The AC-geoelectrical sounding method: a combined electric/electromagnetic prospecting tool

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Since 1979 the Laboratory of Geophysics, University of Aarhus, has been developing a new prospecting tool for obtaining information on the topmost 100 m of the earth. The method is an extension of the conventional geoelectric sounding method, but instead of direct current (DC) the AC-geoelectrical sounding method uses alternating current (AC) with frequencies in the range 100 Hz to 20,000 Hz. The use of alternating current adds an inductive contribution to the ordinary galvanic electric field, thus producing two different sorts of information about the underlying earth structure. These two sets of information are, in many cases, of complementary nature, which enables determination of the ground parameters much more accurately than would otherwise be possible from ordinary DC-geoelectrical soundings. Among these cases is the high resistivity equivalence which appears so frequently in Danish Quaternary deposits.

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The geoelectrical sounding method is one of the most well-established geophysical prospecting tools. For decades this method has been in widespread use all over the world in many different contexts. In Denmark the method has been used mainly for investigations of the upper 100 m of the earth with the purpose of gathering geological information in general, prospecting for raw materials like sand and gravel, and for hydrogeological surveys. The method is characterized by ease and versatility of application and a solid background of practical experience and theoretical knowledge of assets and drawbacks.

Geoelectrical sounding uses direct current (DC) for the measurements and is thus a galvanic method. The measured voltage between the potential electrodes, ΔV, is converted to an apparent resistivity

$$\rho_a \equiv K(L/2) \cdot \Delta V/I \qquad (1)$$

where K(L/2) is the geometrical factor which depends only on the electrode configuration, and I is the strength of the current. The apparent resistivity is plotted against L/2 – half the length between the current electrodes – in a double logarithmic coordinate system, whereby a curve of apparent resistivity is obtained. The type of information obtained from application of the method is determined from the behaviour of galvanic conduction of current in the ground, which has certain built-in limitations on the possibility of determining the earth parameters from the measurements. Among these limitations the equivalences of high resistivity layers and low resistivity layers are well known. Especially the high resistivity equivalence, where neither the thickness nor the resistivity of a highly resistive layer embedded in better conducting surroundings may be determined but only the product of the two, is very annoying in many contexts of practical application. In many cases highly resistive layers of dry sand and gravel are underlain by either wet and better conducting layers of sand and gravel or by low resistivity clays. In these cases it becomes impossible to determine the amount of dry sand and gravel from DC-geoelectrical soundings alone when prospecting for raw materials, and in hydrogeological applications the depth to the ground water is often undetermined. Furthermore, DC-geoelectrical measurements do not allow a determination of the anisotropy of the ground.

Besides the galvanic method of DC-geoelectrical soundings there are a number of electromagnetic or inductive methods: SLINGRAM, AMT (audiomagnetotelluric) with or without controlled source, etc. The information gained from these methods is determined by the behaviour of induced currents in the ground and differs from the galvanic information. Measurements with the inductive methods are strongly influenced by the presence of good conductors, while poor conductors are more or less invisible. The depth to a good conductor is usually well determined from inductive methods.

Though the galvanic and inductive methods are often applied in different prospecting situations they may also be combined in the same survey. This gives the possibility of a joint interpretation of the galvanic and inductive measurements, which in some instances is capable of resolving the high resistivity equivalence of the galvanic methods (Jupp & Vozoff 1975; Jepsen 1977). Galvanic methods often determine the thickness of the overburden overlying a high resistivity layer, and the inductive methods can determine the depth to the good conductor underlying the high resistivity layer, if it is not shielded by surface near good conductors. Thus the thickness – and thereby also the resistivity – of the high resistivity layer may be determined from a combined use of galvanic and inductive measurements.

In the AC-geoelectrical sounding method an alternating current (AC) source is applied to a grounded electrical dipole of finite length at a number of different frequencies, and the potential difference, ΔV, between the endpoints of the receiver dipole is measured. The method is thus a combined one. Galvanic current is put into the ground by the current electrodes and the use of AC current gives an inductive contribution to the fields (Sørensen *et al.* 1979; Sørensen 1981; Christensen 1985).

