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Dense resistivity and induced polarization profiling for a landfill restoration project at Härlöv, Southern Sweden

A resistivity and time-domain induced polarization (IP) survey was conducted at a landfill site under restoration at Härlöv in Southern Sweden. The covering of the landfill had begun some years ago, without keeping precise records of the work done, as is usual in such procedures. The survey was conducted in two steps, on two adjacent areas. First, a number of geoelectrical sections were made on a partly covered area that had been investigated earlier by auger drilling, in order to assist restoration. Then, a second area that should have received its final cover was imaged, and some defects in the cover could be detected and repaired. The resistivity and time-domain IP results were consistent with the results of the geotechnical drillings, and they enabled quasi-continuous mapping along the profiles. Three-dimensional visualization showed the overall consistency of the two-dimensional lines, and helped to generate a global view of the site. In spite of some ambiguities, cover and waste could be distinguished in most cases. In particular, fine-grained cover materials could be clearly distinguished from other cover materials.

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Introduction

Needs at landfills

In Sweden the regulations controlling the supervision and maintenance of old landfills have changed a lot during the last few years. In 2002 all landfills had to produce a plan including procedures for either shutdown or continued use. The plans included solutions for reducing infiltration of surface water and leakage of contaminated water. To get a permit to close down a landfill the cover of the site has to be able to limit infiltration of surface water to a rate of 50 mm year^{-1}. This could be achieved by a combination of the thickness of material used, and the hydraulic conductivity of that material.

A common procedure at old landfills has been to use any soil-like material that is convenient for covering the household waste when the final level has been reached. This has most often been done informally, without keeping records of cover construction. Some material may be fully suitable as a hydraulic barrier, whereas other materials are better used for drainage. Since the final covered areas are often rather large, cost savings can be achieved if only the necessary volume of appropriate material has to be bought. Large areas also require numerous geotechnical borings for controlling the function of the cover. Thus, a combination of limited geotechnical soundings with a sampling programme and geophysical profiling was an attractive proposal. In this case, the geotechnical investigations were limited to in-situ determination of the material in place. One could also measure the permeability, as well as the local value for resistivity (with RCPT (Cone Penetration Test (CPT) with resistivity measurement) for instance) in the soil and in the water, but it has not been done here.

Capabilities of the geoelectrical techniques

Distinguishing between cover and waste

Resistivity can be a relevant parameter for landfill applications since a significant contrast in resistivity occurs between the waste materials and the cover that is often drier, as was found by, for example, Aristodemou & Thomas-Betts (2000). The high salinity of fluids saturating refuse usually makes them very conductive. However, if the waste is dry, then it is likely to be rather resistive (e.g. Aristodemou & Thomas-Betts 2000, Ogilvy *et al.* 2002, Rivière *et al.* 2003). Likewise, if the water table is inside the cover layer, and/or if clay constitutes a large fraction of the cover, then the resistivity of the cover can drop, so as to make it practically impossible to distinguish cover material from the waste. Another difficulty is the extreme inhomogeneity of waste materials (Bernstone *et al.* 2000).

Time-domain induced polarization (IP) has been used successfully for similar applications. The published results all show that waste most often exhibits chargeability values that are higher than the geological background (Carlson *et al.* 1999, Iliceto & Morelli 1999).

Although it might yield more detailed information, spectral IP has not been in much use for such applications, due to its cost. Since the results achieved with the time-domain method are good enough, spectral IP is viewed as not necessary. Weller *et al.* (1999, 2000) have observed increased phase angles in waste containing disseminated metals and various contaminants. Several authors (among others Vanhala 1997) have reported distortions in the phase spectra due to organic contamination changing with time. Recent studies have tried to relate hydraulic conductivity of geological materials to their spectral IP parameters, and the method might be able to yield more detailed results in the future.

Distinguishing between coarse- and fine-grained materials

Combining resistivity and IP techniques can in some cases make it possible to distinguish between coarse- and fine-grained materials, provided we have some knowledge of their nature and different saturation levels do not complicate the problem. Unless saturated by saline water (leachate), most coarse-grained materials are likely to have higher resistivity than finer materials. The chargeability will be higher if fine particles are found between the grains, or coating the grains. Pure clay has very low chargeability, but till can have low to moderate chargeability, depending on its clay content. Moreover, the issue of a loose soil material being coarse grained or fine grained usually determines its hydraulic conductivity. However, if it is often possible to distinguish between fine- and coarse-grained materials; the contrast depends on the local site conditions, since resistivity depends on several different parameters, (e.g. Mazáč *et al.* 1990), and some ambiguity can remain. IP could in some cases resolve ambiguities.

Site description

Regional situation

The 52-ha Härlöv landfill is located close to the city of Kristianstad in Southern Sweden. It has received all sorts of common unsorted domestic waste and construction refuse, as well as sludges and industrial waste since the beginning of the 1950s; and it was closed for new deposits in July 2002, due to its inappropriate location. The landfill is placed rather close to the centre of the small town, and very close to the small river Helge, adjacent to an area of national natural interest that includes a segment of the river Helge and the lakes Araslöv and Hammar. In a few years, when the reclamation is completed, it should become a green recreational area, naturally placed between the urban facilities and the neighbouring natural and historical reserve.

Landfill site

Before it was possible to close the landfill, alternatives and agreements with the neighbouring districts concerning waste management had to be established. There is now another modern installation that handles the sorted materials, and the Härlöv site will only accept some construction and demolition remnants to serve in the reclamation process (Kristianstad's district public information 2004).

