Assessment of two automated DC resistivity data acquisition systems for landfill location surveys: Two case studies

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Assessment of Two Automated Electrical Resistivity Data Acquisition Systems for Landfill Location Surveys: Two Case Studies

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ABSTRACT

Two types of automatic DC resistivity data acquisition systems, the Aarhus PA-CEP system and the ABEM Lund Imaging System, are assessed in connection with surveys for characterization of future landfill sites. In the first case, the extent of a natural clay layer in connection to an enlargement area of the Filborna landfill was mapped, and in the second case the soil cover at a proposed new landfill at Fläskebo was examined. At Filborna both resistivity systems and seismic refraction were used, whereas at Fläskebo the Lund system was used together with a VLF survey. At both locations 5 km of resistivity profiling were achieved. The resistivity datasets were interpreted with a smoothest constrained inversion. At Filborna a layer of thick clay till was identified in the southwest part of the investigation area, and thin clay tills were found in other parts. It was clear from the PA-CEP resistivity models that the underlying sedimentary rock possesses an undulating surface, which has an important implication regarding the soil cover barrier properties. At Fläskebo the resistivity survey successfully delineated the bedrock surface and effectively mapped the soil cover. Both resistivity systems worked well acquiring data suitable for data inversion. The seismic refraction model and resistivity models corresponded reasonably well. The pulled array continuous electrical profiling (PA-CEP) is fast, but has limitations on the traversability of the site conditions. When fourteen different electrode spacings are used the Lund Imaging System is four to five times slower than the PA-CEP system in an open terrain. However, using fourteen different electrode spacings the Lund system has a much higher vertical resolution. Furthermore, as experienced in Fläskebo, the Lund system works well in very rough terrain.

Introduction

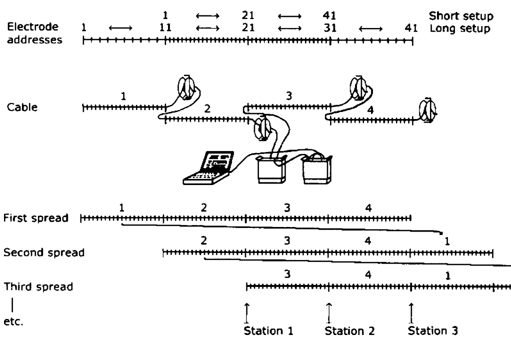
It is well known that in locating and constructing landfills several aspects of design must be considered (Begassat *et al.,* 1995). Prevention of the contamination of ground and water resources is one important example. An updated set of guidelines (SEPA, 1996) compatible to suggested European Community directives on waste landfilling (*e.g.,* Petersen, 1997) have been introduced to advance the quality standards of landfills in Sweden. Because one of the objectives is to implement a minimum standard for the geologic barrier, quantification of the barrier material properties is required. If strictly applied this standard would lead to a substantial reduction in the number of suitable landfill locations in Sweden, and would require the use of advanced technology to construct artificial geological barriers.

Whether regarding the extension of operational landfills, or completely new landfills, site investigations are, and will remain, an important part of the location process. These investigations commonly include a drilling program that gives important ground truth information. Direct and supplementary information is given when such an investigation is done in combination with a geophysical survey. The usefulness is determined by the reliability of data, the density of the measurements, and the quality of the interpretation (Christensen and Sørensen, 1996).

Examples of successful geophysical investigations for landfills are presented by Lankston (1990) who used seismic refraction to investigate a proposed landfill site, and by Slaine *et al.* (1990) who used shallow seismic reflection to map the overburden stratigraphy at a proposed hazardous waste facility. Okko (1993) combined multi-electrode resistivity and seismic reflection to map an impermeable clay layer at a landfill enlargement intended for municipal waste in an important groundwater area, and Frohlich *et al.* (1996) used geoelectric soundings to characterize fractured bedrock prior to a landfill extension. High resolution resistivity methods have also been used to map the vulnerability of groundwater aquifers (*e.g.,* Sørensen *et al.*, 1995; Dahlin, 1997).

Two case histories based on two-dimensional (2-D) resistivity are presented in this paper. The primary aim of the investigations was to evaluate two efficient automated resistivity data acquisition systems that have been developed over recent years for use in landfill location surveys. Both systems can cover large areas in a short time with a small field crew collecting detailed subsurface information.

In the first example a regional landfill, Filborna in



Electrode spacings		
No.	A	B
1	120	48
2	110	44
3	100	40
4	90	36
5	80	32
6	70	28
7	60	24
8	50	20
9	40	16
10	30	12
11	20	8
12	15	6
13	10	4
14	5	2

Figure 1. The principle of roll-along measurements using the Lund Imaging System. Each mark on the cables indicates 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 lists the electrode separations (in meters) of the 100 m (A) and 40 m cable (B) types used in the case study section.