Analogous to the DC geoelectrical soundings the apparent resistivity is defined by

$$\rho_a(f) = K(Y) \cdot |\Delta V(f)/I| \quad (2)$$

where K(Y) is the same geometrical factor as would be used in the DC case, I is the amplitude of the current, and f is the frequency used. The apparent resistivity is plotted as a function of Y – the transmitter/receiver separation – in a double logarithmic coordinate system. Thus, instead of one curve of apparent resistivity, a curve for each frequency is obtained. For low frequencies and/or small transmitter-receiver separations the apparent resistivity will equal the DC value.

The theory of AC-geoelectrical soundings

The first necessity of the theoretical work is the calculation of electric and magnetic fields from a grounded electrical dipole of finite length carrying AC current assuming a plane parallel, horizontally stratified earth (Fig. 1). The layers are assumed to be homogeneous but anisotropy is allowed.

The theoretical problem of calculating electric and magnetic fields from a grounded electrical dipole of finite length was in principle solved many decades ago (Sommerfeld 1926; Foster 1933). The first formulations were naturally concentrated about the homogeneous halfspace model, since this is the only model for which analytical solutions exist, but expressions for two-layer earths were also found (Riordan & Sunde 1933). An extensive study of the responses of a multi-layer earth was done by Dey & Morrison (1973), and Wynn & Zonge (1975) take the effect of anisotropy into account when calculating the mutual coupling between grounded electrical dipoles. All of the previously mentioned studies were carried out with the purpose of finding adequate models for the calculation of the inductive coupling so as to enable a correction of IP measurements, where the inductive coupling almost always appeared. Only recently has it been suggested (Wynn & Zonge 1977) that the inductive coupling between the transmitter and receiver dipoles would contain useful information about the earth parameters. The principle of the AC-geoelectrical sounding method is specifically to make use of the full

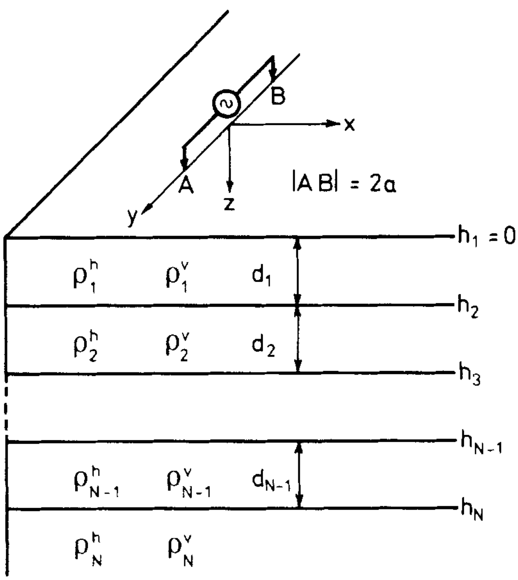

Fig. 1. The source and model configuration. ρ_i^v, ρ_i^h and d_i are the horizontal resistivity, the vertical resistivity, and the layer thickness of the i'th layer respectively.

response from an AC dipole source, i.e. both the galvanic and the inductive coupling between the transmitter and receiver.

In the solution to the theoretical problem, parts of the electric and magnetic fields are expressed as integrals involving Bessel functions of the first kind J_ν

$$E \sim \int_0^\infty k(p_i, \lambda)\, J_\nu(\lambda r)\, d\lambda \qquad (3)$$

where $k(p_i, \lambda)$ is a kernal function depending on the earth parameters. These integrals are conventional Hankel transforms and may be computed using the linear filter theory developed for that purpose. However, integrals appear which are not reducible to this form, but by applying the same logarithmic substitution for these integrals as for the ordinary Hankel transforms, a modified filter theory has been developed, which makes the computation as fast, accurate and easy as for the Hankel transforms (Sørensen 1979; Christensen 1983).

Without these newly developed possibilities of fast and reliable computations of electric and magnetic fields from a grounded electrical dipole of finite length carrying AC current, the interpretation of AC-geoelectrical soundings would be extremely time consuming.

This paper focuses primarily on the AC-geoelectrical sounding method as a geological prospecting tool, and no further details shall be given concerning the theoretical developments behind the AC-geoelectrical method.