At present, drainage pipes collect the leachate and transport them to the local water treatment facility until the construction of a dedicated treatment facility is achieved.

The landfill-produces biogas and the exploitation should continue for some 15 to 20 more years. The biogas is either collected directly in place or transported through a network of collecting pipes.

The surrounding natural landscape is rather flat and over the years the waste has formed a small flat hill, a few metres high, above the natural topography. From the beginning, the waste was laid on the natural ground, which is comprised of peat, clay and till layers, and which, according to earlier studies, should constitute a relatively good natural barrier to infiltration. Nevertheless, due to its proximity with the river, large parts of the landfill are more or less permanently saturated with water. The restoration plan includes covering the whole area so as to prevent leakage, as well as excessive rain infiltration, so that the landfill can remain in the category 'non-hazardous deposit'.

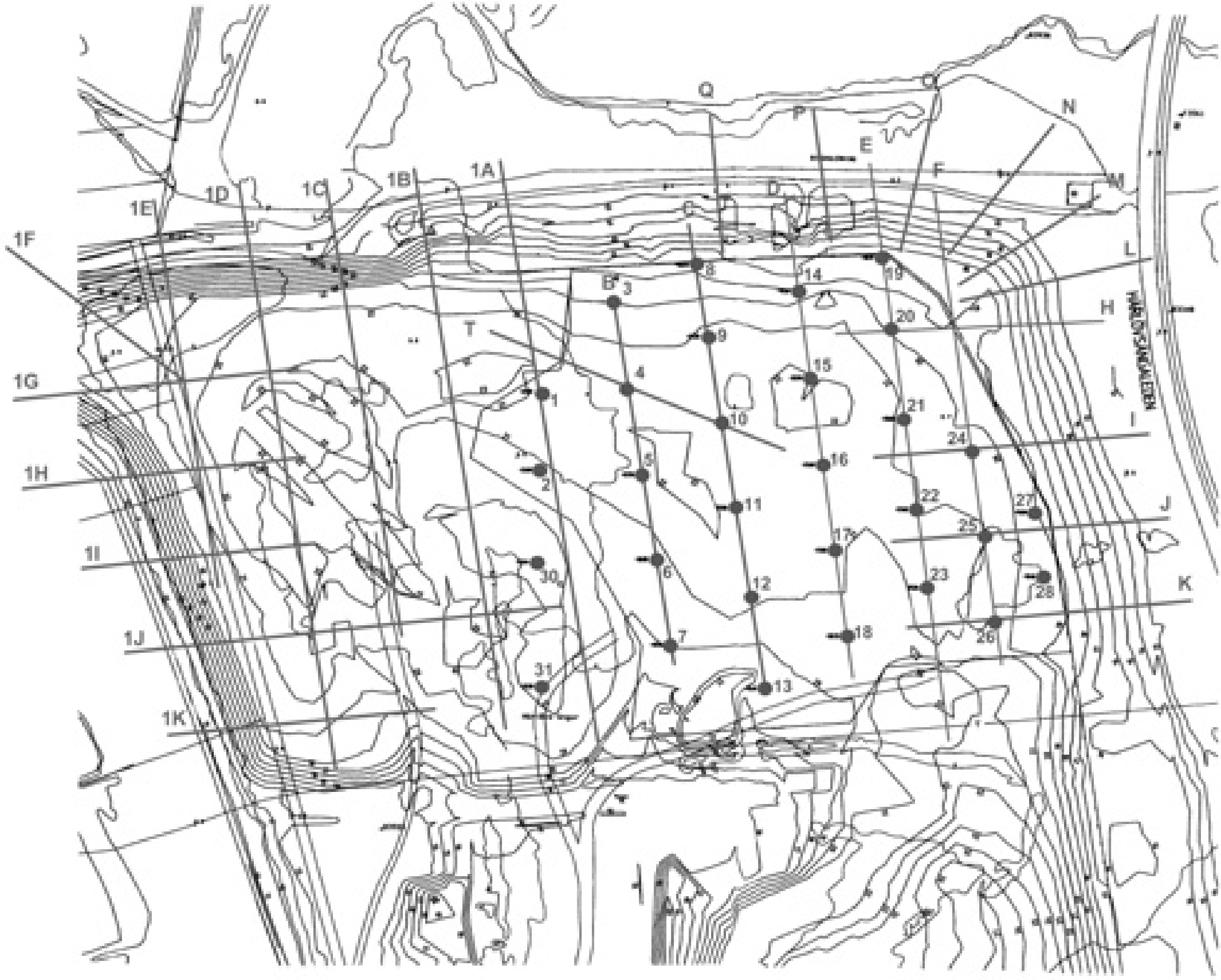


Fig. 1: Map over the investigated part of Härlöv waste site with locations of auger drillings and resistivity lines.

The landfill is actually divided into two areas on either sides of a small road. The easternmost part, which is also the oldest, is now completely covered and is a recognized restored area. It is the western part which was subject to this study. It has accepted 10 to 12 m of waste, and the covering of the landfill began some years ago, with various soil and construction materials, of which no precise record was kept. Since environmental requirements have progressively become stricter, it appeared necessary to map the thickness and location of the cover materials, in order to design the most economical plan for continuing the reclamation work.

Field work at Härlöv

The first field investigation at Härlöv presented here was made at the beginning of 2001 and comprises 31 superficial auger drillings through the cover.

