosections (on top) and 2D inverted models (below) of line A and C (East-West).
Figure 5. Depth slicing of line A-J ([1] 0-2.6 m., [2] 2.6-5.8 m., [3] 9.8-14.8m., [4] 14.8-21.0 m., [5] 21.0-28.9 m., [6] 28.9-38.6 m.).

The transition of resistivities is fairly horizontally uniform outside the pond area, as is exemplified in profile A (Fig. 4), with quite high values in the dry soil and somewhat lower in the clay tills. The continuous resistivity decrease in the deep part is due to the coastal salt water front, which extends from north north-west (Fig. 5). The low resistivity zones in the upper parts of profile C (and in level 1 and 2 in Figure 5), reflect the disposed waste. Even though the resistivity structure of the pond area is complex the individual ponds can be delineated in a plane, and approximately in depth. The available chemical data suggest that, e.g., the zone at 150 metres in profile C (Fig. 4) is interpreted as due to a contaminant plume.

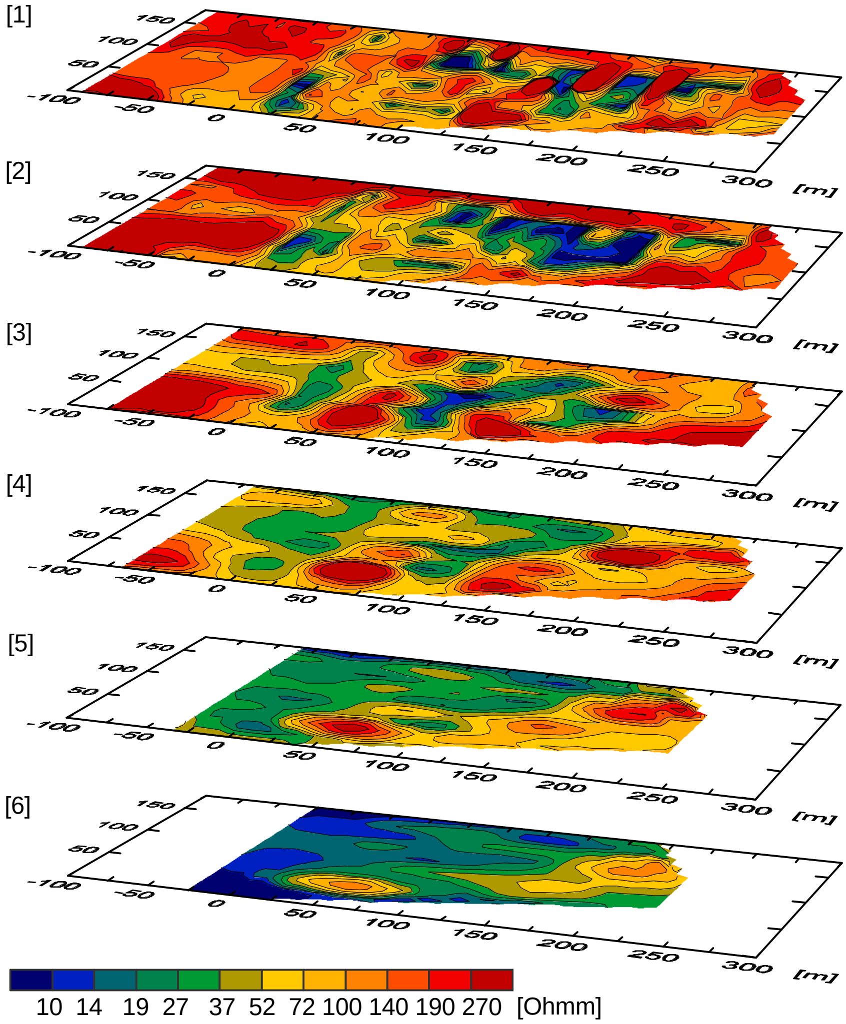

Fig. 5. Depth slicing of line A-J ([1] 0-2.6 m., [2] 2.6-5.8 m., [3] 9.8-14.8 m., [4] 14.8-21.0 m., [5] 21.0-28.9 m., [6] 28.9-38.6 m.).

