Open access • Journal Article • DOI:10.3997/1365-2397.1996014

2D resistivity surveying for environmental and engineering applications

— Source link

Torleif Dahlin

Published on: 01 Jul 1996 - First Break (EAGE)

2D resistivity surveying for environmental and engineering applications

Dahlin, Torleif

Published in:
First Break

DOI:
10.3997/1365-2397.1996014

1996

2D resistivity surveying for environmental and engineering applications

Torleif Dahlin[1]

Introduction

Pressure on natural resources from growing populations, with growing demands for water supply, infrastructure and housing, has increased in the past decades and can be expected to continue to rise. Further stress on the environment due to pollution will increase the need for detailed geological knowledge, for geotechnical, hydrogeological, and environmental protection purposes.

Geophysical methods can play an important role in the acquisition of such knowledge. However, the complete survey procedure, including data acquisition, data processing, interpretation and presentation, must be efficient in terms of time and manpower. It is also essential to provide a continuous cover, along transects or over an area, to complement point information obtained from traditional methods such as drilling, mechanical sounding, test pits, etc. This implies that at least two-dimensional (2D) information is required, and a number of 2D sections may be used to build a quasi-3D picture. Finally, the presentation must be in a form that is easily understood by the non-specialist, e.g. geologists, hydrogeologists or geotechnical engineers. Geophysical results are often presented in a form that is incomprehensible to anyone but the dedicated geophysist.

In the case of DC resistivity surveying these requirements make it neccessary to automate as far as possible the entire data handling process, from the field data acquisition to the presentation of interpreted results. This paper describes a surveying procedure, including data acquisition, processing, interpretation and presentation, and its application to a number of example sites in Sweden.

Data acquisition

A number of multi-electrode resistivity data acquisition systems have appeared in recent years (e.g. Griffiths and Turnbull 1985; Overmeeren and Ritsema 1989). A multi-electrode system developed at Lund University (Dahlin 1993; Dahlin *et al.* 1994) was used for data acquisition in this study. The system consists of a standard resistivity meter (ABEM Terrameter SAS300C), a 4 × 64 channel relay-matrix switching unit, four electrode cables each with 21 take-outs, a portable PC-type computer, steel electrodes and various connectors (Fig. 1). Alternate cables with 2 m and 5 m take-out spacings were used, which gave 160 m and 400 m layout, respectively, with four electrode cables linked together. For measurements with the longer cables a separate current amplifier (ABEM Booster SAS2000) was also used. A further developed version of the system is now comercially available as the ABEM Lund Imaging System.

The data acquisition process is completely controlled by the computer software, which checks that all the electrodes are connected and properly grounded before measurement starts. After adequate grounding is attained the software scans through the measurement protocol selected by the user.

Wenner CVES (*c*ontinuous *v*ertical *e*lectrical *s*ounding) was used for the data presented here, where the measurements at each instrument station are divided into two parts. The first part involves all four electrode cables, and uses every second or fourth electrode take-out depending on the version of the system. These electrode take-outs are colour coded to facilitate field work. A measurement procedure is used which allows roll-along of cables and electrodes while measuring is in progress. When the measurements involving cable one and four are finished, the procedure continues using only the two central cables. In the meantime cable one can be disconnected and moved to the far end of the layout, and electrodes installed while measuring is still in progress. After measuring is complete at the first midpoint, the instrument is moved and measuring continues at the new midpoint with every second or fourth electrode active. The electrodes that are not active on cable one (former cable two) can be moved to the new cable three, to be in place when measuring involving only the two central cables starts.

The measurement protocol used for the data presented here provides Wenner CVES with 10 different spacings (a) ranging between 2 and 48 m (short cables), or between 5 and 120 m (long cables).

Data processing and presentation

The methodology adopted for data processing and presentation comprised four steps:

1 Pseudosection plotting in greyscale or colour;
2 Calculation and plotting of sections by means of one dimensional depth interpretation;

[1]Department of Geotechnology, Lund University, Box 118, S-221 00 Lund, Sweden. Tel + 46/ 46 222 96 58; Fax: + 46/ 46 222 91 27; E-mail Torleif.Dahlin@tg.lth.se

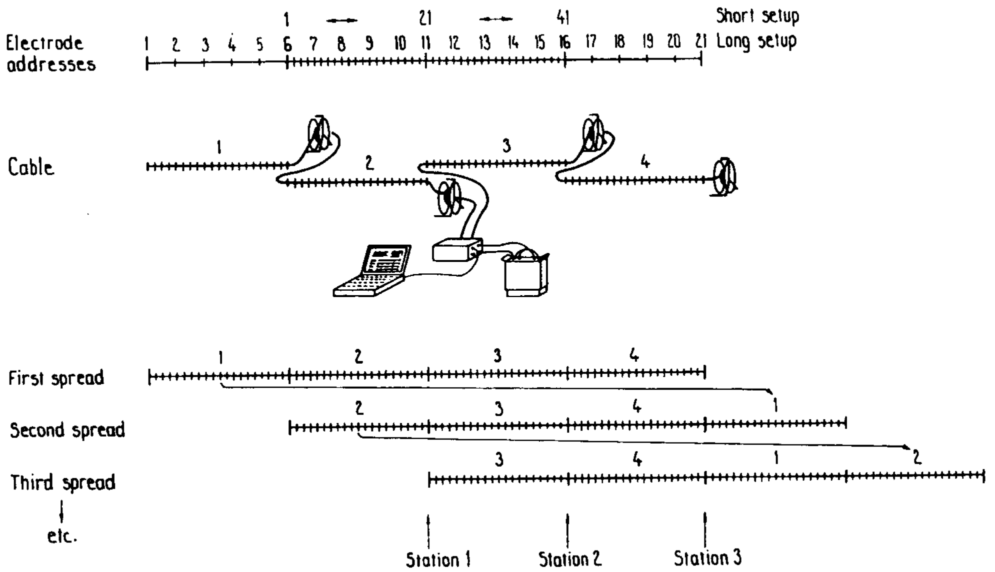

Fig. 1. Schematic layout of data acquisition system, indicating the different parts of the system and the roll-along process (modified from Overmeeren and Ritsema 1988).