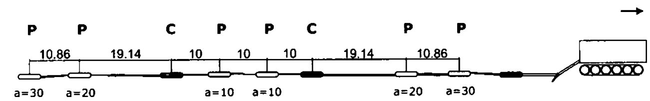


Figure 2. The design of PA-CEP electrode tail (after Jansson and Wisén, 1998). It holds one ground (G), two current (C), and six potential electrodes (P). The vehicle has dimensions 2.0 × 0.7 × 0.8 m (length, width, height). All distances are in meters.

southern Sweden, was investigated prior to an enlargement. A layer of clay till is present at the site, but the geometric extent of the clay till and its thickness had not been mapped. A survey including PA-CEP the technique, a multi-electrode resistivity system, and seismic refraction was done to map the site-specific geological conditions. The second case study reports on an investigation using the same multi-electrode resistivity system to map the glacial deposits in an area, Fläskebo in western Sweden, which is planned as a new landfill. The area lies in a difficult terrain where a complete drill program would be expensive. The survey findings were to be used to control or revise the plans of the two facilities. In both cases lithological drill core data was available that could be used to constrain the interpretations.

Methods

2-D Resistivity Surveying: two automated systems

Lund Imaging System—a multi electrode resistivity system. Automated systems based on continuous vertical electrical soundings (CVES) are a direct extension of their manual counterparts. The multi-electrode resistivity data acquisition system used was the ABEM Lund Imaging System (Dahlin, 1996). The system has been used extensively in environmental and engineering investigations (Dahlin, 1996; Baumann *et al.*, 1997; Bernstone and Dahlin, 1998; Bernstone, 1998) and has proved to work reliably under difficult weather and in rough terrain. It collects data according to a roll-along principle as depicted in Fig. 1. With a set of 100 m cables about a 1 km profile can be measured per day in favorable terrain.

The hardware (Fig. 1) consists of 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 rod electrodes. A separate current amplifier is optional. A modified version is employed to increase control over the measurement process whereby the resistivity meter is replaced by a 24 bit A/D-converter that measures the potentials. Data acquisition is controlled by software that checks the electrodes are connected and properly grounded and then scan through the measurement protocol. The equipment needs two operators for the best performance in most cases, but one operator is sufficient.

A recent evaluation of inverse modelling has pointed out the importance of dense data sampling (Dahlin and Loke, 1998). After considering the tradeoff between time spent in the field and the possibility of resolving complex structures a measurement protocol file which covers 14 electrode spacings was chosen. At Filborna the applied cable type supports spacings ranging between 2–48 m whereas the longer type used at Fläskebo supports 5–120 m spacings (Fig. 1). In both surveys the Wenner electrode configuration was used. Two operators were used in both cases.

The Aarhus Pulled Array System (PA-CEP). The PA-CEP data acquisition system which was used in the Filborna survey was developed at Aarhus University in Denmark. In the prevailing Danish open landscape 10–15 km of profile per day of geoelectrical data can be measured with a density of 1 sample per second. Sørensen (1996) describes the system in detail.

Instead of separate cables a small terrain vehicle pulls a 100 meters long tail as shown in Fig. 2. The tail carries 9 heavy stainless steel electrodes (10–20 kg each). Two electrodes supply a constant current (maximum 36 mA), six electrodes are used for potential measurements, and the first electrode is used as a ground electrode. Three different Wenner configurations are measured simultaneously (three channels of 10, 20 and 30 meter respectively). However, it is not possible to measure a true normal 20 m Wenner array. The developers have instead optimized these electrodes as being most sensitive for the same depth as a normal 20 m Wenner array.

Ditches and other minor obstructions can be passed over using an aluminum bridge (3 m long) fastened to the vehicle. A measuring wheel was used to keep track of the

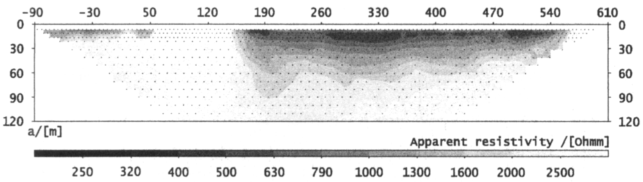


Figure 3. An example of a Lund CVES apparent resistivity pseudosection collected at the Fläskebo along profile 7.

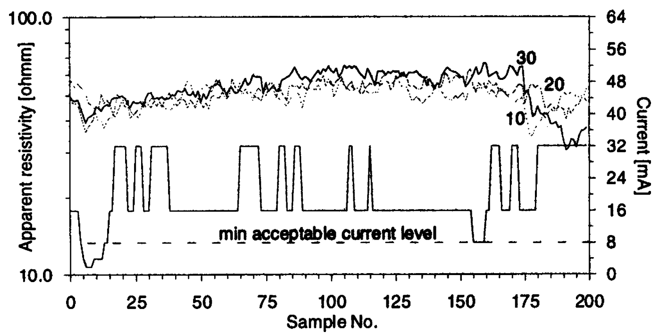


Figure 4. An example of a PA-CEP data control plot showing the apparent resistivity of the three electrode separations. The maximum transmitted current is 32 mA. Data below 8 mA are considered unacceptable.

distance profiled (one sample every 1.5 m). Two operators were needed, one driving the vehicle and one to operate the instruments.