Conclusion

Figures 3-5 illustrate the location of the waste. The relatively high and homogeneous resistivities of the fill material, compared to the resistivities of the waste, make it possible to differentiate the waste ponds from the fill. The continuation of low resistivity values below the ponds also contrast to the adjacent resistivity values, and are clearly anomalous. These low resistivity zones reflect drainage of high conductivity water from the ponds, passing through the fill to the groundwater table.

Case 2: Mapping of a landfill to be excavated, Lackalänga

Background and site description

A railway track extension passing Lackalänga village (Fig. 6) was constructed in 1994/95. The investigation area covers a small valley that at the time of the survey was filled with domestic and industrial waste, deposited in the 1950s and 60s. The landfill area is shown in Figure 6a; the valley incises Quaternary clay tills (Fig. 6b). The waste was deposited on top of a layer of peat, and after deposition the waste body was covered by demolition/excavation masses and soil. The survey was carried out along 8 profiles, 4.5-5 metres apart, placed perpendicular to the valley structure.

Results and interpretation

<u>Magnetometry</u>

The magnetometry data are contoured in Figure 7. M1-M4 are anomalies characterised by a minimum towards north and a maximum towards south; the shape indicates the presence of magnetic objects with no remanant magnetisation or remanant magnetisation parallel to the Earth’s field. There are no geological structures in the area which can cause such large anomalies and therefore they must be due to metal objects. A broad west-east extending anomaly crosses the area and indicates a strike parallel to the valley structure.

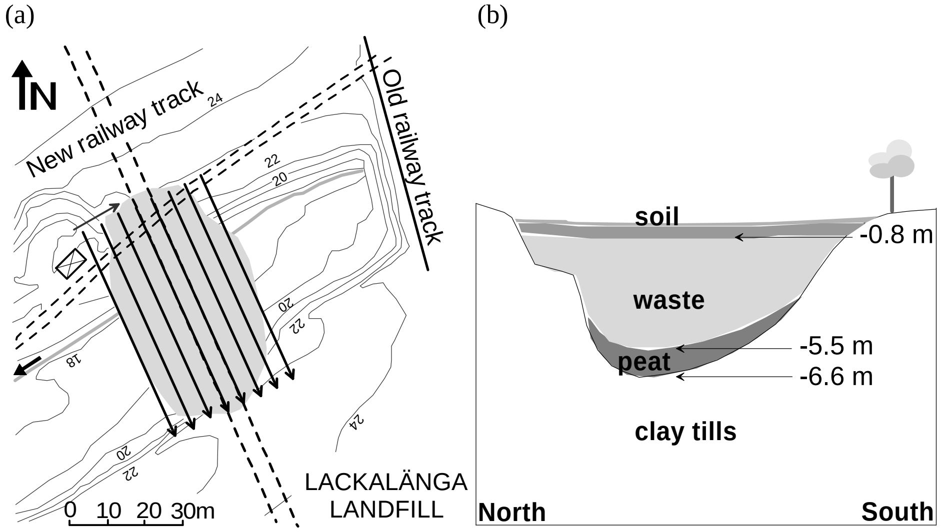

Fig. 6. (a) The Lackalänga landfill site, and (b) principle section through the valley.

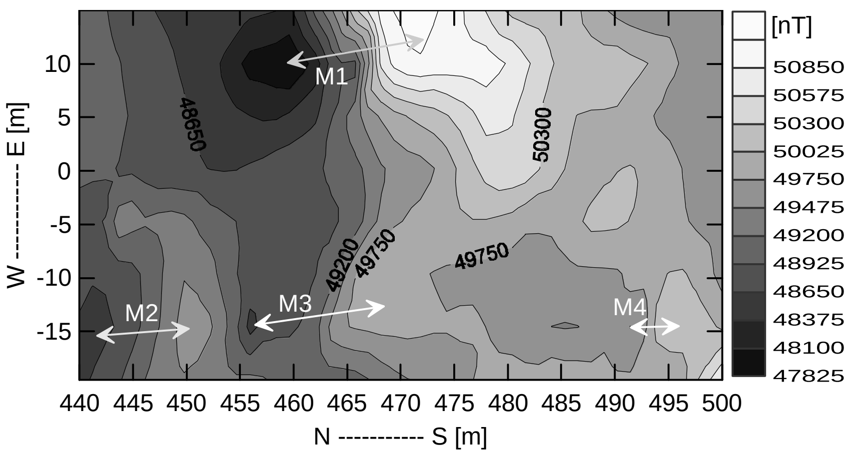

Fig. 7. Result of total magnetic field measurements. Four anomalies M1-M4 are marked.

