Pulled Array Continuous Electrical Profiling

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Introduction

The electrical profiling method has been used widely for decades and has proved to be a powerful technique for mapping near-surface geology. Applications have been manifold: prospecting for raw materials, hydrogeological investigations, road and pipeline construction, etc. During recent years the method has gained a central position in Denmark for the detailed, regional mapping of protective clay caps of aquifers (Christensen and Sørensen 1994).

In this application electrical profiling is conventionally carried out using a Wenner array. Usually, arrays with electrode spacings of 10 m and 30 m are employed at typical sampling intervals of 60 m. In this way 1.5–2 km of profiling with three arrays can be achieved in one working day using metal rods as electrodes and with a crew of three skilled workers (Sørensen and Pedersen 1992). This substantial manpower requirement per profile kilometre has been the main obstacle to a more intensive application of the method.

To meet the demands of high productivity, reliability and detailed, dense sampling, a new method of electrical profiling which we refer to as Pulled Array Continuous Electrical Profiling, PA-CEP, has been developed. Electrodes with processing electronics are mounted on a tail pulled by a small vehicle carrying the measuring equipment. By this method several electrode arrays may be measured simultaneously and continuously while the tail is towed. The continuous measurements along profiles ensure a high quality and reliability of the recorded data sets. The equipment is operated by one or two skilled persons. Profile lengths of 10–15 km are generally recorded in one working day (Sørensen 1994).

The principle of the PA-CEP method

The PA-CEP method is simple in principle (see Fig. 1) but has presented many interesting technical problems which will be addressed below. The resulting implementation of the method is as outlined below.

The electrodes are cylindrical steel tubes with a weight of 10–20 kg for the current electrodes and 10 kg for the potential electrodes. Two electrodes are maintained as current electrodes; the current limit is 30 mA for the safety of the operating personnel.

The electronics are mounted inside the potential electrodes in order to suppress the influence from strongly varying electrode–ground contact, and to reduce crosstalk and noise interaction in the tail. The digital data acquisition is performed by equipment placed on the vehicle. By applying a synchronous detection technique with a frequency of 15–25 Hz followed by robust averaging rejecting outliers, the noise voltages from fast varying electrochemical surface activity and from external sources (power lines, terrestrial currents etc.) are strongly reduced.

Several facilities are incorporated to monitor the quality of the measured data, such as detection of insufficient galvanic contact at the current electrodes, and measurement of the contact resistance at the potential electrodes. Furthermore, the magnitude of the emitted current is adapted automatically to obtain the best signal-to-noise ratio.

The pulling vehicle is a cross-country caterpillar with a height of 80 cm and a width of 70 cm which makes it possible to pass under fences and between trees, etc. Furthermore, a small bridge of 3 m length is carried along and used when crossing small creeks and ditches.

The challenges

Two main challenges were met when implementing the method. First it was necessary to obtain sufficient galvanic contact with the ground at the current electrodes in order to maintain a constant (alternating) current. Secondly, a data acquisition technique had to be developed which would remove the distorting effects of noise voltages at the potential electrodes. Beside these main challenges, crosstalk between signals in the tail and capacitive coupled noise in the cabling arising from the high voltage source current generation, also presented interesting and not easily soluble problems.

In this paper the approaches to the main challenges will be addressed, as they play a central role in the understanding of the method.

Using an oblong cylindrical mild steel electrode (30 cm long) with a weight of 10–20 kg as a current electrode, a current of 10–30 mA is transmitted into the ground. The current is maintained at a constant level in order to facilitate the data processing, by using a