The geoelectrical field study at Härlöv was conducted in two steps. First, a 90 000 m^2 area was covered by ten resistivity sections (B, C, D, E, F, H, I, J, K, T), as shown in Figure 1, and IP was measured on five of them. This survey took place during spring 2002. Six complementary IP and resistivity sections (L to Q) were added on the north-east corner of the area in autumn 2002. This zone had been investigated through geotechnical auger drillings placed on a 50-m grid and the geophysical results could be compared with the borings. The aim was to determine what kind and thickness of material was needed to cover the area.

A second survey was conducted in the area immediately adjacent to the west, which was covered by eleven resistivity and IP sections (1A to 1K, see Figure 1) in autumn 2002. The aim was to ensure that the covering material was sufficiently dense and thick to comply with the new regulations.

In both cases, the topography along the lines was surveyed and taken into account when interpreting the data.

Measurement of DC resistivity and time-domain induced polarization

A modified version of the ABEM Lund Imaging System was used for both surveys. The system comprised a current transmitter, an electrode selector, and a dedicated voltmeter. The equipment used for the first campaign had only one channel, but seven channels were available for the second survey. Both voltmeters were based on 24 bit A/D converters. The whole system was controlled via a microcomputer. The electrodes were connected to the instrument via ordinary multielectrode cables, and no specific problem was observed at this location where the galvanic contact with the soil was good and enabled the use of a 100 to 200 mA current. Stainless steel electrodes were used throughout, both for transmitting current and measuring potentials. Moderately high self potentials were observed and corrected for in the measurements. The measuring sequence was designed so as to minimize charge-up effects (Dahlin 2000).

A difficulty here is that the cover was the target, and this was only 0.4 to 2 m thick. One metre was chosen as the minimum inter-electrode spacing. A first test with a 0.5 m electrode spacing on line B had shown that no significantly extra amount of information was gained using this spacing, and that it consequently was not worth the extra time needed for the measurements.

A 50% duty square wave transmitting cycle of 4.4-s period was used. For measuring the IP, a 10-ms delay was taken after the current turn-off and the potential was integrated over 10 successive time windows of 100 ms each. The chargeability M is expressed in mV/V as:

$$M = \frac{1}{V_{DC}[t_{i+1} - t_i]} \int_{t_i}^{t_{i+1}} V dt \tag{1}$$

where V_{DC} is the potential used for calculating the resistivity, V is the potential and $[t_{i+1} - t_i] = 100$ ms.

The simplified logistics used were successfully applied at other sites (Dahlin *et al.* 2002) and by other authors (Iliceto *et al.* 1999), and they made a relatively quick data acquisition possible, especially when using the gradient array. The gradient array provided data with good lateral and vertical resolution, as numerical comparisons (Lu *et al.* 1999, Dahlin & Zhou 2004) and field comparisons (Dahlin & Zhou 2006) have shown.

The overall data quality at this site was good. It was checked by controlling that the levels of the measured potentials were sufficient and realistic and that the pseudo sections had a smooth appearance.

Interpretation method

All the interpretations were done using the commercial program Res2Dinv (Loke & Barker 1996, Loke *et al.* 2003) for inverse modelling (inversion). The so-called robust constraint or L1 norm constraint were used as well as consistent damping factors and the same number of layers with the same thickness for all the sections,. The L1-norm constrained inversion is less sensitive to noisy data and yields sharper limits between rather homogeneous regions (Fahrquarson & Oldenburg 1998, Loke *et al.* 2003), therefore it is often preferred to the more commonly used L2-norm inversion.

The IP is inverted concurrently with the resistivity using the same finite-element grid. The resistivity model found at each iteration is used for calculating the potentials in the chargeable medium, using:

$$\rho_i = \rho_i^{\mathrm{DConly}}(1 - m_i) \tag{2}$$

where ρ_i^{DConly} is the resistivity of the non-chargeable medium, m_i the chargeability and ρ_i is the resulting resistivity of the chargeable medium. The program does not take into account the time at which the apparent chargeability was recorded, nor the integration time.

The inversion of this low noise level data set was quite easily achieved, and relatively low model residuals were attained.

After individual interpretation for each of the 2.5-dimensional inverted sections, they were plotted together as three-dimensional views with the commercial program Rockworks that treats them as pictures. These views enable a good overview of the information actually yielded by the geophysical measurements, and they also facilitate checking the crossing inverted two-dimensional sections for consistency.

Results

Geotechnical auger drillings

The 31 shallow auger drillings were made through the cover in a 50-m grid covering the eastern part of the studied area (Figure 1). They reached the waste at 0.5 to 2 m depth. The cover materials found were classified according to the geotechnical standards, and were very diverse, comprising clay, clay till, mould, sludge, sand, gravel, bricks, lime and gypsum, which also can be expected to have very different hydraulic conductivities.

No distinction was made between different kinds of waste. It is assumed that in the major part of the landfill it is similar to that photographed in Figure 2, which is mostly mixed materials with a lot of organic matter and plastic bags, and diverse disseminated objects. Trenches such as the one that was photographed were opened during the course of the survey and they rapidly filled with liquid mud to a depth of around 1 m.

The distribution of the various materials found is summarized in Figure 3. The cover was very inhomogeneous,

Fig. 2: View of excavated waste material in a trench.