3 Inversion and plotting of the sections, using 2D smoothness constrained inversion;
4 Extraction of selected vertical electrical soundings along the section, for more detailed layer depth analysis.

The first two steps can be performed on-the-spot in the field for data quality control and for the first interpretation of the data, which often provides a very valuable guide for the data acquisition process. The use of linear interpolation for the pseudosection plotting means that there is no smoothing of the data, and thus an immediate image of the data quality is provided.

Quasi-2D sections were made by regarding the pseudosection as a series of closely spaced VES, extracted one after the other. Each sounding is interpreted in terms of a multi-layer model using the technique suggested by Zohdy (1989) and merged together to form a section. The Zohdy technique automatically creates and adjusts a multi-layer model to fit the data as closely as possible. A major advantage of this technique is the speed of operation, a full day's work with the data acquistion system described above can be interpreted and plotted automatically in less than a minute on a notebook computer. This efficiency makes the technique useful for preliminary evaluation of the data in the field.

The true resistivity structure was interpreted using 2D smoothness constrained inversion. For the inversion 2D structures are assumed, 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 smoothness constrain prevents unstable and extreme solutions. The program employs 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. The result of a day's data acquisition may take around 10 min to invert on a modern PC.

All multi-layer inversion results in more or less gradual layer interfaces even if the geological boundaries are sharp and distinct. This smoothing is necessary in order to prevent the creation of exteme and unstable solutions, and is connected to the principle of equivalence. Thus, although automatic imaging will give a picture of the electrical structure and variation of the sub-surface, it will not provide any detailed information on the depths of the strata. In order to get more quantitative information on the layer resistivities and depths, vertical electrical soundings were extracted from selected points along the profiles. The points were selected (on the basis of the pseudosections and automatic depth sections) to avoid points with too much lateral variation. The extracted VES were inverted and analysed using few-layer models with a 1D interpretation program (Christensen and Auken 1992). In this case a reasonable start model is defined by the user and optimized iteratively against the measured data. The offset variation (Barker 1981) was used to assess the lateral variation of the extracted VES data sets.

Field examples

Revinge

An area close to the village of Revinge in southern Sweden is characterized by ridges of coarse-grained Quaternary sediments. Around the ridges fine-grained and organic sediments cover the coarse sediments which can be up to 20 m thick. The coarse-grained sediments rest on 10–20 m of glacial clay, which may in places be overlain by clayey