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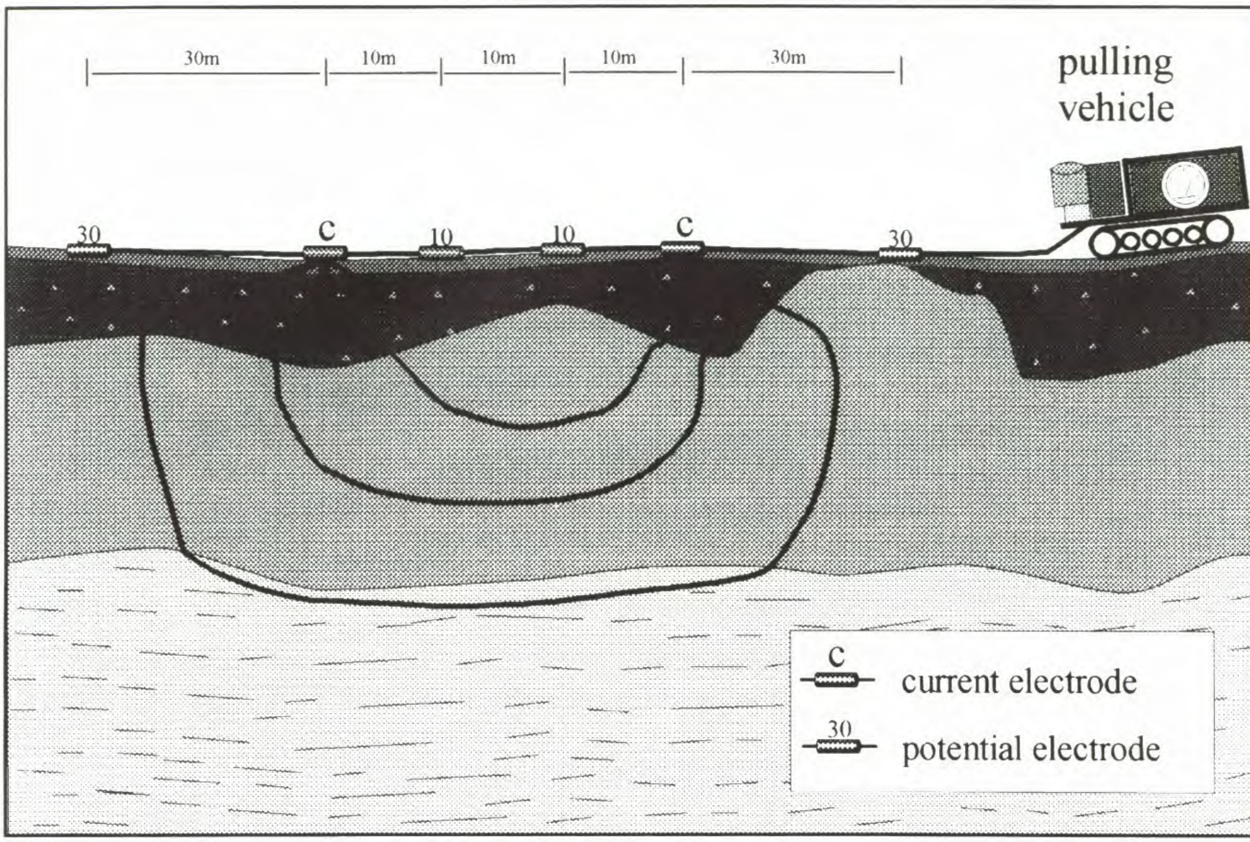

Fig. 1. Principle of the Pulled Array Continuous Electrical Profiling Method. Electrodes are mounted on a tail and pulled by a small vehicle carrying the measuring instruments. Two electrode arrays are measured continuously and simultaneously during towing of the tail. The potential electrode pairs are labelled according to their electrode spacing. The arrays labelled 10 and 30 are Wenner arrays with electrode spacings a = 10 m and 30 m.

constant-current generator and alternating the signal polarity with a frequency of 15–25 Hz.

A typical variation of the contact resistance between the current electrodes and the ground is shown in Fig. 2. This author's experience from more than 1000 km of PA-CEP profiling demonstrates that it is possible to emit a constant current in the range of 5–30 mA into the ground using a fast operating current generator with a maximum voltage less than 250 volts. Even in dry soils the ever-present soil moisture reduces the contact resistance between the electrode and the ground and makes it possible to emit the required current.

Processing electronics with high input resistance (5–10 Mohm) are mounted inside the potential electrodes to diminish contact problems, crosstalk and coupling effects in the tail. Also analogue bandpass filtering is implemented to reduce the noise effect of slowly varying SP voltages (less than 1 Hz) and the influences from power lines (50 and 60 Hz). Due to the high input resistance only lightweight electrodes with a maximum of 10 kg are necessary as potential electrodes.