Electromagnetics

The slingram results, both in-phase and quadrature components, are contoured in Figure 8. The two maps differ: the in-phase component map is irregular with no obvious strike and with discrete anomalies, the quadrature component map is smoothed with a rise towards the central part and has a marked W-E strike. The in-phase to quadrature ratio, which gives a measure of the target conductivity (APEX 1976), is high for EM1. A conductive overburden can create a quadrature response of its own, due to eddy currents induced in it by the primary field. The response profiles become positive, and are normally broad and wavy without sharp peaks (APEX 1976). This is probably the case with the broad zone of high conductivity values that coincide with the waste body, and could explain the low in-phase to quadrature ratio of EM2-EM4. However, because the in-phase component is particularly sensitive to the presence of metal (Jansen et al 1993) the distinct anomalies of EM1-EM4 are probably due to metal objects. The maximum in-phase component anomaly for a perfect conductor is a function of the depth to the object and the object dimension. By this, the anomaly at EM1 and EM3 is interpreted as buried objects, EM2 as a small shallow object, and EM4 (Fig. 8a) as a larger near surface object/objects.

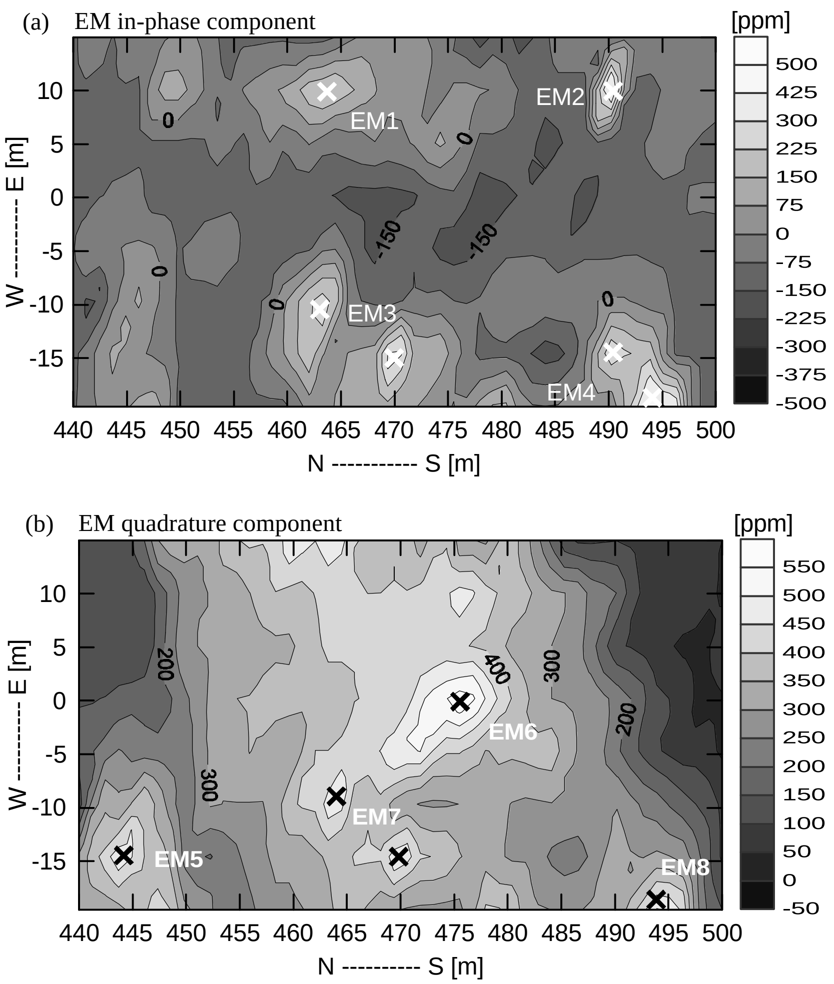

Fig. 8. The in-phase component (a) and the quadrature component (b) of the FDEM. The major anomalies EM1-EM7 are indicated (sensitivity in ppm of the primary field).