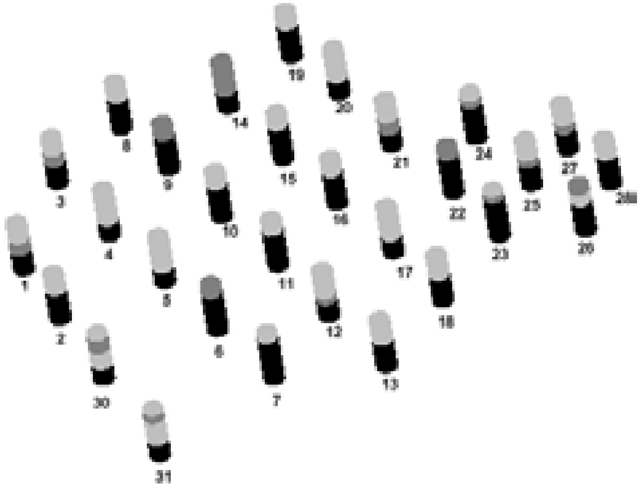


Fig. 3: Result of auger drilling investigation, view from SW. Legend: dark grey, clay; black, waste; light grey, other materials, often mixed (sand, gravel, clay till, lime, mould, sludge, bricks). Vertical enlargement: ×10.

and it was in general not possible to correlate two neighbouring points with certainty. Clay or other impermeable material was not found everywhere. Moreover, the structure of the earth walls towards the river Helge remained unknown. It was clear that the cover was so inhomogeneous that geotechnical drilling would not suffice to image it, thus geophysical electrical imaging could provide useful information.

Resistivity and IP survey phase 1

General description

On most of the lines, an upper inhomogeneous layer with higher resistivity can be seen, overlying a rather conductive material, with a resistivity value most often below 10 Ω m. The inverted IP sections show a reversed picture, with a first layer with low chargeability overlying a highly chargeable background with values over 50 mV V^{-1}.

Correlation with geotechnical data on line C

Six geotechnical auger drillings were placed on line C, and this line was the most favourable for comparison between geotechnical and geoelectrical data (Figure 4a–c).