The noise potentials caused by the electrochemical interactions between the rapidly changing soil and metal contact of the potential electrode are by far the largest noise source. In Fig. 3 it is seen how the magnitude of the noise potential changes from a stationary tail to a moving tail. As can be observed the decay time of the noise potentials is of the order of seconds, which indicates that this noise source will provide no problems for techniques applying stationary rods as electrodes. In the case of moving electrodes the influence from the noise is severe. It should be noticed that other materials for the potential electrodes such as stainless steel have been tested but did not diminish the noise significantly.

The noise is suppressed when applying a synchronous detection technique with a frequency of 15–25 Hz followed by a robust averaging rejecting outliers (Munkholm *et al.* 1995). The data acquisition is carried out on-line, and data sets are digitally stored every second. Due to the averaging width a trade-off exists between data variance and spatial resolution. The data are sampled with a frequency of 80 Hz and the speed of the tail is approximately 0.6 m s^{-1} (2 km per hour). The applied spatial averaging width is related to the electrode spacings (generally 0.1–0.25 times the spacings). This gives a detailed spatial resolution and provides smooth data (see Fig. 4). As the noise voltages do not depend significantly on the character of the surface soils or the speed of the tail, their influence is highest in low-resistivity formations.

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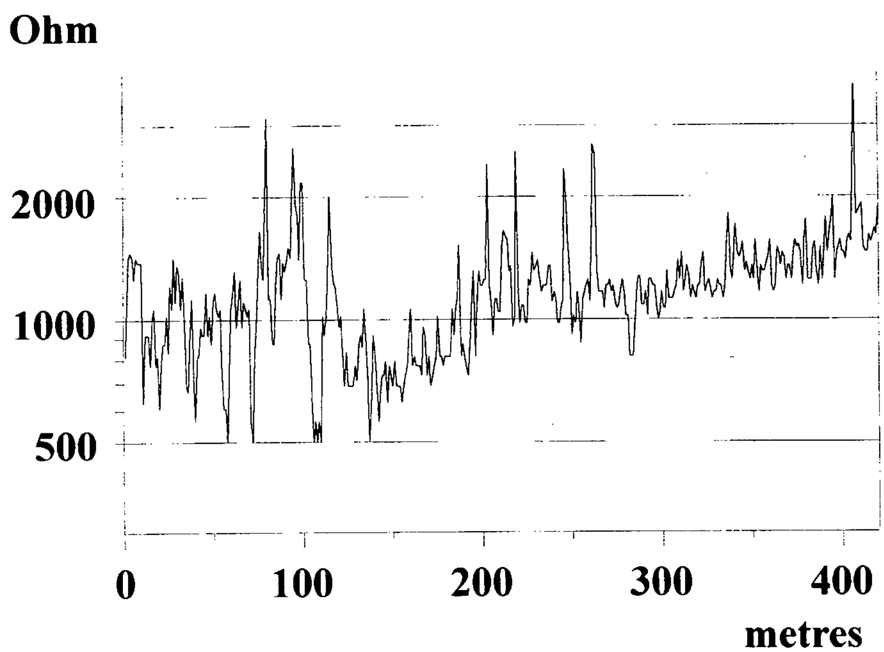

Fig. 2. The figure shows the resistance between the current electrodes as the tail is moved along the test profile. The soil is sandy moraine clay and the work was carried out on a sunny day. The resistance varies rapidly but within the limits of the current generator to be able to emit a constant current into the ground.