Additional methods

At the Filborna site the depth to sedimentary rock was investigated by seismic refraction. The equipment used was the ABEM Terraloc Mark 6 with 24 14 Hz KCL-4 geophones separated by 2 m. Each spread overlapped the next one by one geophone position only. A modified version of the 12 gauge in-hole shotgun, described by Pullan and MacAulay (1987), was used as an energy source. Nine shots were fired for each layout, with the far shots at 92 m from the layout midpoint. A 350 m profile was collected in two days.

In an investigation in the Fläskebo area in the 80's several lineament structures were identified (Jansson and Wisén, 1998). The findings in this investigation were followed up by a VLF survey using the ABEM Wadi VLF instrument and the 18.3 kHz Le Blanc and the 23.4 kHz Pearl Harbour transmitters.

Data Analysis

General aspects on resistivity data

Automatic pseudosection plotting allows for quality control and a first interpretation of a CVES dataset. A pseudosection is constructed by contouring the apparent resistivities computed from measured voltages where the midpoint between the electrodes in a measurement constitutes the length scale and the electrode separation the depth scale (Fig. 3). Plotting is carried out with linear interpolation and poor quality data points are usually easily identified. Pseudosections can also be useful for preliminary qualitative interpretation, but in complex environments it may be difficult to obtain a good image of the section's structure.

The PA-CEP data are collected in a series where each data point is indicated by a tic mark. These must be translated into real coordinates later on. Because the profiles can be very long the use of pseudosection plotting is not a convenient presentation. Instead the data may be plotted in a diagram that shows the resistivity value for each electrode separation, together with the corresponding current used to collect the data (Fig. 4). Low current values are considered unacceptable below 8 mA and are generally obtained when ground conditions are unfavorable, *i.e.*, dry ground or bad contact between the ground and the electrodes. Such data are easily identified in the diagram and must be excluded.

Inversion of resistivity data

General. To assess the resolution and determine the limitations of the dataset it is necessary to do some kind of resistivity modelling. Two dimensional (2-D) techniques are becoming increasingly common, and as shown by Dahlin and Loke (1997), the CVES technique using the Wenner array works rather well, even in the case of large 3-D variations. 2-D inversion interpretation is often satisfactory.

Quasi-Newton/Gauss-Newton inversion. The true resistivity structure was estimated using a least-squares smoothness constrained inversion algorithm, RES2DINV, version 4.0 (Loke and Dahlin, 1998). The subsurface was divided into a number of rectangular blocks (Loke and Barker, 1996) and the resistivity of the blocks were adjusted in an iterative manner to minimize the difference between the measured and calculated apparent resistivity values. The latter were calculated by the finite difference (FD) method of Dey and Morrison (1979). A measure of the model fit of the inversion resistivity model was given by the mean residual value.

The smoothness constraint prevents unstable solutions (deGroot-Hedlin and Constable, 1990). In the 2-D inversion of resistivity data, Dahlin and Loke (1998) have found that in areas with large resistivity contrasts the Gauss-Newton least-squares inversion method leads to significantly more accurate results than the quasi-Newton method (Loke and Barker, 1996). In the Gauss-Newton method the Jacobian matrix of partial derivatives is recalculated after each iteration, whereas in the quasi-Newton method the partial derivatives are estimated by using an updating method.

A 2-D inversion algorithm, based on a deconvolution

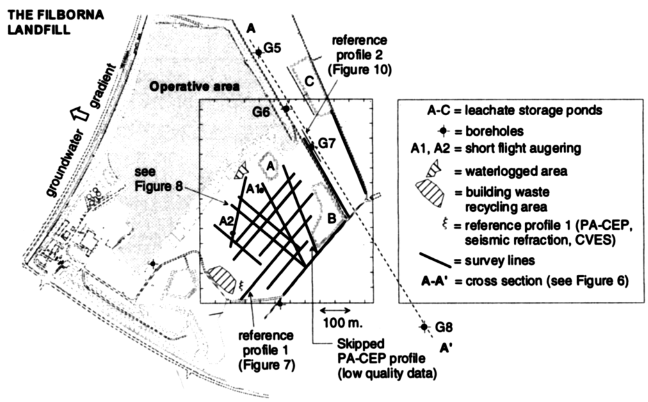


Figure 5. A sketch of the Filborna landfill site modified from Jansson and Wisén, 1998. The operating landfill in the northwest directly adjoins the planned extension. The line marked A-A′ represents the location of the cross section in Fig. 6. The survey coverage is also indicated.

algorithm using the Born approximation, has been developed in conjunction with the PA-CEP system (Christensen and Sørensen, 1996; Møller *et al.,* 1996). Its fast performance make time efficient interpretations possible even in the case of very large datasets collected by the PA-CEP system.