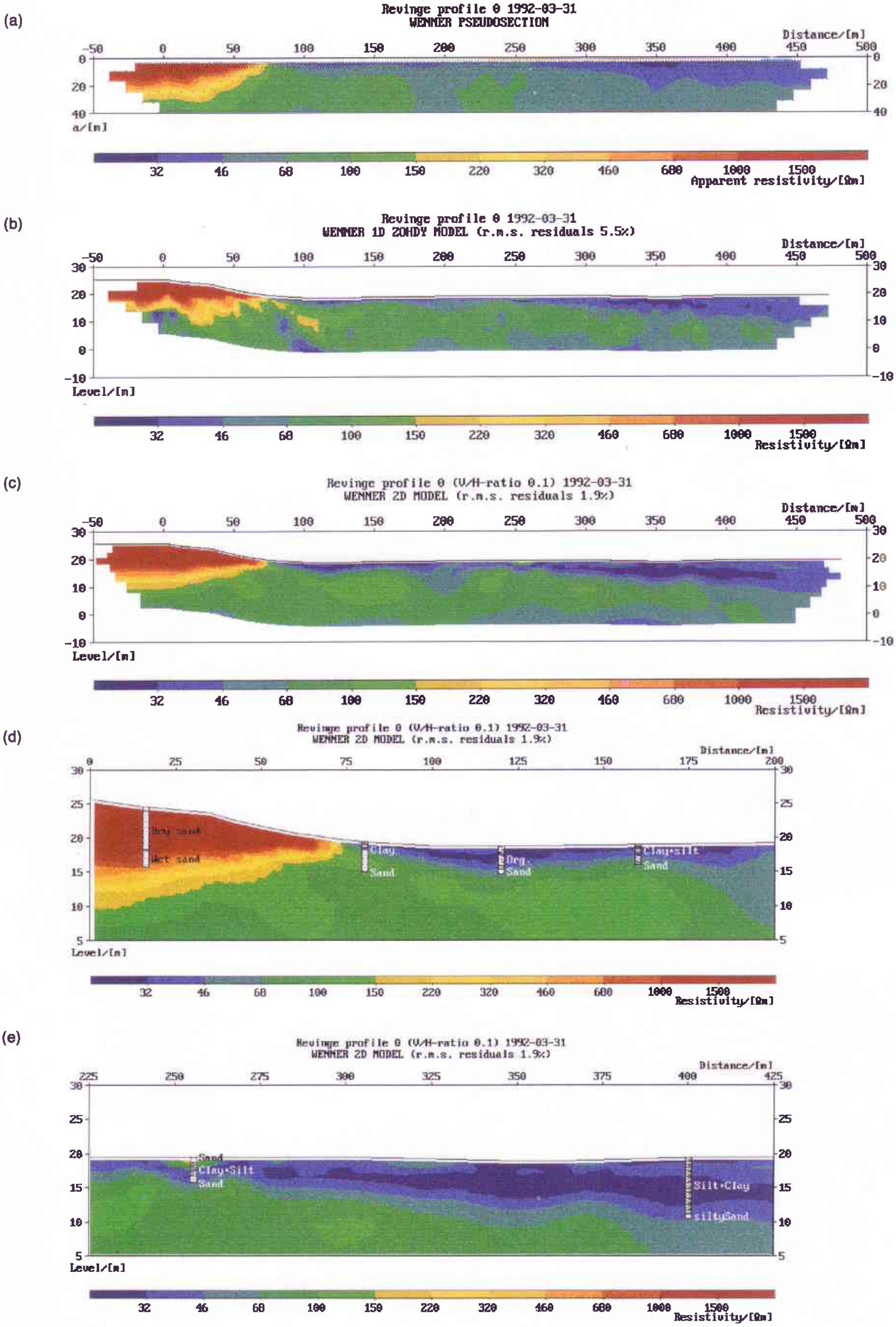

Fig. 2. Revinge profile, (a) pseudosection, (b) 1D Zohdy interpretation section, (c) 2.5D smoothness constrained inversion section, (d) details of inverted section with augering data superimposed.

till. These layers rest in turn on glacial till and sedimentary rock (Gustavsson 1980; Bjelm and Malmberg-Persson 1982). The profile presented here stretches from a coarse sediment ridge to a depression covered by fine and organic sediments. This example illustrates the mapping of a fine sediment cover over a coarse sediment aquifer, which is applicable to, e.g., groundwater vulnerability studies and aquifer volume estimations. The extent of fine and organic sediments may also be crucial in geotechnical applications.

The pseudosection (Fig. 2a) as well as the 1D Zohdy section (Fig. 2b) and the 2.5D inversion section (Fig. 2c), show high resistivities at the surface in the first part of the section (over the coarse sediments) and low surface resistivities for the parts with fine sediments at surface. Below these layers the resistivities are intermediate, which corresponds to water-saturated sand. A lateral effect caused by the strong change in surface resistivities is visible in the pseudosection in the distance interval around 100 m. This effect is amplified by the 1D Zohdy interpretation, as can be clearly observed in Fig. 2b, but is removed by the 2.5D inversion (Fig. 2c). Apart from the lateral effect the two depth sections largely have a similar appearance.

Figure 2d shows augering results superimposed on details of the inverted section. The depth to groundwater in the coarse sediments appears exaggerated, while the variation in depth of the fine and organic sediments is well mapped. There is no evident resistivity difference between the fine and organic sediments in this case.

Data extracted and interpreted in terms of 1D models (Fig. 3) show that a good model fit is obtained with the layer depths fixed to those shown by the augering, and provides true resistivities of the layers. A low resistive bottom layer was needed for a good model fit, but the depth to and the resistivity of that layer is poorly determined. The interpreted resistivities can then be used for a better layer estimation at other points where the lateral variation is not too marked, so that a limited number of reference points provides a good estimate of the true depths and resistivities within the investigated area. Figure 4 shows an interpreted geological section based on the data presented above, and it is obvious that only a very limited number of reference points would be needed for creating a reliable model of the subsurface at this site.

Gladökvarn

This field example was measured along part of a planned road near Gladökvarn south of Stockholm. The area is typical of large parts of Sweden, and consists of a gneissic basement overlain by till and post glacial sediments (SGU 1968). From a geotechnical point of view the bedrock topography and the extent of postglacial clay cover are of primary interest.

The result is presented as pseudosection, section based on a 1D Zohdy interpretation, and a 2.5D inversion section in Fig. 5a, b and c, respectively. A region with low resistivities, corresponding to clay, is visible in the central part of the sections with depths reaching over