DC Resistivity

The model fit values of the inversion for the individual resistivity profiles are between 4.2-7.8%, which because of lateral deviation from the 2D assumption, must be considered reasonable. From Figure 9, it is evident that the internal resistivity structure of the waste body is anisotropic. The anisotropy can be explained by internal blocks of different materials, such as metallic waste, but also by preferential pathways of infiltrated waters. The waste body, and the original valley structure, is clear from level 3-6, where the transition from high to low values reflects passage from the tills to the waste. The preferential N-S elongation of the resistivity structures is due to the direction of the CVES- measurements. This is especially marked at depth, where the resolution is poor.

Summary

There is a good general agreement in the pattern between the three geophysical methods used at Lackalänga, although, there are some differences. A comparison of the location of the major anomalies in Figures 7-9 is made in Table 2.

Table 2. Comparison of the locations of the anomalies (Figs 7-9) identified by the geophysics.

Magnetics	FDEM (in-phase component)	FDEM (quadrature component)	Resistivity (level)
M1	EM1	-	4, 5
M2	-	EM5	3, 4
M3	EM3	EM7	4, 5
M4	EM4	EM8	2
-	EM2	-	-
-	-	EM6	4, 5

The resistivity data cannot resolve individual anomalies, but can confirm or reject the results from the magnetics and the FDEM. In all cases, except for EM2, the anomalies in Figures 7 and 8 are located in the low resistivity zones in Figure 9. An additional reason for EM2 not being detected by the resistivity could be small size and shallow location. The interpretation that EM4 is a near surface anomaly is strengthened by the resistivity data.

Several metal objects were found when the waste was excavated. The largest item was a two square metre sized water heating tank found at about 2 metres depth, corresponding to anomaly M2 (EM5). Smaller metal objects, for example pieces of a car, were found near surface at EM2 and M4 (EM4, EM8). A large number of compressed metal drums were found at 2-4 metres depth in the central parts of the valley, corresponding to M1 (EM1) and M3 (EM3, EM7). The anomaly EM6 has not been characterised, and may well be a result of the conductive overburden.