In both the Filborna and the Fläskebo investigations the RES2DINV algorithm was applied using the Gauss-Newton method. The choice of the interpretation tool was based on the relatively small lengths of the individual PA-CEP profiles (700 m), *i.e.,* computer times remained acceptable. Furthermore, it was considered interesting to evaluate this routine for PA-CEP datasets which are usually interpreted with the deconvolution algorithm. The individual interpreted 2-D sections were finally merged into 3-D models by triangulation with linear interpolation, and slices from selected depths extracted.

Interpretation of additional methods

The seismic refraction data were interpreted using the Viewseis software (Kassenaar, 1992, version 1.74) which is based on the general reciprocal method (GRM). A buried tele-communication cable made it difficult to use the VLF method at the Fläskebo site, however, it was possible to distinguish a few anomalies. Trials using the VLFMOD software (Edsen and Nissen, 1997) method gave some positive results, but the overall data quality was not considered good enough to warrant the effort of further processing.

Case Histories

Two case histories of recent surveys are presented: the expansion of the Filborna landfill outside Helsingborg

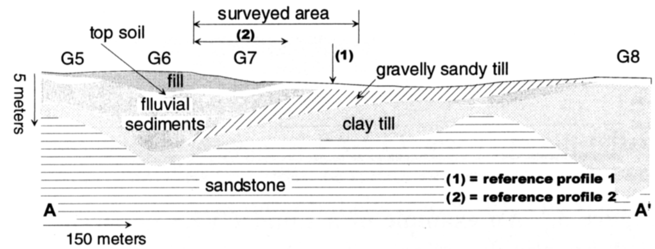


Figure 6. A geologic cross section of the site based on information from six boreholes (see Fig. 5 for location). Modified from Hydro-Consult (1997). The section extends over a larger area than that covered by the investigation surveys.

in southeast Sweden, and the new Fläskebo landfill close to Gothenburg on the west coast.

The Filborna Landfill (Case I)

Background and site description. This 46 year old landfill is operated by the Northwest Scania Solid Waste Company, and is situated to the northeast of Helsingborg in southern Sweden. The company has a permit to extend the active landfill into a larger area further to the southeast (see Fig. 5). The landfill is built on ground with a relatively complex hydrogeology. The planned enlargement area has been investigated with PA-CEP to map the extension of a quaternary clay till of good barrier properties. To a smaller extent the Lund system and seismic refraction were used as well.

The investigated area (Fig. 5) is approximately 600 m long and 400 m wide and slopes gently towards the northeast where it becomes forested. The otherwise open area has a bush and grass vegetation. Two brine ponds and several ditches are found in its central part. The ground close to the brine pond A is waterlogged.

In 1997 a groundwater monitoring system was installed in and around the landfill (Hydro-Consult, 1997). Of 19 drilled wells, 11 were equipped with a level specific groundwater sampling system. The wells have given valuable drill cores and groundwater quality data that could constrain the geophysical results.

Geology and hydrogeology. The predominate surface formation in the region are the claystone-siltstone-sandstone layers of Lower Jurrasic-Rhaetic age (Gustafson, 1986). In the survey area these correspond to a sandstone underlain by claystone; the sandstone is overlain by a sheet of glacial till of variable thickness (Fig. 6). The transition to consolidated sedimentary rock is diffuse, and includes a layer of eroded unconsolidated sandstone. The Quaternary cover, which ranges between a thickness of 0–5 m, is composed mainly of clay till, or clayey till, and stratified glacial sediments. Coarser material forms relatively permeable bodies especially in the uppermost part. A buried braided

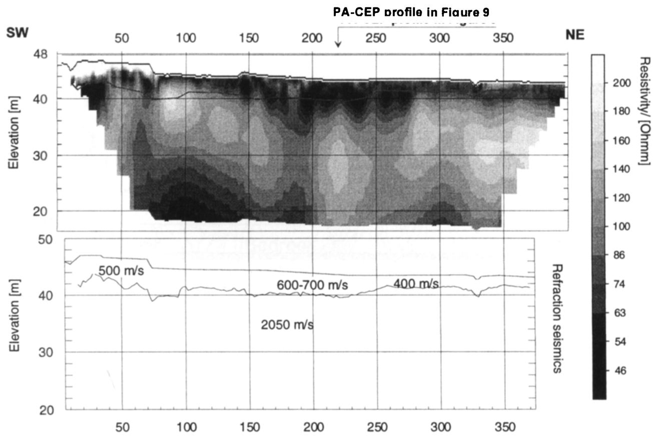


Figure 7. The result from the first reference profile where both a Lund CVES and a seismic refraction dataset were acquired. The depth to the 2050 m/s velocity layer is superimposed on the resistivity model (rms fit 3.7%).

river that passes through the Filborna area has important implications for potential leakage water pathways. The sediment thickness is here thicker, up to 10 m.

