Combined Resistivity Imaging and RCPT for Geotechnical Pre-investigation

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Abstract: Combined resistivity imaging and CPT with resistivity (RCPT) can be a powerful tool for geotechnical pre-investigation, as demonstrated by a field example. Resistivity imaging can in a time and cost efficient way provide two-dimensional (2D) or three-dimensional (3D) models of the ground. Resistivity imaging should preferably be carried out in an early stage of a geotechnical pre-investigation, to provide an overview of the extent of soils and rocks with different properties. The resistivity model(s) can serve as an excellent basis for planning continued detail investigation, to design for example a drilling programme. Added value is achieved if the detail investigations include RCPT in selected points, to be used as reference data for a refined interpretation of the resistivity imaging. Furthermore, it can serve as a key for possible correlation between the resistivity and the mechanical or chemical properties of the ground, as base for extrapolation of the soil layers and their properties from the CPT soundings.

1 INTRODUCTION

Over the past decades growing populations have increased the pressure on natural resources, raising demands for water supply, housing and infrastructure. This pressure can be expected to rise, and combined with environmental stress caused by pollution, there is a growing need for detailed geological studies connected to environmental protection and infrastructure development. Geophysical methods can play an important role in these studies, where DC (direct current) resistivity imaging is one of the methods of primary interest.

Resistivity imaging provides continuous images of the subsurface in two or three dimensions, most commonly carried out as two-dimensional (2D) imaging for logistical and economical reasons. It can thus give a good overview of the variations of the ground conditions, and highlight anomalous areas. A limitation is that the resolution decreases with depth, but on the other hand, it provides an excellent basis for designing a drilling and sampling programme.

Direct investigation methods such as for example cone penetration test (CPT) can provide much more detailed information than surface geophysical methods, and may thus serve as a base for a refined interpretation of the surface geoelectrical imaging data. A CPT probe with resistivity measuring capability (RCPT) is an important improvement compared to conventional CPT, which has potential to characterise the soil hydraulic properties, such as pore fluid resistivity, soil porosity and degree of saturation. Applications include environmental investigations of mine tailings, delineation of salt-water intrusion and quality control of geotechnical ground densification (Daniel et al. 2003). It may also provide a key for correlations between the resistivity and other parameters of the ground. Depending on the site conditions there may be clear correlation between resistivity and other parameters measured by the CPT probe or a lack of correlation. In the latter case, resistivity variation may be caused mainly by water quality, in which case it can be a valuable tool for mapping e.g. groundwater contamination (Draskovits et al. 2003).

This paper is based on investigations at two sites in southern Sweden, where two-dimensional (2D) resistivity imaging and RCPT was tested together. Field results from one of the sites are presented here. All the investigations presented in this paper were part of a Master of Science project at Lund University (Leveen & Palm 2000).

2 METHOD DESCRIPTION

2.1 Resistivity Imaging

The resistivity surveying was made as two-dimensional imaging, also called continuous vertical electrical sounding (CVES), which is presented as cross sections of the resistivity of the ground. The ABEM Lund Imaging System was used for the data acquisition, a computer controlled multi-electrode system. Four electrode cables with 21 take-outs each were laid out on a line, and the lines extended using a roll-along technique (Dahlin 1996). The Wenner-Schlumberger and dipole-dipole arrays were tested.

The data was processed using inverse numerical modelling (inversion), in which a finite element or finite difference model of the subsurface resistivity distribution is automatically adjusted to minimise the residuals between the model response and the measured data (e.g. Loke & Dahlin 2002). Two different optimisation methods were tried for inverting the data, L_2-norm and L_1-norm inversion. In the commonly used L_2-norm, or least-squares inversion, the squares of the differences between measured data and model response are minimised. This method gives smooth transitions in resistivity between zones of different resistivity. In L_1-norm, or robust inversion, the absolute differences are minimised. This method is more robust against noise in the data, and gives sharper boundaries between zones of different resistivities (Loke et al. 2003). The software Res2dinv was used for the inversion.

2.2 RCPT

The RCPT probe that was used is manufactured by Geotech AB, and is placed immediately above the standard CPT probe during operation. The 4 electrodes on the probe are placed in a Wenner array starting 550 mm above the tip of the probe, where the 10 mm wide electrodes have a centre distance of 30 mm. The drill rig that was used during the probing and drilling is a Geotech 604D.