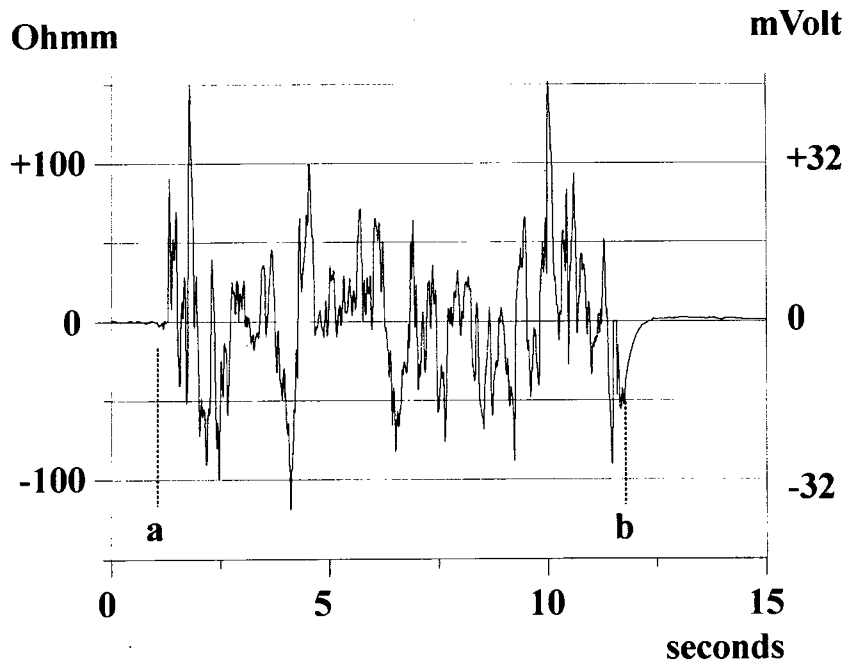

Fig. 3. An example of the variation of the noise voltages between two potential electrodes in the Wenner array (a = 10 m). At a speed of 0.3 ms^{-1} the time interval of 15 seconds represents 4.5 metres of profile. At 'a' the movement of the electrodes starts, and at 'b' it stops. In between 'a' and 'b' the movement of the electrodes is kept constant. At 'b' a decay in the noise voltages is observed of a duration of 2–3 s. The noise voltages are transformed into apparent resistivity values using an emitted current value of 16 mA. As indicated by the figure the noise voltages are of the same order of magnitude as the measurements shown in Fig. 4.

Test of the method versus traditional techniques

When a new method is introduced its accuracy has to be tested, i.e. its reproducibility against traditional well-documented techniques, and its own repeatability.

For this purpose a test site was set up with a profile length of 420 m. The apparent resistivity was measured using a conventional technique with four moving rod electrodes with a spacing of 10 m and a sampling interval of 5 m. Along the profile PA-CEP measurements were performed with similar Wenner arrays mounted on the tail.

Four PA-CEP profiles were carried out in alternate

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directions and the averaged result compared with each separate profile to establish the repeatability of the method (see Fig. 4).

The mean PA-CEP profile was compared with the profile measured by rods to document the reproducibility of the method (see Fig. 5).

The results of the experiments demonstrate that the PA-CEP method reproduces the result obtained by traditional methods and that it has a remarkable repeatability.

Discussion and results

In using traditional profiling techniques with stationary rods as electrodes three main problems arise.

How reliable are our data? The sampling distance when performing electrical profiling is conventionally equal to the electrode spacing. Within this distance the variation in the apparent resistivity is often large. Hence it may be difficult to estimate the quality of the data sets by correlation between adjacent data points.

How do we interpolate between the profiles? The data sampled along the profiles constitute the material for estimating the variability between the data points. For interpolation, kriging is often used with success, but requires a measure of the variability of the data. This measure is obtained from the profiles, but its reliability depends critically on the sampling density.

How many electrode arrays should be used in order to obtain a reliable interpretation? With the traditional technique two arrays (electrode spacings of 10 m and 30 m) are generally used. Based on the measurements three isoresistivity maps are produced, one for each electrode spacing. Without further data processing these maps give insight into the subsurface resistivity structure down to approximately 30 m. If measurements from several arrays were available resistivity modelling could