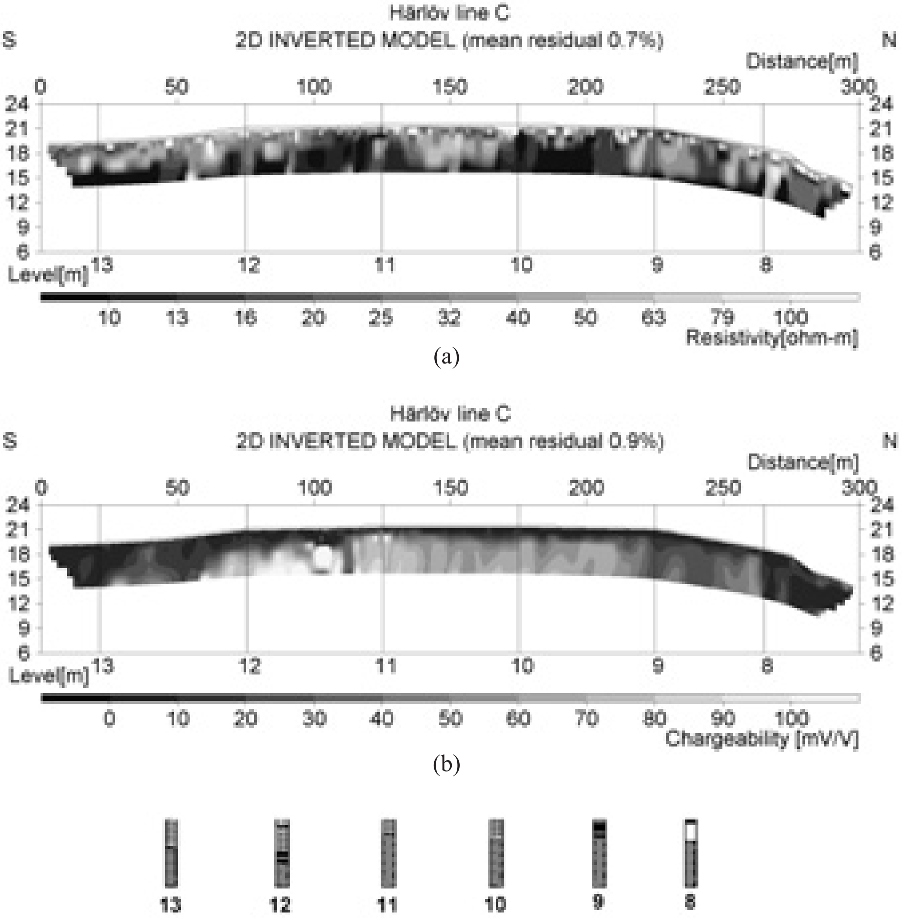


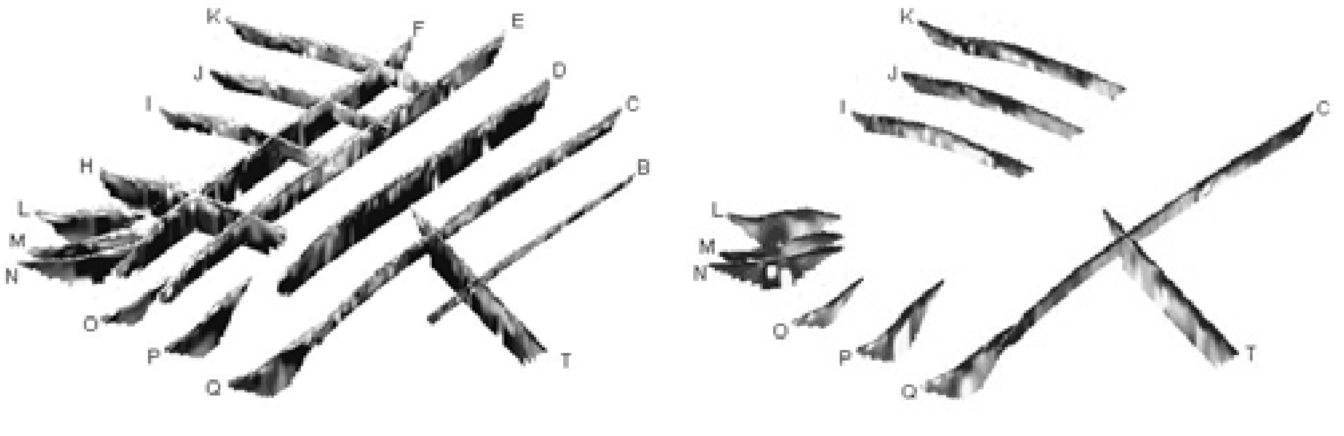
Fig. 4: (a) Inverted resistivity section for line C (Wenner array); (b) inverted chargeability section for line C (Wenner array, 20 to 120 ms); (c) profile of auger drilling documentation for line C. Legend: white with large pattern, clay till and sand; black, clay; white, lime; grey with finer pattern, waste. The represented logs are 3 m deep.

At a first glance it is not easy to correlate the two kinds of information. As on the other lines, essentially two kinds of material can be distinguished on the resistivity section: a superficial, resistive and very inhomogeneous layer and a deeper conductive material. The first layer only partially follows the thickness of the cover as was found by the drillings: it seems thicker at points 12 and 13 than at boring 10, which was confirmed by the borings. This correlation does not work for positions 11 and 9, unless one looks into more detail and distinguishes two sub-layers in the resistive material, separated by a very thin conductive one. This intermediate conductive layer correlates with clay at location 9 but not at location 11, where no clay was found. It seems however likely that this intermediate thin conductive layer is caused by clay.

Looking at the inverted IP section (Figure 4b), chargeable material is found at depth, whereas very little IP effect is visible in the uppermost layer. The high chargeability values seem to correlate well with the distribution of the waste, especially at locations 11, 10, 9 and 12. Small discrepancies appear at locations 8 and 13, but they could be due to lateral effects, limitations in the drilling documentation or uncertainty in the relative locations of auger drillings and resistivity lines. The inhomogeneity in the material is very high in all three space directions.

Using both resistivity and chargeability results, a material with high chargeability (> 30 mV V^{-1}) and low resistivity can be identified as waste. A material with higher resistivity (> 10 Ω m) and low chargeability can be classified as covering soil material, probably medium grained to coarse grained. In between materials with higher resistivity and intermediate chargeability can be found; those can probably be identified as waste also, but of another composition. A part of the cover is made of low resistivity material with very weak chargeability, and this is probably clay.

It is important to note that the geotechnical drillings reached only depths between 70 cm and 2 m in most cases, and that represents only one-sixth to one-third of the apparently investigated depth on line C. Nevertheless, it is likely that the effect of the first layer – the cover – is comparatively important on the inverted sections.



(a) (b)

Fig. 5: (a) Three-dimensional view of survey 1 results: interpreted resistivity (from NW); (b) three-dimensional view of survey 1 results: interpreted chargeability (20–120 ms).

3D views

Since eighteen resistivity sections and twelve IP sections were measured in the area, it can be difficult to get a good overall picture of resistivity and IP changes and thus three-dimensional visualization can help. Fence diagrams were used as they have the advantage of just gathering the images without using interpolation that may add artefacts.

It can be seen that most intersecting sections agree well (Figure 5a for the resistivity sections and Figure 5b for the chargeability sections), although all of them have been interpreted using a two-dimensional assumption of the structure of the ground. The bottom of the landfill cannot be identified, which should be found around level 0, on any of the inverted sections. This may be due to insufficient depth of investigation, but other likely explanations are that the geoelectrical contrast with the natural soil is too weak, or that conductive water has leaked from the landfill into the soil and thus wholly or partially removed the natural electrical contrast.

Final cover plan

Based on the geoelectrical results and on the auger drillings, distinct areas could be identified for cover improvement. On line D, the chargeability was not measured but the thickness of the first resistive layer indicated that the cover was most probably made of drier coarse-grained, and therefore probably permeable, materials at this location. A similar character was observed at the western extremities of lines J and K, and on the southern end of line C. Moreover, the cover appeared thinner on the western ends of lines J and K. Likewise, the cover was estimated as either thin or permeable on the northern end of line B and on the western extremity of line T. These areas should consequently receive a thick complementary cover of appropriate materials (more than 1 m). The cover on the edges of the eastern part of the landfill was judged more satisfactory and a reduced thickness of complementary cover was required there (less than 0.5 m), as around the southern part of line B. An intermediate thickness (0.5–1 m) of complementary material was required otherwise. The produced plan for the continuation of the reclamation work is shown in Figure 6.

Resistivity and IP survey phase 2

The westernmost part of the investigation area was surveyed by twelve resistivity and IP sections, measured with the gradient array. This area had just been covered with fine materials and the purpose was to assess the regularity of the cover. Four auger drillings were made in this area, and only drilling 1 is situated on a geophysically investigated line (line1A).