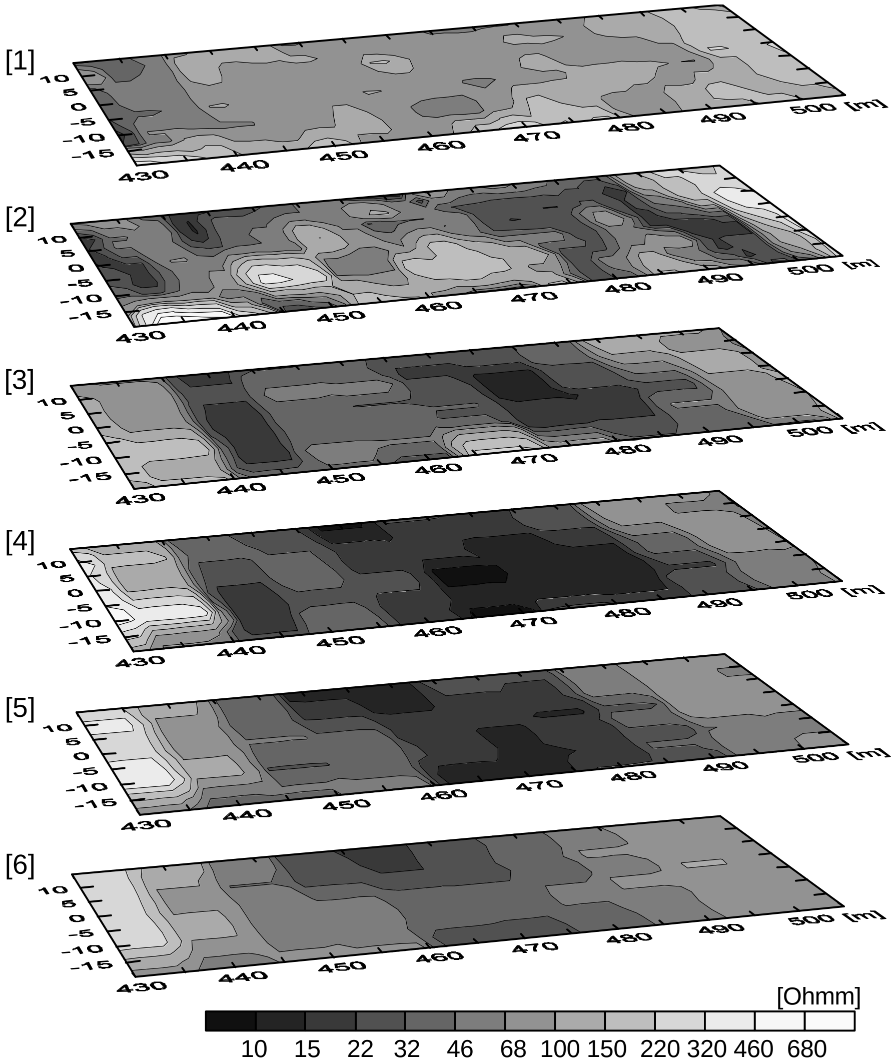

Fig. 9. Depth slicing of the resistivity ([1] 0.5 m., [2] 1.6 m., [3] 2.8 m., [4] 4.3 m, [5] 6.3 m., [6] 8.7 m).

CONCLUSION

The two case studies described have shown that electromagnetic, electric and magnetic methods can be powerful tools for locating and mapping contaminated ground. The methods measure three different physical properties and consequently the results look different. However, different aspects of the physical properties of the subsurface all contribute to the knowledge of the investigated areas. It is also important to bear in mind that geophysical methods can never be used alone, but need support from other independent data for a reliable evaluation.

In the Lernacken case it was possible to distinguish the waste ponds from the fill, and to detect leakage plumes with the resistivity method. At Lackalänga it was possible to point out five locations with a probable metal content, and the locations were confirmed by the later excavations. Both the magnetics and the FDEM worked well for metal detection, and the methods were consistent, but with one exception. The resistivity model gave a good general overview of the waste body, delineating it from the surrounding soils, but could not resolve any discrete anomalies caused by buried metal objects. The geophysical results have formed a valuable part of the investigation scheme of the two areas. The pond area will receive a well designed impermeable soil cap to minimise infiltration, and the excavation of the waste at Lackalänga was approached cautiously.

The slingram EM method is rapid and suitable for reconnaissance, whereas a 2D DC resistivity survey provides valuable depth information that make it possible to build quasi 3D models of the ground. The in-phase component in slingram measurements is especially good at localising individual metal objects, but the total field magnetic measurements also worked well. It is possible to get indications of the relative depths to the objects from the FDEM results. Compared to the FDEM and magnetometry, the resistivity method is time consuming, although the instruments available today have increased the data collection procedure considerably. The time consumption is partially inherent in the method but faster instruments, which can measure simultaneously on several channels, are now being developed and will further increase the speed of surveying.

ACKNOWLEDGEMENTS

The authors thank AFR (Swedish Waste Research Council) and SGU (Swedish Geological Survey) for financial support for the work carried out for this paper. We thank SVEDAB (Lernacken), Hans Jeppson at VBB VIAK and SYSAV (Lackalänga) for the fruitful co-operation. We are also grateful to the students involved in the survey work: Jonas Falk, Åsa Joelsson, Mårten Rundgren, Jörgen Brorsson and Ulrika Lerjefors. We are further indebted to Jörgen Brorsson and Ulrika Lerjefors for the compilation of the large amount of information from Lernacken in their M.Sc. thesis.

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