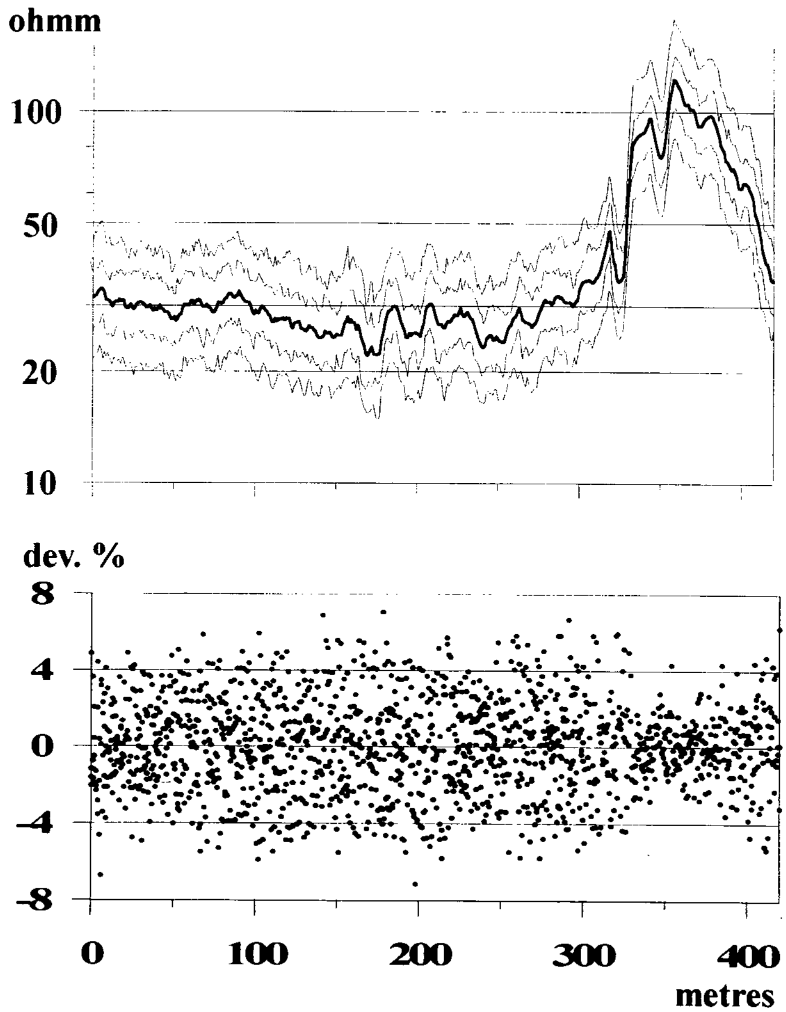

Fig. 4. The upper figure shows the four individual PA-CEP profiles (thin lines) and the average of these profiles (thick line). Two individual profiles are shifted each by a factor 1.2 and two each by a factor 0.8 in order to be able to distinguish the reproducibility of even small features in the apparent resistivity. The lower figure presents the deviation (in percent) of each individual profile measurement from the averaged profile. The apparent resistivity for each profile is recorded for every 1 m along the test profile and the averaging length in the instrument-filtering is approximately 1 m.

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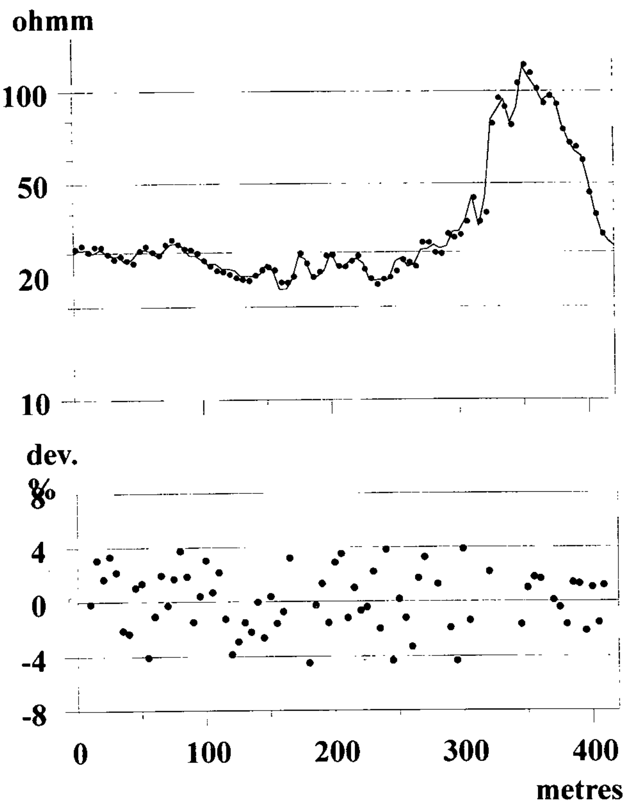

Fig. 5. The upper figure shows the averaged PA-CEP profile (full line) together with the profile measured with rods (dots). The lower figure presents the deviation (in percent) of measurements carried out with rods from the averaged PA-CEP profile. The apparent resistivity measured with rods is recorded for every 5 m along the profile.

be carried out, providing a better estimate of the subsurface resistivity structure.