General description

A major difference appears at first sight between the results of the first and the second survey: here the first layer was mostly conductive, overlying a more resistive one that was placed on a conductive deeper substratum. Otherwise, the resistivity values were in the same range as those found in the first study.

This first layer was not chargeable, and it must be the clayey cover. Chargeable materials were found at depth, and they most probably can be interpreted as waste, similar to the first survey.

Line 1A

Line 1A can be used as an example (Figure 7a and b). On the interpreted sections, it can be seen that the first conductive layer – the clayey cover – is not continuous. It is clearly absent between *x*-coordinates 118 and 270 m, as well as between *x*-coordinates 0 and 50 m. The more resistive and very inhomo-

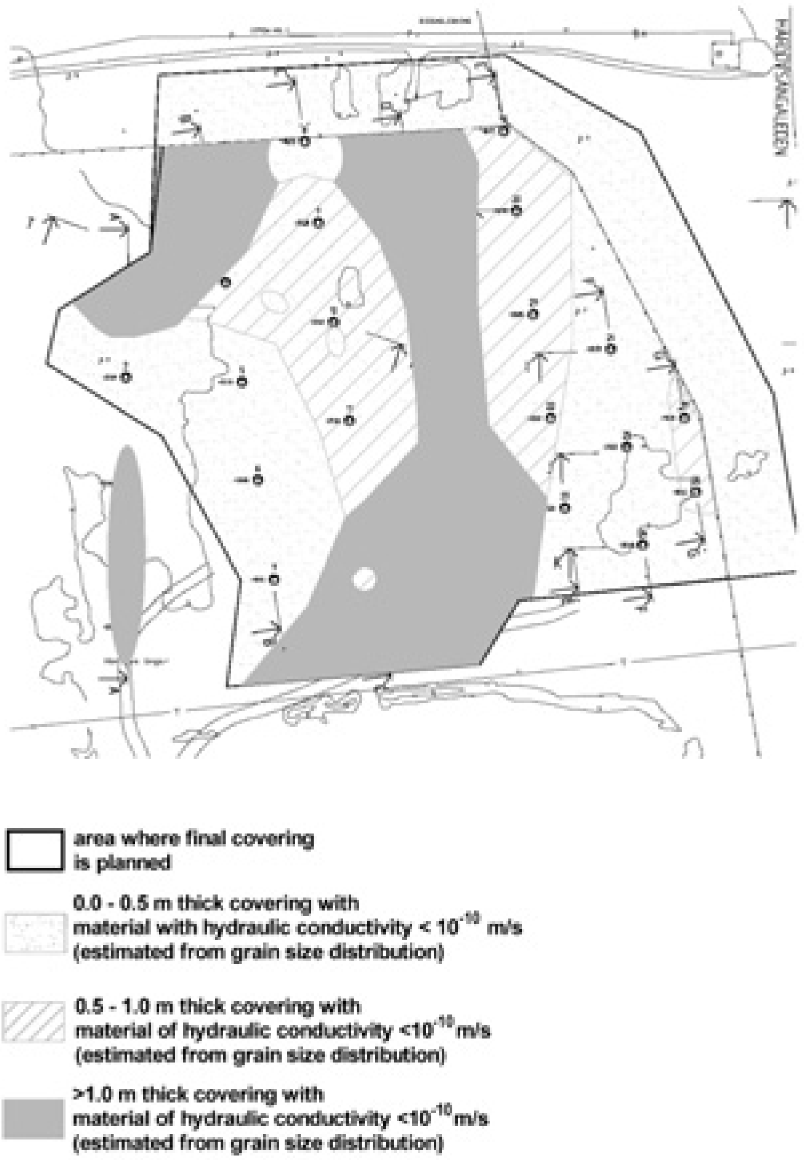


Fig. 6: Revised plan for continuing reclamation work.

geneous superficial layer found between x = 118 m and x = 270 m is most probably composed of coarser materials. It has weak and mixed chargeability. The clayey cover is not chargeable. At depth, resistive material can be either waste or coarse soil materials. Material with high chargeability is probably waste. Boring 1 was situated on line 1A at around 121 m, boring 2 was very close to it at around 155 m and borings 30 and 31 were still rather close at 203 and 266 m, respectively. The clay layer seems to appear on the resistivity section around boring 1 but it is not clear on the IP section. It does not appear at the location of boring 2, as it does not exist there. Borings 30 and 31 might be located too far from the line to draw certain conclusions, but it seems that the waste was located deeper towards the southern end of profile 1A. Between 120 and 260 m the waste is covered by mainly non-clayey material, as is apparent on the geoelectrical sections and confirmed by the borings, contrary to the northern part of the profile between 60 and 100 m and the southern end, that are most probably covered by clay.

The bottom of the landfill, which should be found around level 0 here as well, could not be clearly imaged on the inverted sections, as had already happened before.

3D view

The intersecting sections here are also very consistent (Figure 8a for the resistivity sections, and Figure 8b for the chargeability). The superficial clayey cover can be easily followed everywhere, except where it is missing, in the middle of lines 1A and 1B, at the end of line 1E and on the slopes. Resistivity gives clear enough results here for detecting possible infiltration windows in the landfill that were not covered by clay.