The field measurements with the RCPT probe were carried out when the data from the resistivity imaging was processed. Besides the RCPT probing, auger drilling and piston sampling was carried out. The auger drilling was executed for identifying different layers in the soil profile and the piston samples were used to perform tests in the laboratory.

2.3 Laboratory tests

The tests were carried out on the piston samples by applying a controlled electric current (1 mA) between two plates at the sample ends, creating a uniform potential field. Two electrodes of 2 mm diameter with a distance of 50 mm were used to measure the potential in the sample. An ABEM Terrameter SAS 300 was used for the laboratory tests.

3 FIELD EXAMPLE: BARA

3.1 Site Description

The Bara test site is located approximately 5 km south-east of Malmö in southern Sweden. The test line is located within the grounds of the company Bara Mineraler, where clay was quarried for industrial purposes until 1992. The clay is postglacial, and it rests on and can also be covered by coarser sediments. An auger drilling was carried out at section 90 m on the test line, and the layer sequence showed sand, clay with sand and silt lenses, clay and silt in the bottom (Table 1).

Table 1. Auger drilling documentation from Bara test line (at section 90 m).

Description	Depth interval
Fine sand	0.0-0.8 m
Clay w. sand layers	0.8-3.0 m
Clay w. sand and silt layers	3.0-5.0 m
Clay	5.0-8.6 m
Silt	8.6-10.0 m

3.2 Resistivity Imaging Results

The resistivity imaging was done under favourable field conditions, i.e. with good electrode grounding contact and low ambient noise levels, resulting in stable data of high quality. A minimum electrode separation of 2 metres was used.

Inversion with the different electrode arrays and different optimisation methods resulted in rather similar inverted sections with a horizontally layered structure, as shown in Figure 1. Four different layers are clearly visible in the inverted sections, with close to 100 Ωm in the top layer, around 20 Ωm in the second layer, followed by a layer of around 30 Ωm, and approximately 70 Ωm in the bottom layer. This corresponds very well with what can be expected from the soil sequence documented in by the auger drilling (Table 1).

One difference between the sections in Figure 1 is that the robust (L_1-norm) inversion sections have sharper boundaries than the least-squares (L_2-norm) inversion sections, which tend to have more gradual layer transitions. One striking discrepancy is seen around section 80 m in the dipole-dipole least-squares inversion section (Figure 1c), where there is a major disturbance. It appears that the dipole-dipole array picks up disturbances that are not affecting the Wenner-Schlumberger array. These disturbances cause the least-squares inversion to create artefacts, whereas the robust inversion handles it in a more stable way.