The application of the PA-CEP method reduces these problems. Measurements are performed continuously along the profiles, and therefore the reliability of the data can be examined by correlation between adjacent data sets. As the data sampling is dense, a good estimate of the variability along the profiles is achieved. Finally, the mounting of several arrays on the tail and thereby obtaining a continuous electrical sounding will be an obvious continuation of the presented method. The data from a continuous electrical sounding will require effective interpretation and imaging techniques.

The issues of physical planning of land use today demand a detailed and regional mapping of the near-surface geology in order to locate raw materials and delineate the inhomogeneities in the protective clay caps of aquifers. These demands require efficient and detailed mapping methods. In this context the PA-CEP method proves very useful.

In the County of Aarhus large sandy aquifer systems are located in valleys eroded down into Tertiary clay. The aquifers are covered by an inhomogeneous moraine clay cap. The task of estimating the vulnerability of the aquifers requires location of sandy permeable areas in the clay cap. Around the village of Grundfor electrical profiling has been carried out in order to map the near-surface geology and determine the presence of sandy permeable areas. Two isoresistivity maps of the apparent resistivity from a PA-CEP survey are presented in Fig. 6a and b. The profile lines are dense, and high lateral resolution of the subsurface resistivity structure is therefore achieved. The isoresistivity maps are interpreted in a qualitative manner having in mind the sensitivity function of the array (Oldenburg 1978). In this area the moraine clay has formation resistivities below 50–60 ohmm, whereas the sandy formations have resistivities above 80–100 ohmm. The thickness of the clay cap varies, but does not exceed 20 m. Figure 6a displays the lateral variations in apparent resistivity in the upper part of the clay cap, with a maximum sensitivity of the array at a depth if 3 m. Three major coherent areas are found with resistivities above 125 ohmm indicating sandy permeable formations. Figure 6b shows the lateral variation in apparent resistivity in the deeper parts, with a maximum sensitivity of the array at a depth of 9 m. Two coherent high-resistivity areas are present. When the isoresistivity maps are combined two areas with minor or no coverage by a low-resistivity clay cap appear. In the north-eastern part a highly resistive area stands out in both maps indicating that a sandy permeable formation cuts through the clay cap. In the southern part the clay cap is absent, and the near surface formation is dominated by highly resistive sandy formations with superficial clay coverage in the centre of the area.

The interpretation of the profiling results is carried out qualitatively and is based on combined use of the apparent resistivities from each electrode spacing. However, it is desirable to perform a more quantitative interpretation. In the present case two electrode spacings are applied, which allows an iterative inversion of the data based on a horizontally layered model to have only two free parameters. The application of this inversion to achieve quantitative estimates will have only a very limited use. Two or three dimensional models may be used but in most cases do not give results justifying the effort. A new approach for approximate interpretation of resistivity data is the deconvolution of measurements along profiles (Moller *et al.* 1996). This approach uses a Born approximation and is based on a deconvolution using a 2D Frechet kernel. It is very fast and therefore suitable for processing large data sets. The application of this approach to PA-CEP data is only at a preliminary stage and will therefore not be presented here.