The groundwater system is complex. In places where the glacial till is present it is possible to separate the soil and sandstone aquifers. The hydraulic conductivity of drill core samples has been determined by laboratory measurements in a triaxial test cell. Values for the sandy till range between $5 \times 10^{-7} - 1.6 \times 10^{-6}$ m/s, and for the glacifluvial coarse sediments between $3.5–1.2 \times 10^{-6}$ m/s. The sandstone hydraulic conductivity is 3.8×10^{-6} m/s. The clay till and gravely silty clay till have hydraulic conductivities ranging between 5.6×10^{-11} m/s and 6.9×10^{-10} m/s. Clearly, the material properties are highly variable and it is essential to map the extension of the clay till well.

The depth to the groundwater level is small, in the lowest part it almost cut at the surface level. The groundwater electric conductivity for well G6 is high (600 mS/m), but low for well G5 and G7 (20 and 10 mS/m respectively). Although this difference implies that the buried river drains the operative landfill of leachate water, the effect is limited to the thickest sediment section.

Surveying conditions. The PA-CEP was carried out in September 1997. Data acquisition of the 5 km profile took 1 day. Several days of work were undertaken prior to the survey to place the survey lines and to ensure that they were as traversable as possible.

An area such as the Filborna extension is not ideally suited for the PA-CEP system. Even though the vehicle can traverse deep tractor tracks and earth walled ditches, such conditions prevent good ground contact on the electrode array resulting in poor data quality. Approximately 15% of the data were discarded (Jansson and Wisén, 1998) including one whole profile (see Fig. 5). Another fact to consider in relatively small areas with few easily traversable areas is that it is difficult to turn the vehicle. To get good data coverage the entire electrode tail must pass over the survey area, but it is not possible to measure close to major obstacles. The tail must be manually moved before new measurements can start on a new profile.

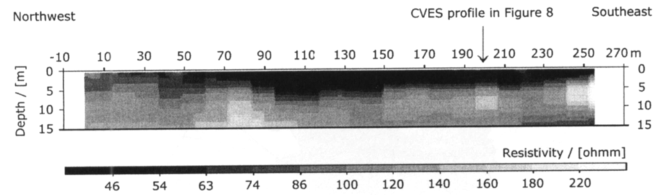


Figure 8. A 2-D inverted PA-CEP section along profile 7 (rms fit 6.5%).

The seismic refraction data were collected under ideal circumstances, i.e., no wind and a shallow groundwater table which enables good coupling between the energy source and the ground.

Data presentation and interpretation. The result of the first reference profile of Lund CVES and seismic refraction data is shown in Fig. 7. Three layers of roughly horizontal continuity can be distinguished in the resistivity model. On top of the first layer there is, in the very southwest part, a high resistivity material which exist as building refuse (>220 Ωm). The first layer has low resistivities (<46–120 Ωm) and corresponds to quaternary till. The middle layer follows a layer of relatively high resistivities (140–>220 Ωm) and the lower resistivity layer (≈60 Ωm), corresponds to sandstone and claystone.

The two-layer seismic model indicates that the soil cover along the profile is generally 4 m thick, though shallower at the northeast part. Although similar it is not entirely in accordance with the result obtained from the resistivity model. The first 70 m of the profile runs over the building refuse material. It has not been possible to resolve this material from the soil, and therefore the depth to rock may be incorrect in this part of the profile.

Both methods indicate a thicker soil cover in the central part of the profile. The soil resistivities increase slightly towards the northeast, due to an increasing amount of sandy sediments and/or a thinner clay thickness (confirmed by augering). The seismic velocities of 600–700 m/s correspond well with the location of the clay layer given by the resistivities. The following transition to 400 m/s reflects the transition to sandier sediments.

The profile in Fig. 8 demonstrates the result of inversion on the PA-CEP apparent resistivity data. The data coverage is very dense in the horizontal direction, but poor in the vertical direction, yet the low resistivity layer along the profile between 50 and 220 m is acceptably resolved.

A quasi 3-D model of the inverted PA-CEP data is shown in Fig. 9. The four resistivity depth slices represent