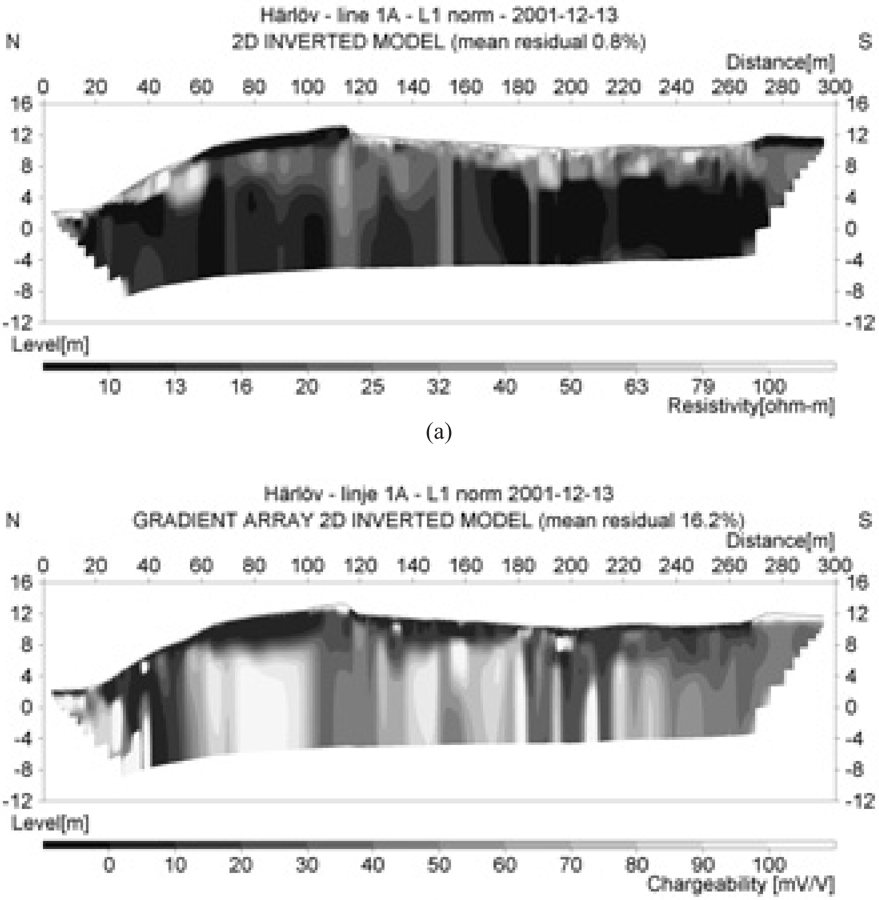
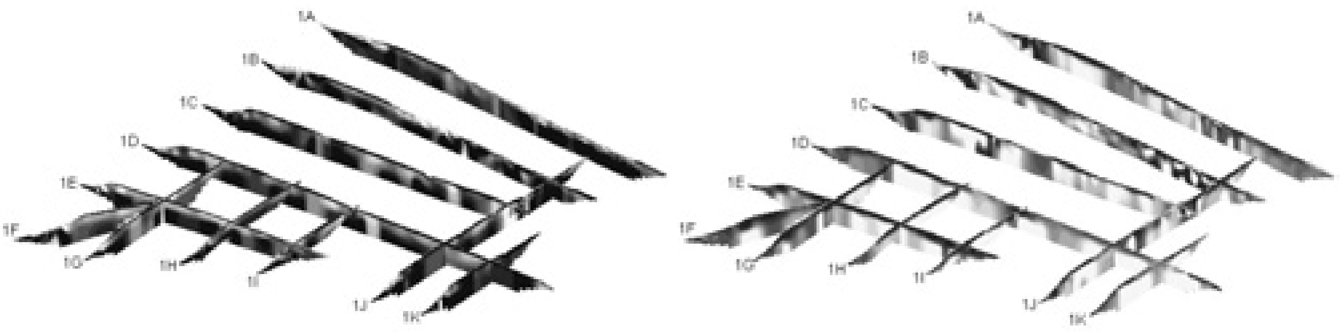


Fig. 7: Inverted resistivity section for line 1A (gradient array); (b) inverted chargeability section for line 1A (gradient array, 10–110 ms).

This type of cover is apparently missing on the slopes, although they did not appear to be naked when the measurements were taken. On the other hand, it is not likely that several metres of soil and construction remnants are present under the clayey cover. The more resistive underlying material must therefore be either coarse soil material or waste, and they cannot be distinguished using resistivity only. The conductive material at depth could be saturated waste or mark the bottom of the landfill.

On most of the lines, the uppermost conductive cover corresponds to a low-chargeability material, which is consistent with clay only. Some parts seem to have intermediate chargeability, which may show that a coarser fraction is present. On the inverted chargeability views (Figure 8b), we seem to have a clear image of the cover overlying the waste in the landfill. Waste is here also characterized by high chargeability values. The bottom of the landfill could not be imaged with the chargeability, possibly for the same reasons as in the first area.



(a) (b)

Fig. 8: (a) Three-dimensional view of survey 2 results: interpreted resistivity sections. (b) three-dimensional view of survey 2 results: interpreted chargeability sections (10–110 ms).

Final cover plan

Areas where clay materials were missing were identified with the resistivity results, principally along a large part of line 1A and the southern half of line 1B. This possible infiltration window could be repaired. The clayey cover requirements seemed to be satisfied almost everywhere else on the resistivity and chargeability sections of this second surveyed area.