Development of the PA-CEP method is being continued to achieve a continuous electrical sounding method using several electrode arrays on the same tail—a method which in a fast and efficient way may establish detailed and reliable resistivity models of the near-surface resistivity structure (Overmeeren and Ritsema 1988). The PA-CEP method calls for quantitative

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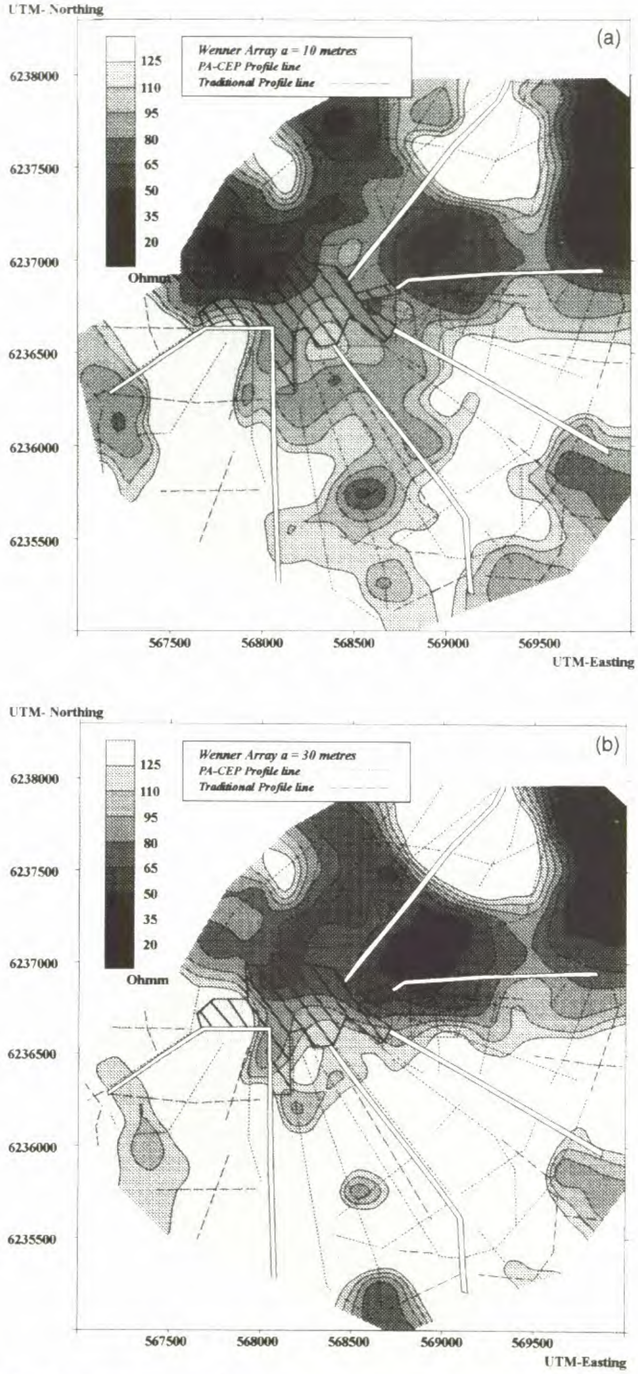

Fig. 6. The result of a PA-CEP at electrode spacings of (a) 10 m and (b) 30 m. The map is produced applying a kriging interpolation procedure using approximately 50 km of profile. One can observe very high gradients between clayey impermeable low-resistivity areas and sandy permeable high-resistivity areas. The investigation indicates that profiling must be carried out on a dense grid in order to obtain a detailed delineation of the near-surface geology.

interpretation schemes capable of handling large and densely sampled data sets. One approach would be an inversion based on 1D smoothness-constrained resistivity models with many layers and fixed boundaries and, in intervals where strong lateral variability is encountered, to use 2D interpretation techniques. Unfortunately the amount of data will be large and requires high computational capacity. In this context the deconvolution technique mentioned may provide a fast approximate interpretation which in most cases will be sufficient.

Conclusion

The PA-CEP method is a fast-opening method for continuous electrical profiling simultaneously measuring several electrode arrays. The method gives results similar to those produced by traditional techniques and provides a remarkably high repeatability.

Due to the dense sampling an estimate of the reliability of the data is provided from correlation of adjacent data sets. Furthermore, a good measure of the variability can be achieved from the densely sampled profiles thus enabling well behaved and reliable interpolation between profile lines.

In hydrogeological investigations of the protective clay caps of aquifers, in prospecting for raw materials, and in road and pipeline constructions the method provides an efficient approach to detailed mapping on a regional scale.

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