Field equipment and measuring procedure

The field equipment consists of a transmitter unit and a receiver unit. The transmitter yields AC current at a number of different frequencies differing by a factor 2 in the range 1 Hz to 40 kHz. The sinusoidal signal is governed by a 10 MHz oscillating crystal. Maximum voltage is 180 V RMS and maximum current is 1 A RMS. The transmitter is operated in a constant current mode with an output current between 30 mA and 200 mA into a source dipole with a length equal to 10 m. Six standard frequencies are used: 76, 1221, 2441, 4882, 9765 and 19531 Hz. The lowest frequency of 76 Hz has been chosen sufficiently high to avoid IP effects and sufficiently low to be comparable to DC in most instances. This frequency contains almost

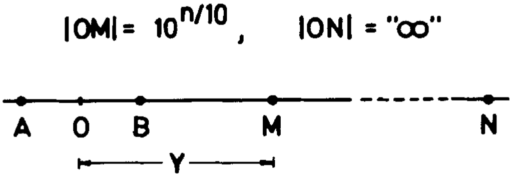

Fig. 2. The half-Schlumberger electrode configuration. A and B are current electrodes, M and N are potential electrodes. |OM| = Y is taken as the abscissa of the following model responses and data.

exclusively galvanic information. The five higher frequencies yield the inductive information under typical Danish geological conditions.

The receiver box uses a phase-locked technique of detection by referring the measured signal to an oscillating crystal matching the one in the transmitter box. A microprocessor controls the measurements and calculates accumulated mean value and standard deviation of the apparent resistivity with an automatic quality control of the measurements. Furthermore, the receiver is equipped with a thermo printer and a digital cassette tape unit for data storage and communicates with the field operator by means of two 16 key pads and two 32 character LCD's.

In principle any conventional DC electrode layout can be used for AC soundings, but in practice the directly induced coupling, which is a geometrical effect independent of the earth parameters, makes the popular Schlumberger and Wenner configurations unattractive. Dipole–dipole configurations with transmitter and receiver dipole lengths of approximately 10 m solve these problems but suffer from the well-known effects of near surface inhomogeneities. At present the most promising configuration is the half-Schlumberger array. In this configuration a current dipole with a length of 10 m remains fixed during the sounding, while one potential electrode is placed 'infinitely far away' (in practice 250–400 m) and the inner potential electrode is moved (Fig. 2). Measurements are made with a density of 10 per decade in the interval 6.31 m to 199.53 m (or more) and computations make exact account of the finite distance to the outermost potential electrode.

Typical model curves

In the following a number of typical curves of apparent resistivity shall be presented for the six standard frequencies mentioned earlier. It is cus-

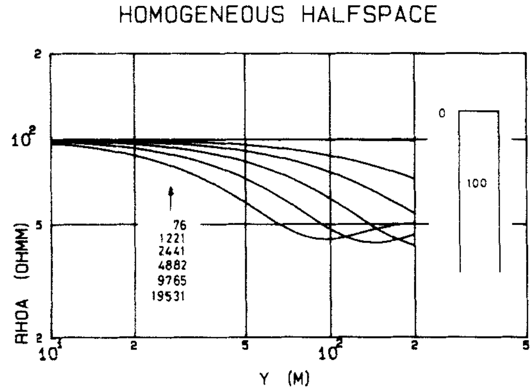

Fig. 3. Apparent resistivity curves for the six standard frequencies for a homogeneous halfspace.

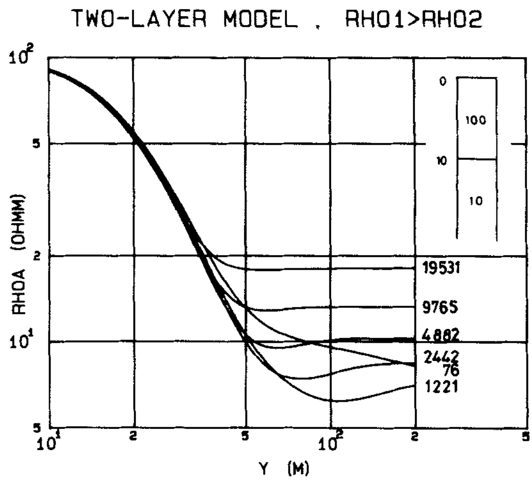

Fig. 5. Apparent resistivity curves for the six standard frequencies for a two-layer model of decreasing type.

tomary in DC-geoelectrics to present these curves in a normalized form, i.e. all models have unit resistivity and unit thickness in the top layer. This is not possible for AC-geoelectrical soundings once the frequencies have been chosen, because the only possibility of normalization lies in the constant product of conductivity and frequency.