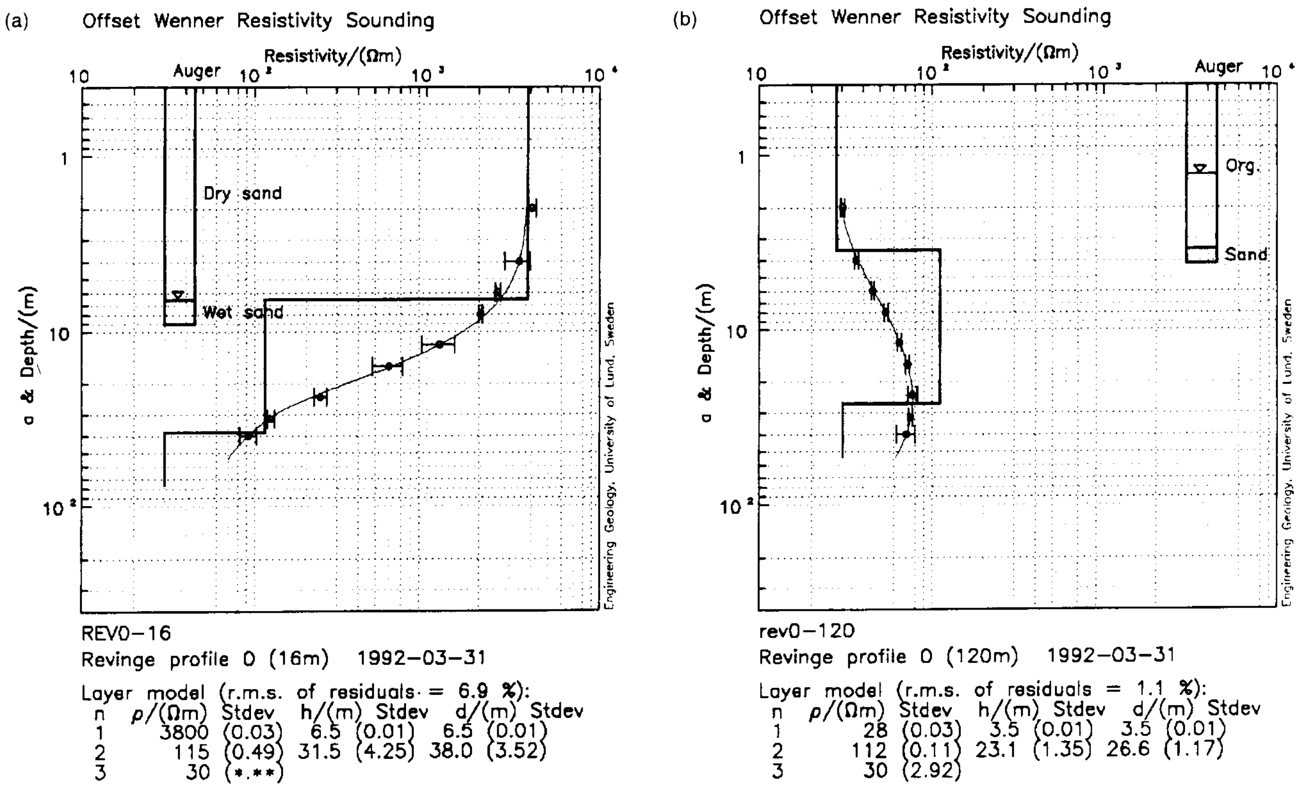

Fig. 3. Extracted VES from Revinge profile, (a) distance 16 m (b) distance 120 m.

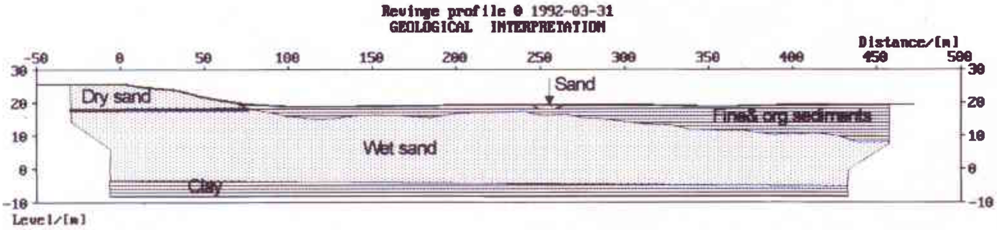

Fig. 4. Geological interpretation of the Revinge profile.

(a)

(b)

(c)

(d)