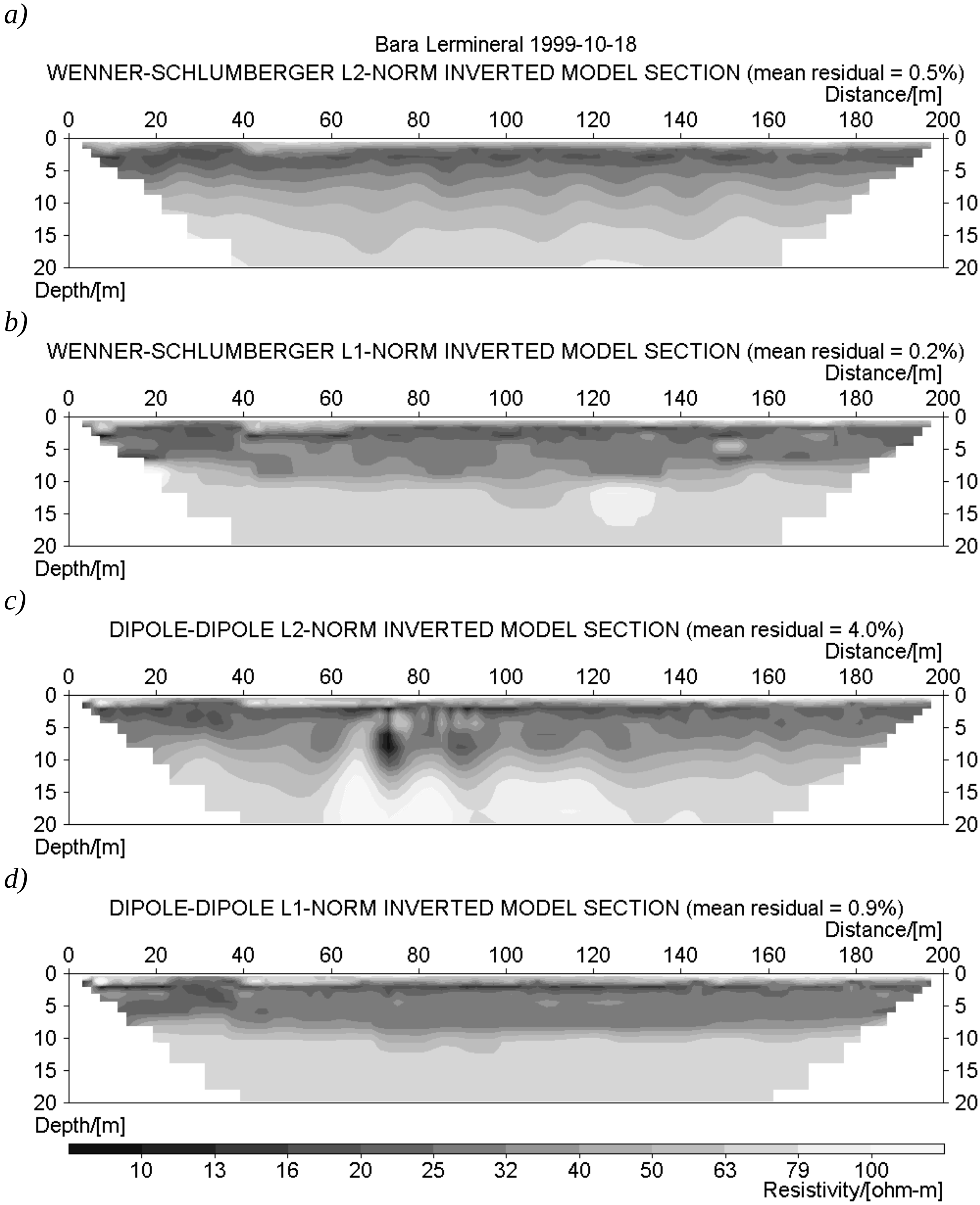

Figure 1. Inverted resistivity sections from the Bara test line: a) Wenner-Schlumberger w. L_2-norm, b) Wenner-Schlumberger w. L_1-norm, c) dipole-dipole w. L_2-norm, and d) dipole-dipole w. L_1-norm.

3.3 RCPT Results

The probing was carried out during good weather conditions with satisfactory results. The probing took place at section 30 m, 50 m and 90 m. In Figure 2 the results from section 90 m is presented, showing correlation between the mechanical CPT-parameters and resistivity. A layer with higher resistivity than the rest of the probing is detected at the top of the soil profile, corresponding to the sandy top layer. Between 1 and 3 m depth the resistivity lies around 20 Ωm, corresponding to the clay with sand layers according to the auger drilling documentation (Table 1). From 3 - 8 m below the ground surface the resistivity oscillates around 30 Ωm, corresponding to clay with silt and sand layers and clay. The curve has a varying appearance indicating layers/beds of silt or sand. From around 8 m depth the resistivity increases to about 40 Ωm, with significant peaks at 8.5 m and 10 m depth, classified as silt from the auger samples. This indicates a significant variation in properties in the layer classified as silt. The features described for the resistivity corresponds with changes in cone resistance, pore pressure and sleeve friction.