Fig. 3 shows apparent resistivity curves for a homogeneous half-space with a resistivity of 100 ohm m. The 76 Hz curve is seen to be almost equal to the DC-curve, while the curves for the higher frequencies display lower values of apparent resistivity, approximating an asymptotic value equal to half the resistivity of the halfspace for large Y. The curves display the general behaviour of AC resistivity curves: all curves coincide for small Y and for increasing Y the departure from the DC-curve is greater the higher the frequency.

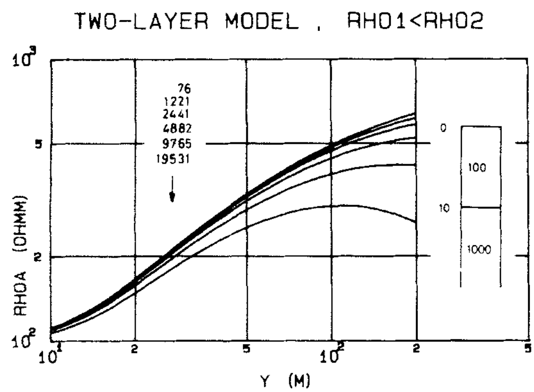

Fig. 4. Apparent resistivity curves for the six standard frequencies for a two-layer model of increasing type.

Figs. 4 and 5 show resistivity curves for two-layer models of increasing and decreasing type, respectively. For the increasing type the curves of the higher frequencies are seen to fall lower than the DC-curve (76 Hz). This is also the case in Fig. 5 for moderate Y, but the curves for the higher frequencies level out separated rather widely from one another and attain an asymptotic value thereby crossing the DC-curve. This is the AC-geoelectrical sounding method's particular version of the general behaviour of inductive methods: there is a strong reaction to the presence of good conductors, and the depth to the good conductor is well determined.

Similar patterns are observed with three layer curves of double increasing and double decreasing type.

Apparent resistivity curves for a three-layer maximum model are shown in Fig. 6. For small to moderate Y the curves are almost coincident, but for increasing Y the curves begin to differ, thereby showing the effect of the well conducting bottom layer. The difference between the apparent resistivity curves of the higher frequencies is indicative of the depth to the good conductor, as will be seen from an analysis of variances of the model parameters.

Interpretation and analysis of solutions

The interpretation of measured data is done by means of a computer program based on the well-

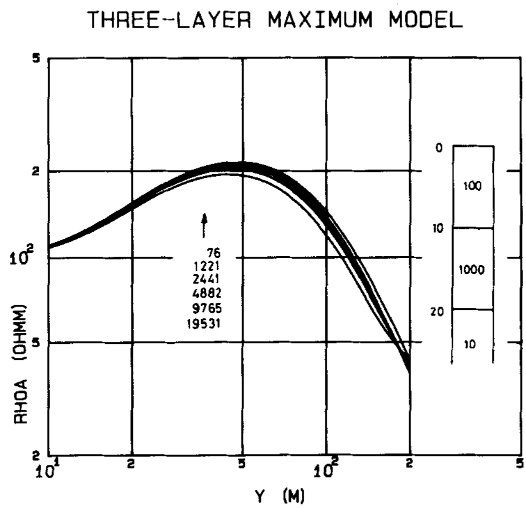

Fig. 6. Apparent resistivity curves for the six standard frequencies for a three-layer model of maximum type.

Table 1. An analysis of the uncertainty of the model parameters of the three-layer model from Fig. 6 in three different cases: a pure DC sounding, a DC sounding combined with one higher frequency, and an AC sounding with the six standard frequencies. It has been assumed that measurements were made in the interval from 10 m to 200 m with a density of 10 per decade and with a data error of 3%.

MODEL		STD. DEV. IN PCT.		
parameter	value	DC	DC+2441 Hz	6 std. freq.
ρ_1	100 Ωm	11	4	2
ρ_2	1000 Ωm	∞	15	4
ρ_3	10 Ωm	17	12	6
d_1	10 m	62	6	3
d_2	10 m	∞	16	4
h_2	10 m	62	6	3
h_3	20 m	∞	8	2

known iterative least squares procedure. The inherent non-linearity of the problem is somewhat reduced by working with the logarithm of data and the logarithm of model parameters. Coefficients of anisotropy are included in the model parameter space and a priori data may be treated in the inversion scheme thus making possible so-called 'elastic bounds' on the parameters (Jackson 1978, 1979; Jacobsen 1982).