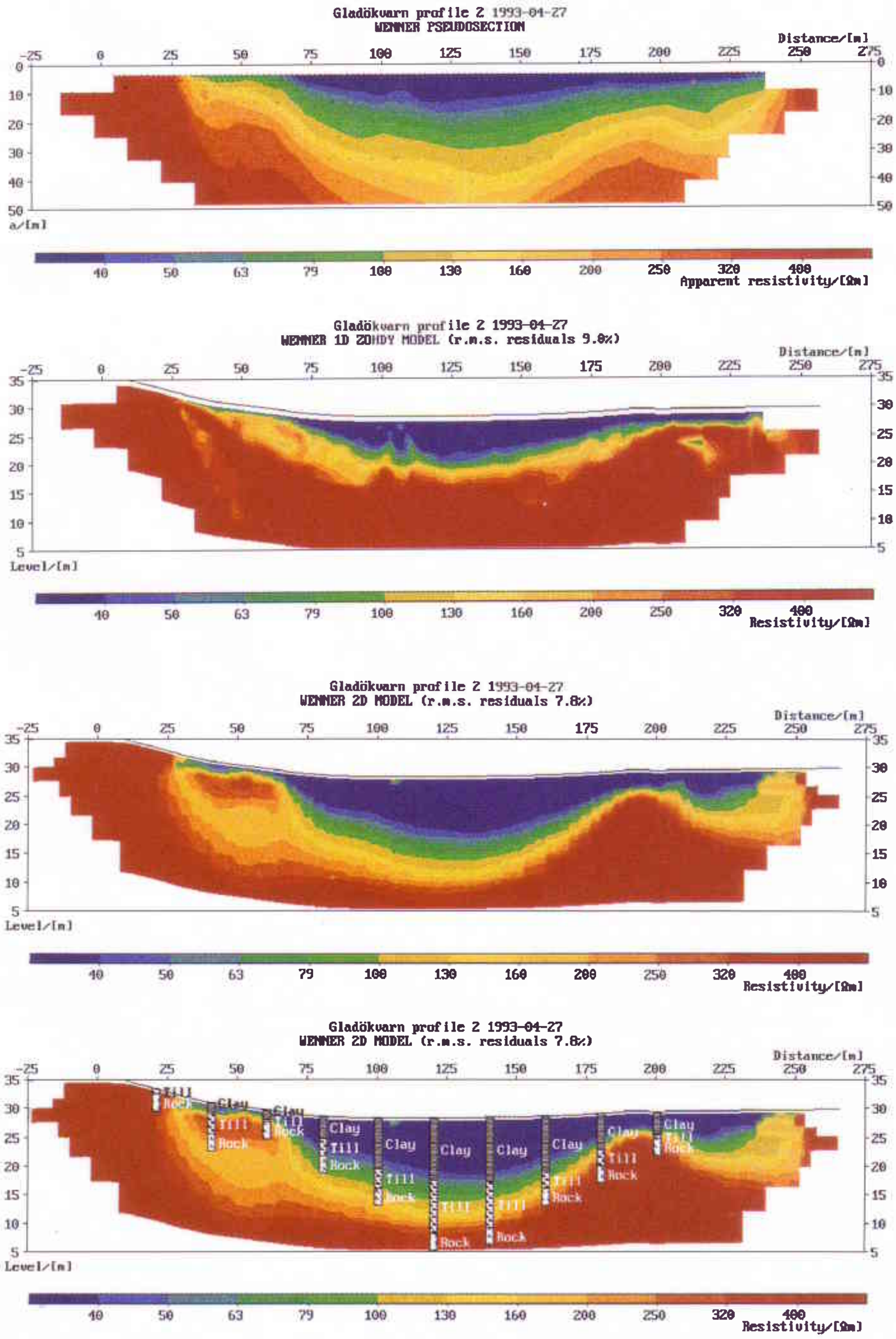

Fig. 5. Gladökvarn profile, (a) pseudosection, (b) 1D Zohdy interpretation section, (c) 2.5D smoothness constrained inversion section, (d) inverted section with drilling data superimposed.

10 m. A high resistive bottom layer is evident, with resistivities typical of igneous rock. An intermediate zone between the clay and bedrock has resistivities indicative of coarse grained till and coarse post glacial sediments. As can be seen the Zohdy interpretation gives a preliminary estimation of the structure which is similar too the more rigorous 2.5D inversion.

Figure 5d displays drilling data superimposed on the 2.5D inversion section, where the material indicated as till may also include coarse-grained post glacial sediments. The lowest resistivity intervals correspond well to the extent of the clay layer, although the thickness of the underlying coarse-grained material is not well defined (especially in the left part). The latter is partly due to the principle of equivalence, because the coarse grained deposits are of intermediate resistivity. However, in the left part of the section a 3D effect should be expected since the sediment depths increase rapidly on one side of the profile. This effect is manifested as the occurence of intermediate resistivities at greater depths than the depth to bedrock from drilling. The 3D effects are also indicated by the relatively high model residuals (7.8% r.m.s.).

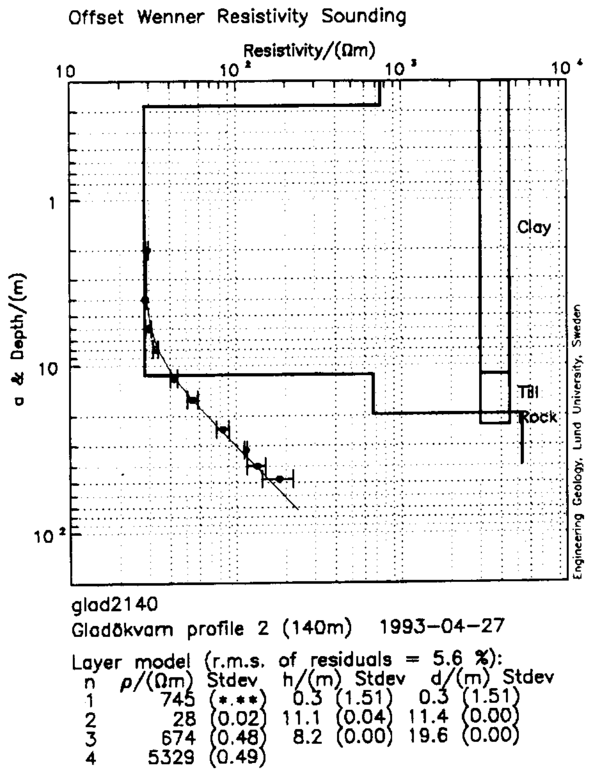

Fig. 6. Extracted VES from Gladökvarn profile, distance 140 m.

Figure 6 shows data extracted and interpreted as VES, and demonstrates a good correlation between interpreted model and drilling data, but a poor model fit for the longest electrode spacings. The poor fit for the longest electrode spacing is clearly caused by the deviation from the assumptions made for 1D theory, but nevertheless the technique can be used for a better estimate of the thickness of the top layer.

Östra Odarslöv

A profile was measured over a dolerite dyke which cuts through shale outside Lund in southern Sweden, known from a nearby quarry, which is overlain by clayey till. The dyke location is clearly visible in the magnetic profile in Fig. 7. The site was chosen to test ability to map variations in rock type and quality, which may be of interest for geotechnical as well as hydrogeological applications. It may be noted that the traverse passes under an electric power line close to the dyke, which rules out the use of most electromagnetic techniques at this location.