Discussion

The usefulness of these results depends on the contrast in electrical properties between the different materials. Here it was very easy to follow the new clayey cover with resistivity, and the waste seemed to be characterized by high chargeability values. The resistivity was higher in the cover made of coarser materials, and also in a large part of the waste filling the landfill. Therefore, the DC resistivity method alone could not distinguish between them. Coarser soil materials can be suspected of having intermediate chargeability, as well as the waste when it contains more construction remnants compared to domestic waste. The exact reason for the high chargeability values observed in the waste is not known, but one can think that at least part of it could arise from the numerous isolating surfaces (plastic bags) disseminated in the otherwise conductive organic matrix. Metallic objects are probably present as well, but they are most likely not all very small and not disseminated in the whole volume. In several published studies, high chargeability values have also been associated with high concentrations of organic contaminants and cyanide (Cahyna *et al.* 1990, Niederleithinger 1994), but this does probably not correspond to the present site.

It is possible that more distinctions could be made after a frequency analysis of the IP data, but such a study has not been made here. However, landfills are so inhomogeneous that such an interpretation is likely to be difficult.

The bottom of the landfill could not be imaged, except maybe with resistivity in the second survey, but even there it is not clear. Similar problems in getting good resolution at depth were encountered at other sites and by Weller *et al.* (1999, 2000), and may be due to screening effects caused by the low resistive lower part of the waste. It may have been possible to image the bottom of the landfill if it would have been worked with larger electrode spacings, but this is not certain, as there may not be enough contrast in electrical properties. It has for example been found that peat can be chargeable (Slater & Reeve 2002), and therefore could be difficult to distinguish from the waste. It is also not possible to give precise estimations of depth with resistivity results due to equivalence. This could possibly be remedied by using constraints on the resistivity at depth when the information is available, but it is seldom the case. Seismic refraction could be a useful technique if the aim was to map the bottom of the waste, but it would depend on the type of geology underlying the waste and hence the velocity contrast. However, it can be very difficult to make seismic waves reach under the waste, thus it is not certain it could be used.

Using a seven-channel instrument for the second measurement campaign significantly improved the efficiency in the field. The twelve sections were measured in less than 2 weeks. Generally, in such good conditions, 1000 resistivity and IP data points could be measured within 1.5 h, which corresponds to 80 m with the gradient array (Dahlin & Zhou 2006) and 1-m electrode spacing, as was used here. Additional time is required for laying out cables and electrodes, and positioning the lines. The time needed for processing the amounts of data acquired here would have been a serious constraint a few years ago, but recent improvements on inversion software and standard personal computers bypass that. The method is reasonably efficient, but it is interesting to consider other alternatives too.

Resistivity can also be estimated by electromagnetic methods and it is possible to reconstruct the resistivity distribution with depth, although generally not in as much detail as with multi-electrode DC resistivity, provided time-domain or multi-frequency methods are used. Tezkan *et al.* (1996), for example, describe a successful joint application of radiomagnetotellurics and transient electromagnetics at a landfill site. A major advantage with these methods is that they are extremely fast and make it possible to map large areas in a short time. One of their drawbacks is that electromagnetic methods are oversensitive to metal objects, unfortunately very common at landfill sites, and they are often discarded for that reason. To obtain information on the chargeability, which proved to be a key parameter in this study, it would be necessary to use methods enabling measurements at several low frequencies. One could then recalculate the chargeability from the percentage frequency effect. On the other hand, the resolution of the thin near surface layers would probably not be reached.

One could also use mobile multi-electrode devices with either galvanic or capacitive-coupled electrodes such as those described by Panissod (1997), which also make it possible to map large areas relatively quickly. However, such equipment usually offers only a limited number of investigation depths, which can be a handicap when seeking for a detailed resolution, and they are at present not available in Sweden.

For future similar studies, however, it may be worthwhile to consider a first rapid mapping of the whole area with an electromagnetic method. The results could be used for selecting the particular sections that should be imaged in more detail with resistivity and IP, as was done here. This should be expected to give good results in some cases, at least when the situation is similar to that encountered in the second surveyed area. In the first surveyed area, however, the results would probably be very difficult to interpret.

It should also be emphasized that reference data from drilling and sampling, for example, are indispensable. However, the degree of detail and the number of parameters documented are often insufficient for a full interpretation or verification of the geophysical data.

Conclusions

The combined resistivity and time-domain IP methods yielded useful results at the investigated landfill site, although some uncertainties in the interpretation remain. These uncertainties are largely caused by limitations in the available reference data.

The geoelectrical data could be correlated with auger drilling documentation and had sufficient resolution to investigate the relatively thin cover (between 0.5 and 2 m). Results were consistent all along the study and even between intersecting sections, when the two-dimensional technique was used.

Waste materials generally appeared as very chargeable and low resistive materials, especially in the deepest parts of the landfill. Their resistivity was higher closer to the surface, maybe because they were drier. Materials with higher resistivity and intermediate chargeability were also present, and they most probably can be interpreted as coarser geological materials or as waste containing a higher proportion of construction rubbish. Soil materials used as a covering layer were clearly identified by their generally low chargeability, and the clayey parts also by low resistivity.

The geophysical work produced the following practical results.

- From the first field campaign, lines B–K and L–Q, the extent of the final covering could be assessed. New material with low permeability was added to the already laid cover, but only on selected areas. A map was produced showing which thickness of material had to be added, resulting in considerable cost savings.
- The geophysical results of the second field campaign showed that, although the final cover was emplaced, in certain areas possible infiltration windows remained. Those areas could be identified using the geophysical surveys and subsequently they could be repaired.

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