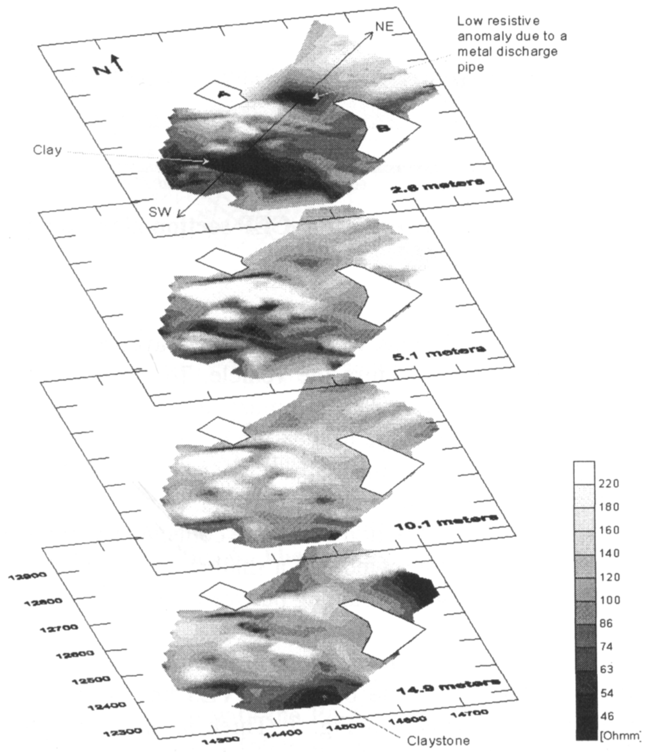


Figure 9. A quasi-3D presentation of the 2-D inverted PA-CEP dataset (rms fit 9%). The area of the thick clays, as well as the position of the metal discharge pipe, are indicated.

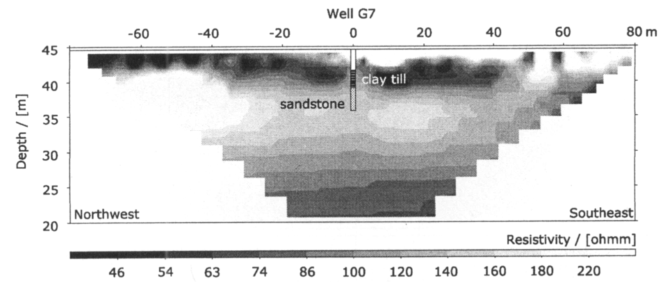


Figure 10. The second Lund CVES reference profile (rms fit 3.6%).

the model distribution at 2.6, 5.1, 10.1 and 14.9 m depth respectively. The central part of the clay layer is clearly distinguishable in the 2.6 m slice, to some extent in the 5.1 m slice, but not at all in the 10.1 m slice. The data coverage does not allow the clay layer to be delimited in the SW direction, but it's narrowing towards the SE is identified. The building waste recycling area hinders surveying towards the southwest. In the NE direction the low resistivities change to somewhat higher values that reflect a thinner clay thickness and/or more sandy deposits. In brief, thick clays are found in a SE-NW trending elongated area, which is at least 150 m long and approximately 80 m wide with the restrictions mentioned above. The low resistivity area that lies between the two brine ponds A and B is due to a metal discharge pipe.

The second Lund CVES reference profile in Fig. 10 shows that the clay till can have resistivity values as high as 100 Ωm. These values mean that even though the thickest clays are found in the southwest part, it is still present to some extent over the whole area. However, it is also clear from Fig. 9 that high resistivity areas (>220 Ωm) are found in several places on, and beneath, the 2.6 m depth slice. These "spots" are probably due to a shallow undulating sandstone surface. Even if a thin clay till layer can be identified in most of the area, it is absent where the sandstone is close to the ground surface. This finding is verified by auguring close to the SW tip of brine pond A where the sedimentary rock was found at 3 m depth, but with no overlying clay till. The low resistivities found at 14.9 m depth correspond to the claystone rock (confirmed by an additional Lund CVES reference profile, not shown here).

In summary, a thick layer of clay till is present in the SW part of the investigation area, but a thin clay till layer can be found in other parts as well. The most important information, as regarding landfill properties, are the locations where the sandstone surface is most shallow. A soil sampling scheme should be designed according to the results of the geophysical investigations to constrain further the geophysical interpretation of the quaternary soil cover.

The Fläskebo Landfill (Case II)

Background and site description. The Fläskebo area is situated 8 km west of the Landvetter airport in the county of Västra Götaland. The need for a new regional landfill has been discussed since 1975, and in 1984 the Fläskebo area was chosen as suitable. The knowledge about the regional hydrogeology is relatively good. Additional information was required however but the proposed area lies in a difficult terrain not easy to access with geotechnical equipment. Therefore, there was a need to extend the reconnaissance work with suitable surveys. A 4 km survey using the Lund CVES was conducted in a rainy week in September 1997. A VLF survey was performed in October 1997.

The proposed landfill area (Figs. 11 and 12) is approximately 600 m long and 300 m wide. It lies on the north slope of a till ridge that passes over to a narrow valley where it meets steeply outcropping bedrock. A small peat bog in the northwestern part is followed by a surface water divide. The divide passes into a gentle slope towards the east. The valley broadens and splits into east and northeast directions and around a peat bog. The area drains to the northeast. However, an old landfill of demolition waste dams the drainage path so that the peat bog is waterlogged.