Figure 8a, b and c shows the result as a pseudosection, 1D Zohdy section and 2.5D inversion section. The presence of the dyke is clearly indicated in the pseudosection, with a top layer of lower resistivities indicated. A top layer thickness of between a couple and a few metres is indicated by the 1D Zohdy section, and corresponds well with the till depths in the surrounding area, known from the Swedish Geological Survey well archive and Nyers and Nilsson (1973).

However, the shortcomings of the 1D approach for the strongly 2D structure of the underlying rock are clearly visible when the 1D and the 2.5D sections are compared. The 2.5D inversion shows a well-defined highly resistive dyke, flanked by zones of significantly lower resistivities indicating zones of fracturing and weathering in the contact zone. The variation in

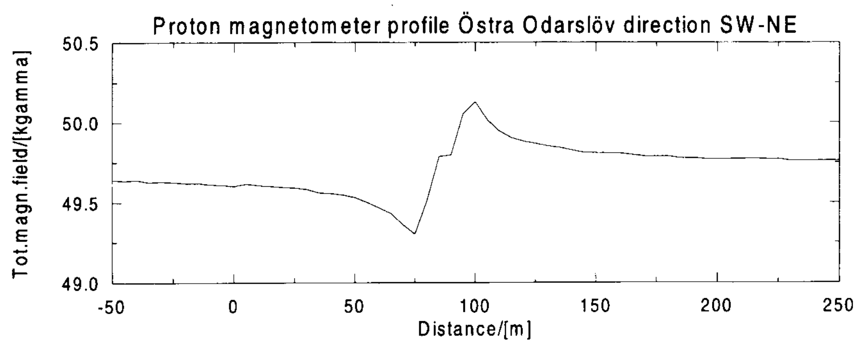

Fig. 7. Total magnetic field profile at Östra Odarslöv.

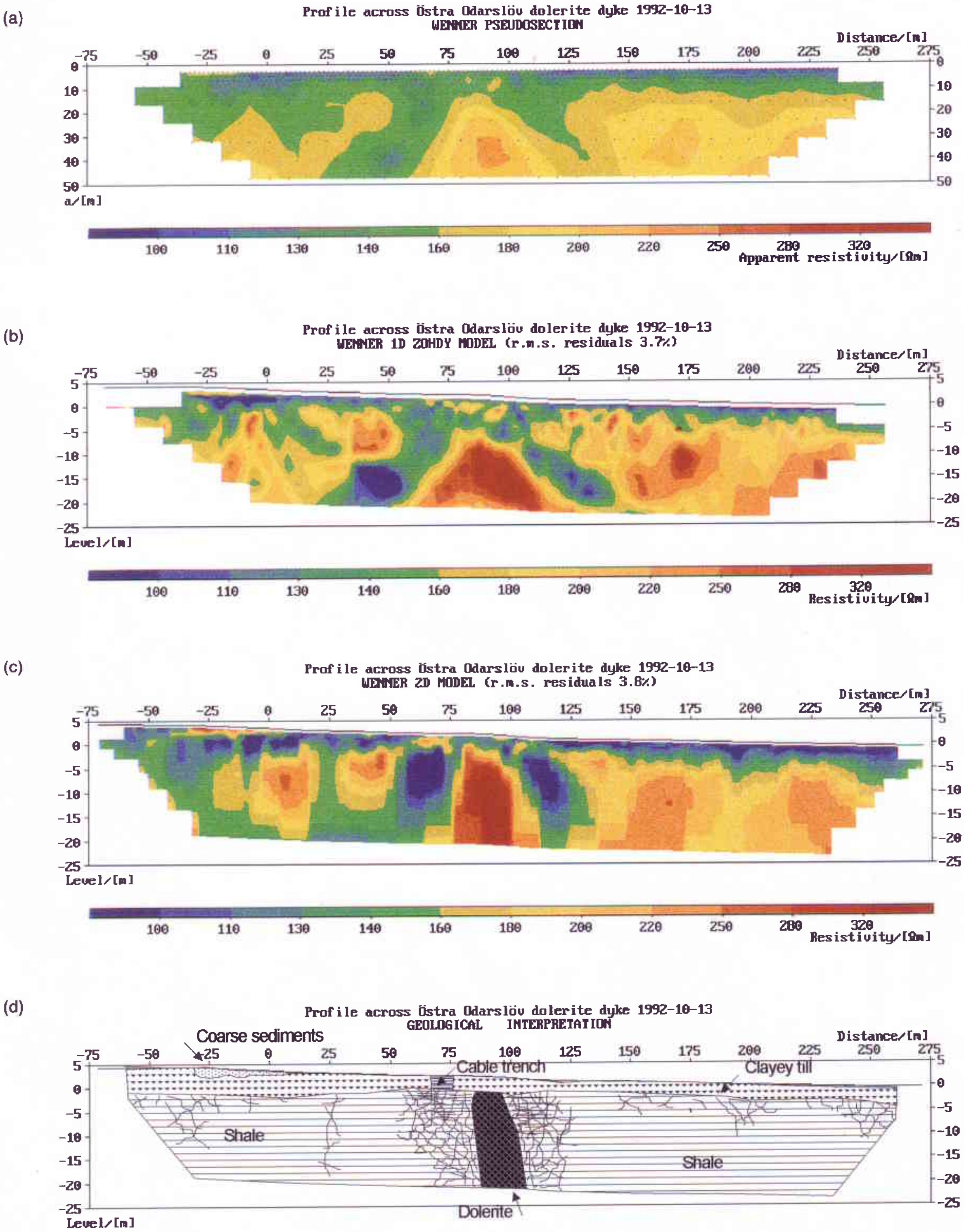

Fig. 8. Östra Odarslöv profile, (a) pseudosection, (b) 1D Zohdy interpretation section, (c) 2.5D smoothness constrained inversion section, (d) geological interpretation.

resistivity within the shale suggests that the rock quality is variable, dependent on, e.g. fracture density variation.