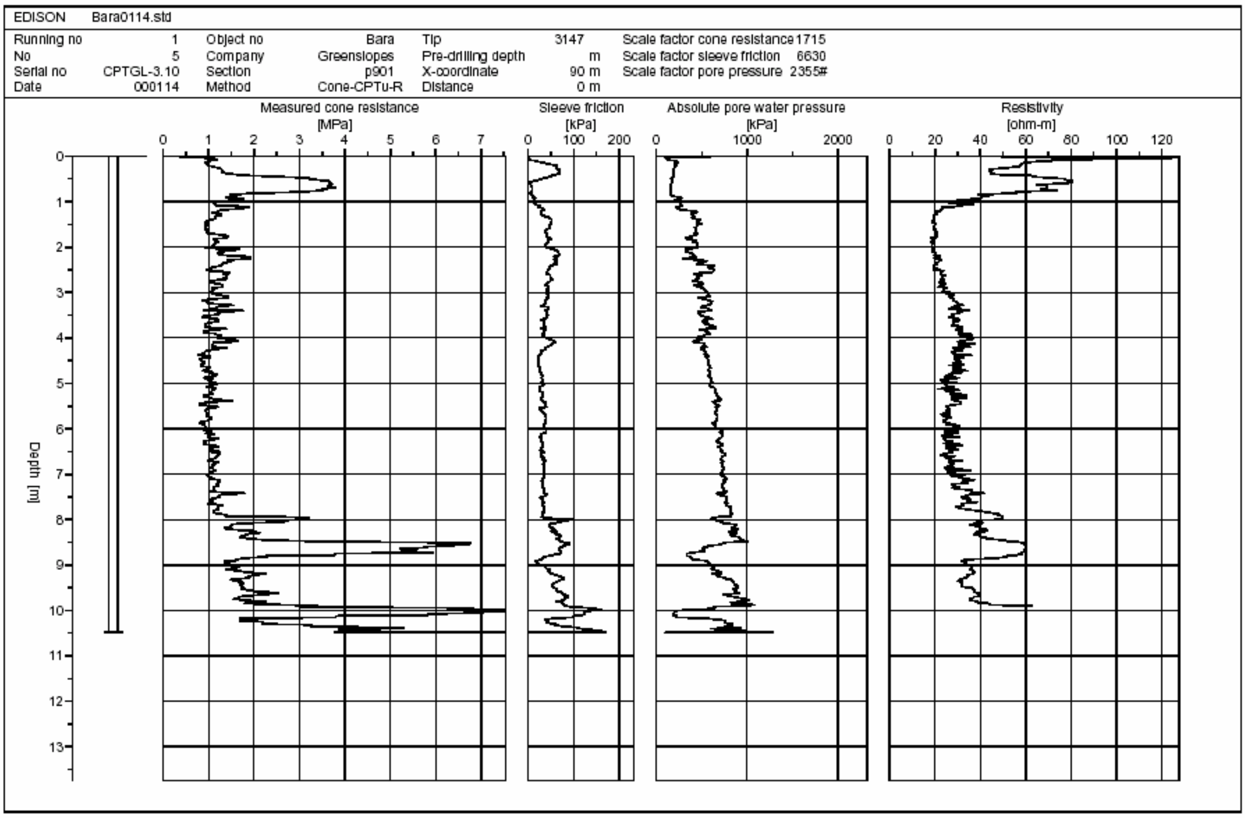

Figure 2. CPT results from distance 90 metres on Bara test line, including measured cone resistance, sleeve friction, generated absolute pore water pressure (atmospheric pressure = 100 kPa) and resistivity.

3.4 Laboratory Test Results

Laboratory tests were carried out on 5 piston samples in the depth range 2.2–5.4 m from section 90 m, with results as presented in Table 2.

3.5 Comparison of Results

The results from the comparison of the resistivity imaging, RCPT and the laboratory tests are presented in Table 2. The resistivity results from the different methods follow each other well, except a slight deviation at level 5.20 m where the resistivity measured on the piston is increased. This is probably due to small-scale lateral variation in the soil.

Table 2. Comparison of results from resistivity imaging (Wenner-Schlumberger, L_1-norm inversion), RCPT and laboratory tests.

Level (m)	Resistivity imaging (Ωm)	RCPT (Ωm)	Sample resistivity Ωm)
2.20	22.5	22.3	22.0
2.37	22.5	20.7	20.5
5.03	28.0	25.2	25.5
5.20	28.0	28.2	34.3
5.37	28.0	28.8	26.1

Resistivity imaging models were extracted from the inverted sections and plotted together with the RCPT results for all the RCPT points. The agreement between the inverted resistivity models and the RCPT results is generally good for the Wenner-Schlumberger array, bearing in mind the decreasing resolution and thereby increasing integration with increasing depth. The dipole-dipole array mostly gave similar results, but in some cases it deviated.

The results from section 90 m are shown as example in Figure 3, where the soil profile according to classification from samples taken by auger drilling is also included. For the Wenner-Schlumberger array both inversion methods resulted in resistivity distributions that match the RCPT well (Figure 3a), whereas for the dipole-dipole array the agreement is not as good, especially not for the least-squares inversion (Figure 3b).