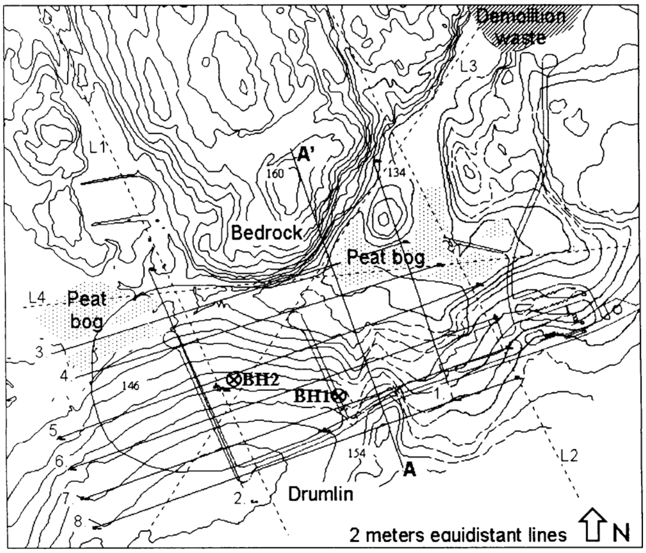


Figure 11. A sketch of the planned landfill area and the connecting infrastructure of the Fläskebo site. BH1 and BH2 are two boreholes drilled into bedrock. The profile no. 5 was not interpreted because it is parallel to a buried electric cable. Hatched lines are lineaments identified from aerial photographic imaging (from GF-Konsult, 1997). The scale 1:10000.

The whole area is forested except for the valley, which has bush vegetation.

Vertical topographic differences along the profiles reach a maximum of 20 m and the ground contains many boulders. Part of the vegetation is thick and as tall as a man. Hence the area is difficult to traverse and results in a lowered production rate of the field crew. The PA-CEP method was impossible to use whereas the Lund Imaging System can be used with some effort. The resistivity profiles were placed to cover the area as well as logistically feasible in 10 days of survey work, including preparation and clearing of the survey lines. The steep hills made it impossible to concentrate the profiles perpendicular to the valley. Instead, the majority of the profiles where placed parallel to the planned landfill main extension. Because of three buried electric power cables, profile no. 5 was excluded.

Geology and hydrogeology. A hydrogeological description of Fläskebo was compiled in 1987 by the regional landfill operator GRAAB (GF-Konsult, 1997). The area is situated on the west part of the 2 km long east-west trending Tahult till ridge (drumlin). The bedrock is a part of the Precambrian granitic complex. Granitic rock is dominant although some greenstone veins that include clay minerals can be found. The bedrock structure trends in a NNW-SSE direction at approximately right angles to the till extension.

Aerial photographs reveal four predominant lineaments (Fig. 11) that run across the planned landfill area that

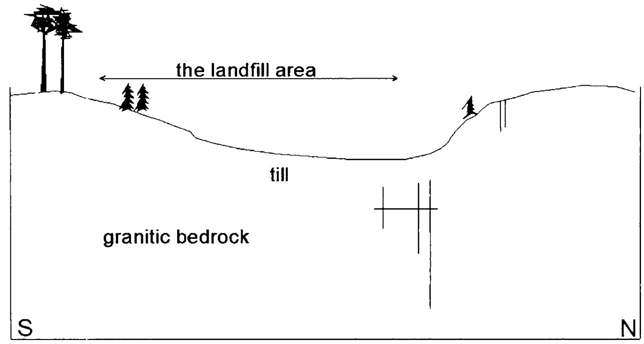


Figure 12. A principal cross section of the site along A-A′ in Fig. 11.

may contribute to the overall fracturing of the crystalline bedrock. However, because the rock mass hydraulic conductivity, including discontinuities, is on the order of 0.2 $\times$ 10^{-7} m/s (GF-konsult, 1997) the importance for groundwater production is limited. Furthermore, because quaternary glaciations have removed the soil cover of former geological eras, the degree of weathering in the Swedish Precambrian rocks is generally very low.

The soil cover is composed of glacial tills (silt or sand till) and peat. The former is a firmly packed lodgement till with a hydraulic conductivity ranging between 2 $\times$ 10^{-6} and 2 $\times$ 10^{-7} m/s. The soil cover thickness varies between 0 and 27 m.

The groundwater level is shallow, at 1 to 3.5 m depth. Locally, both the surface water and the groundwater drains toward the peat bog. The regional flow is towards the north-east.

Data presentation and interpretation. Two examples of interpreted 2-D resistivity sections are shown in Fig. 13. In both cases the interpretation can be constrained by drill core information, and the internal resistivity structure of the geology can be accurately correlated to the soil cover and

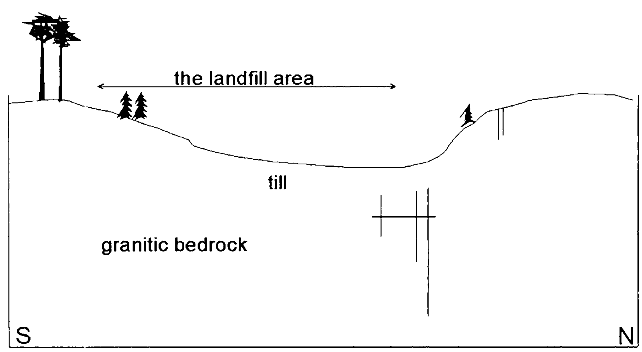


Figure 13. Two 2-D inverted Lund CVES sections along profile 2 (rms 9.2%) and profile 7 (rms 8.6%).