Torreberga

Torreberga is situated east of Malmö, and is used as a municipal water supply. Hydrogeological investigations, including 2D resistivity surveying and drilling among other methods, were carried out for resource management and vulnerability assessement purposes. The area is characterized by the regional aquifer Alnarpsdalen, which is a sediment-filled valley in the limestone bedrock. The aquifer is overlain by clayey till and various sediments, and it was suspected that coarse sediment lenses may exist in the clayey till. These lenses could provide rapid infiltration paths and hence increased vulnerability of the aquifer. (Berglund and Digerfeldt 1970; Barmen 1992).

A pseudosection, 1D Zohdy section and 2.5D inversion section is shown in Fig. 9a, b and c. All these sections clearly show an area of significantly higher resistivities than the surrounding areas, which indicates

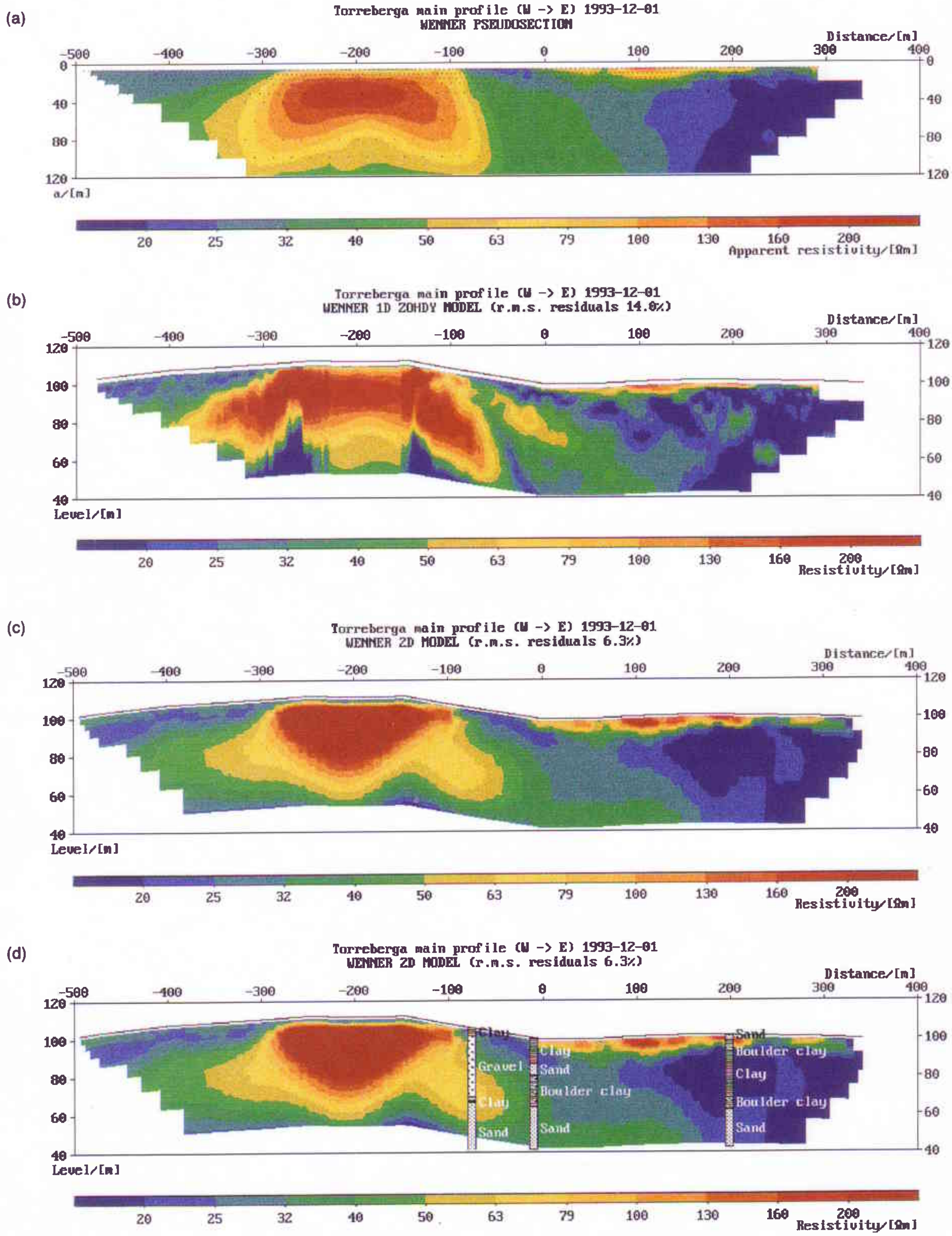

Fig. 9. Torreberga profile, (a) pseudosection, (b) 1D Zohdy interpretation section, (c) 2.5D smoothness constrained inversion section, (d) inverted section with drilling data superimposed (the leftmost drilling point is situated 50 m off the survey line).

a zone of coarser sediments. The interpretation that the high resistivitity zone consists mainly of sand and gravel is supported by an old boring (Fig. 9d) which shows more than 30 m of gravel and more than 30 m of sand, with limited clay horizons. This boring is situated in line with the highly resistive zone, but the location is offset by 50 m from the line of survey. Outside this zone there is more clayey material as verified by the drilling data superimposed on the plot in Fig. 9d.