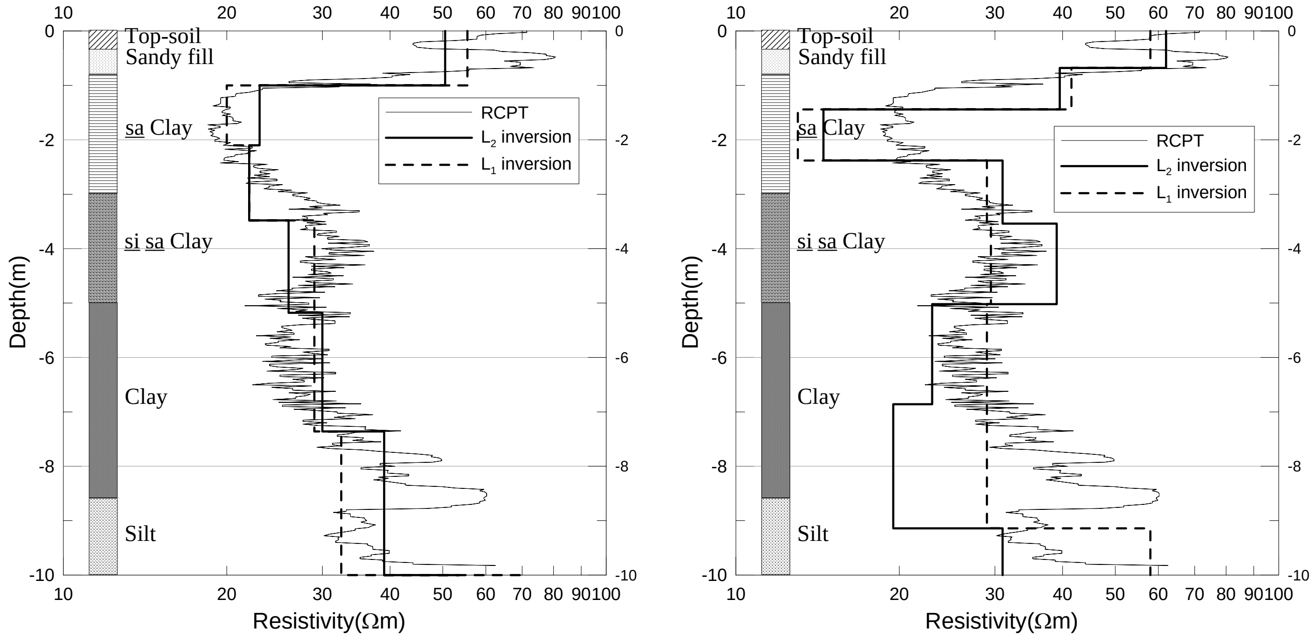

Figure 3. Example data from the Bara test line. Comparision between RCPT, extracted resistivity models from least-squares (L_2-norm) and robust inversion (L_1-norm) and auger drilling documentation: a) Wenner-Schlumberger, b) dipole-dipole.

4 DISCUSSION AND CONCLUSIONS

This study shows a good correlation between resistivity imaging and RCPT. Points with less good correlation correspond to suspected 3D effects from e.g. geological variation perpendicular to the investigation line or metal objects in the ground, the latter at the other test site for which results are not presented here. Robust inversion was less sensitive to disturbances than least-squares inversion, and Wenner-Schlumberger gave more stable results than dipole-dipole. Laboratory resistivity measurements on piston samples gave good agreement with resistivity imaging and RCPT.

Resistivity imaging can be an excellent base for designing a drilling and sampling programme. RCPT in turn is useful for verification of resistivity imaging results, and a base for refined interpretation of the resistivity imaging data. The refined interpretation can be done either qualitatively or by employing the RCPT data as prior information in the inversion process, for example using laterally constrained inversion (Wisén et al 2003).

Including resistivity in the CPT investigation provides a key for correlation between the resistivity variation and the soil layers, and possibly their variation in chemical or mechanical properties. Thus, the resistivity imaging sections can be used for a more reliable interpolation and extrapolation of the soil properties from the CPT soundings. In the example presented here peaks in resistivity correlates with peaks in cone resistance, except at the surface where the higher resistivity is probably caused by drier soil. There is no generally applicable formula for this correlation, so it must be done with caution on a site-specific basis, with as much available good quality reference data as possible.

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