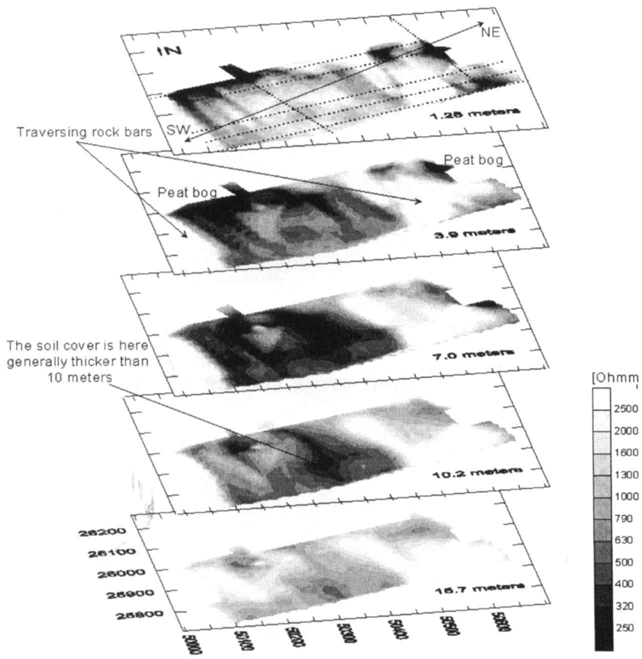


Figure 14. A quasi-3D presentation of the 2-D inverted CVES data.

the bedrock. The resistivity values for the soil/rock interface matches 1300 Ωm. The lowest resistivities in Fig. 13a (<250 Ωm) correspond to the peat bog. The maximum peat thickness obtained from augering was 4 m.

In Fig. 14 the individual inverted resistivity profiles are combined into a quasi 3-D presentation. Only the first five slices are shown. As the 1300 Ωm resistivity value can be taken to be the soil-rock contact it is quite straightforward to evaluate the variation in thickness as well as the depth to the bedrock. The first slice reflects the unsaturated conditions above the groundwater. Two shallow-lying NNW-SSE traversing rock bars are indicated in the 3.9 m slice and below. The soil cover thickness ranges from 10–20 m. The very low resistivities (<250 Ωm) of the two peat bogs are clearly identifiable.

The high resistivity squared area in Fig. 13(a) is probably a 3-D effect created by the low resistivity peat bog to the NW and the high resistive rock bar on the SE of the profile. The mean model fit is 8%, which, considering the high resistivity contrasts and occurrence of 3-D effects, is satisfactory.

Lineament L1, L2 and L4 (Fig. 11) were verified by the VLF data.

Discussion

Thanks to the dense horizontal data cover of the PA-CEP system the inversion algorithm worked well, despite the poor vertical data cover in the Filborna study. It is difficult to cover small areas with the PA-CEP system; the profile layout is more easily optimized by the Lund system which allows for data acquisition close to physical obstacles. However, in the Filborna type of environment the Lund system is markedly slower with the resolution used here (if the number of measured electrode spacings is decreased the speed of surveying can be increased). The seismic refraction two-layer model and the resistivity models correspond reasonably well.

A thick clay layer with ideal barrier properties was identified in the southwest part of the Filborna survey area, and a thinner soil cover was mapped in other parts, as confirmed by augering. The most severe problem regarding landfill barrier properties, occur when the underlying undulating sandstone emerges close to the ground surface. The soil cover is then thin, and the clay content minor. Any pollutants in contact with these areas will rapidly be transported into the sandstone aquifer and away from the landfill area. The resistivity contrast to the sedimentary rock is otherwise small, and the determination of the depth to bedrock is uncertain.

The Fläskebo site showed that the Lund Imaging System works well under difficult terrain and weather conditions. The results allowed the determination of both the thickness of the soil cover and the depth to the crystalline bedrock, which was confirmed by drilling. In contrast to Filborna, the resistivity contrast between the soils and the bedrock was large so that the inverted resistivity data clearly identified the major geological contacts. The depth to bedrock was thus more easily quantified.

Some general remarks can be made. First, the performance of the data inversion was satisfying. The established models correlated well with the geologic interpretation made at borehole locations and provided a means of assessing the lateral continuity of geological formations. Second, the resistivity datasets constitute a valuable reference baseline for later studies on the potential effects of landfills on the environment.

Multi-electrode surveying with a single channel instrument is time consuming, but the instruments available today have improved the efficiency of data collection considerably. Faster instruments, which can measure simultaneously on several channels, are now being developed and will further increase the speed of surveying.

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