The strong lateral variation of this site requires 2D inversion, as it is evidently too pronounced for the 1D approach which gives high model residuals (14% r.m.s.) and amplifies lateral effects. In fact, other profiles in the area show that there is a marked 3D variation, and the low resistivities indicated at depth below the highly resistive zone may be caused by 3D effects. The 3D character of the area is also indicated by the relatively high model residuals (6.3% r.m.s.).

Discussion

The above examples show that 2D resistivity surveying can form a powerful geological mapping tool, for use in engineering and environmental applications, including hydrogeological mapping. In combination with a limited number of drilling reference points, with locations based on the resistivity results, reliable models of the subsurface can be created.

A major advantage of the DC-resistivity method is its relatively small sensitivity to noise. By comparison, electromagnetic methods are normally useless in the vicinity of various human installations such as electric power lines and railways. Often such installations do not affect DC resistivity surveys adversely, as exemplified above.

Data processing and interpretation are often performed in a number of steps, which may vary according to the character of the investigated area, and the purpose of the investigation. Pseudosection plotting provides control over data quality, and may thus be presented along with depth sections as a quality indicator. Pseudosections can also be used in qualitative interpretation. Quasi-2D sections compiled automatically from 1D Zohdy interpretation are suitable for preliminary on-site interpretation of the data, but care must be taken where there is significant lateral variation because lateral effects are amplified. If the lateral variation is gradual the 1D technique may be adequate if lateral effects are recognized, as shown by the Revinge example. However, in areas with significant lateral variation 2.5D inversion is neccessary to arrive at a reasonable estimate of the subsurface structure, as illustrated by the examples from Östra Odarslöv and Torreberga. The smoothness-constrained quasi-Newton technique has proved to work well. However, care should be taken to avoid 3D effects when designing the surveys, or to appreciate them when they occur.

In cases where as much detailed information as possible on the layer sequence is required, VES analysis of selected data is a useful tool. However, this only applies where the lateral variation is small, which can be assessed from the pseudosection and depth sections.

Although 3D resistivity techniques are under development, 2D surveying will probably in many applications remain the most useful for logistic and cost reasons. A number of 2D profiles can be used to compile quasi 3D models. In the future, 3D inversions of a number of combined 2D data sets can be envisaged.

Acknowledgements

The work was partially funded by a research grant from the Swedish Geological Survey (SGU), which is gratefully acknowledged.

MS received December 1995; accepted March 1996.

References

Barker, R. 1981. The Offset System of electrical resistivity sounding and its use with a multicore cable, *Geophysical Prospecting* **29**, 128–143.

Barmen, G. 1992. *On the combination of isotope hydrogeology with regional flow and transport modelling,* PhD thesis, ISRN LUTVDG/TVDG – 1006 – SE, ISBN 91-628-0587-8, Lund University, 201pp.

Berglund, B. and Digerfeldt, G. 1970. A palaeoecological study of the Late-Glacial lake at Torreberga, Scania, South Sweden, *OIKOS* **21** (1), 98–128.

Bjelm, L. and Malmberg-persson, K. 1982. *Kävlingeåns hydrogeologi,* report LUTVDG/ (TVTG-3002)/1-38/ 1982., Lund University, 38pp.

Christensen, N.B. and Auken, E. 1992. Simultaneous Electromagnetic Layered Model Analysis. *Proceedings of the Interdisciplinary Inversion Workshop 1, Aarhus 1992,* B.H. Jacobsen (ed.) *GeoSkrifter* **41,** 49–56.

Dahlin, T. 1993. *On the Automation of 2D Resistivity Surveying for Engineering and Environmental Applications,* PhD thesis, ISRN LUTVDG/TVDG – 1007 – SE, ISBN 91-628-1032-4, Lund University, 187pp.

Dahlin, T., Johansson, S. and Landin, O. 1994. Resistivity Surveying for Planning of Infrastructure. *Proceedings of SAGEEP '94 (Symposium on the Application of Geophysics to Engineering and Environmental Problems),* Boston, 27–31 March 1994, 509–528.

Griffiths, D.H. and Turnbull, J. 1985. A multi-electrode array for resistivity surveying, *First Break,* 3 (7), 16–20.

Gustavsson, O. 1980. *Jorddjupskarta över sydvästra Skåne,* SGU Ser. Ba nr 28, Swedish Geological Survey, Uppsala.

Loke, M.H. and Barker, R.D. 1996. Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method, *Geophysical Prospecting,* **44** (1), 131–152.

Nyers, A. and Nilsson, R. 1973. The lithology, fauna and stratigraphy of two drill cores from the Upper Wenlock in Western Skåne, Southern Sweden, *Geologiska Föreningens i Stockholm Förhandlingar,* **95** (2), 229–235.

Overmeeren, R.A. van and Ritsema, I.L. 1988. Continuous vertical electrical sounding, *First Break,* **6** (10), 313–324.

SGU (Swedish Geological Survey) 1968. *Geologiska kartbladet Stockholm SO,* Map Ser. Ae nr 3, Stockholm.

Zohdy, A.A.R. 1989. A new method for the automatic interpretation of Schlumberger and Wenner sounding curves, *Geophysics,* **54,** 245–253.