The covariance matrix of the least squares problem is used for estimating the uncertainty of the model parameters when a certain data error is assumed. This linear analysis of variances may be used to demonstrate what is already indicated by the apparent resistivity curves: The AC-geoelectrical sounding method is capable of solving the high resistivity equivalence encountered in ordinary DC-geoelectrics. The variance of the model parameters of the three-layer model in Fig. 6 with a high resistivity equivalent second layer is shown in Table 1 in three different cases: (1) a DC sounding, (2) a combination of a DC sounding and one higher frequency of 2441 Hz, (3) a full AC-geoelectrical sounding using the six standard frequencies. In all three cases it has been assumed that measurements were made in the interval from 10 m to 200 m with a density of 10 per decade and with a data error of 3%. An ordinary DC sounding leaves the parameters of the second layer totally undetermined while the addition of just one higher frequency makes the parameters of the second layer determinable. The inclusion of all six standard frequencies gives a very good determination of the model parameters.

An example

As an illustration of AC-geoelectrical soundings I have chosen one made at Skejby Airfield just north of Aarhus in the autumn of 1984. Fig. 7 shows the measured data and the model curves of the interpreted model together with data and model curve for an ordinary DC geoelectrical sounding made at the same location. Good agreement is observed between the measured data and the model curves of the AC sounding, and the minor discrepancies between the AC and the DC models are due to the fact that the DC sounding was made with the Schlumberger electrode configuration, while the AC sounding was performed with a half-Schlumberger array. Thus the earth volumes through which the main part of the current flows are not quite the same for the two soundings, and departures from one-dimensionality will appear as model discrepancies.

Conclusion

The AC-geoelectrical sounding method is a promising new prospecting tool for general geological investigation of the topmost 100 m of the earth. In the prospecting for raw materials the method will be well suited for finding and estimating the volume

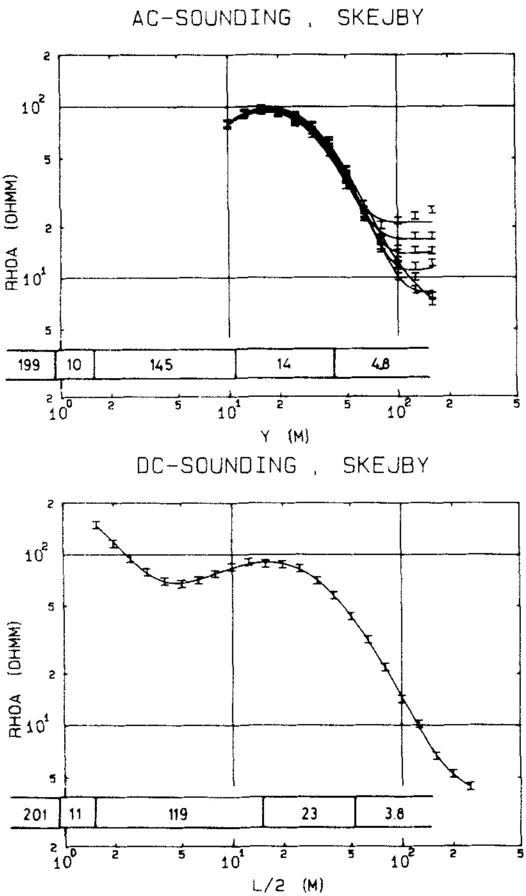

Fig. 7. An interpretation of an AC-geoelectrical sounding together with an interpretation of an ordinary DC-geoelectrical sounding in the Schlumberger configuration made at the same location in Skejby. Data for the AC-geoelectrical sounding have been recorded in the interval from 10 m to 200 m with a density of 10 per decade. The parameters of the topmost two layers of the AC model have been taken from the DC interpretation.

of sand and gravel deposits, which in Denmark are often underlain by well-conducting clays. For hydrogeological surveys the method will be an effective tool in the location and depth estimation of salt-water fronts.

The main asset of the method is that it is a combined one which in the same measuring procedure gives both galvanic and inductive information. The inductive contribution to the measurements of the AC-geoelectrical sounding method makes it possible to find the depth to a good conductor, thus resolving the well known high resistivity equivalence of the DC-soundings.

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