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Magnetic measurements in electrical prospecting by resistivity methods

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Abstract

The electrical resistivity and induced polarization (IP) methods are widely used in geological mapping, prospecting and exploration of mineral deposits, engineering geology, hydrogeology, archaeology, and geotechnical and environmental applications. Historically, these methods have formed the basis of the electrical prospecting technique. In these methods, a DC or low-frequency AC electrical current is introduced into the earth through a grounded transmitter line. The measured quantity is the electric field. However, if the earth's resistivity or chargeability changes horizontally, this change gives rise to an anomalous magnetic field, which is studied by the magnetometric resistivity (MMR) and magnetic induced polarization (MIP) methods, respectively. Along with advantages, some shortcomings are inherent in the MMR and MIP techniques. Apparently, the main drawback of these methods is that the magnetic fields of both the transmitter line wire and ground electrodes on the surface are several orders of magnitude greater than the anomalous magnetic field response. This introduces a significant "noise" to magnetic-resistivity data. We investigate the potential of using a circular electric dipole (CED) in magnetometric resistivity techniques. It has been found that the application of a CED, instead of a conventional transmitter line, dramatically enhances the signal-to-noise ratio.

Keywords: electrical prospecting; resistivity methods; magnetic field; DC; MMR; MIP; circular electric dipole

Introduction

Resistivity methods (electrical profiling, vertical and dipole electrical sounding) and induced polarization (IP) methods have found wide application in geological mapping, prospecting and exploration of mineral deposits, engineering geology, hydrogeology, geotechnical problems, archeology, and environmental applications. Historically, they have formed the basis of the modern electrical prospecting technique.

As a rule, in these methods, a low-frequency DC or AC electric current is introduced into the earth using a grounded line (*AB*) (Fig. 1). The electric field and hence current distribution in the earth depends on the length of the line and the electrical resistivity distribution. The measured parameter is the electric field, which in practice is the potential difference between the electrodes of the grounded receiver line (*MN*). In the resistivity methods, the electric field is measured during current passage, and in the IP method, it is measured after the current is turned off (in pauses between current pulses). In the frequency-domain IP method, the amplitude and/or phase of the potential difference between the receiving electrodes is measured at one or several frequencies (Sumner, 1976); in the INFAZ VP method, the phase difference is measured at two frequencies (Kulikov and Shemyakin, 1978). Abroad the IP method involving measurements at several frequencies is known as the spectral induced polarization (SIP) method (Reynolds, 2011) or the spectral IP method. However, the currents flowing in the earth produce not only an electric field, but also a magnetic field. On the surface of a horizontally layered earth, the vertical component of the magnetic field of these currents is equal to zero. The horizontal component is not zero but does not depend on the vertical distribution of electrical conductivity and/or chargeability. If the earth's resistivity or chargeability changes horizontally, this change gives rise to an anomalous magnetic field, which is studied by the magnetic resistivity and induced polarization. These methods are used mainly abroad, where they are known, respectively, as the magnetometric resistivity (MMR) method (Edwards and Nabighian, 1991) and the magnetic induced polarization (MIP) method (Seigel, 1974).

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In the MMR and MIP methods, a magnetic field, or more often EMF, is measured in the receiver coil proportional to its rate of change. The horizontal magnetic-field component perpendicular to the line connecting the transmitter electrodes is usually recorded. Since the measurements are noncontact, these methods have an advantage over the traditional ones in cases where grounding of the receiving electrodes is difficult or impossible (arid regions, rocks, caving, loose rock, permafrost, etc.). Other advantages of the MMR and MIP methods are the possibility of studying bodies overlain by conducting sediments and the weak influence of near-surface inhomogeneities.

Magnetic-field anomalies result from the fact that the currents flowing in the earth are concentrated in areas of reduced resistivity or are expelled from areas of increased resistivity. Therefore, the MMR and MIP methods are particularly effective in searching and studying elongated bodies with a strike direction close to the line connecting the electrodes *A* and *B*. These are the so-called concentration type anomalies (Dentith and Mudge, 2014). In relative terms, their amplitude does not depend on the absolute values of the electrical parameters of the host medium and the anomaly-producing body, but only depends on their contrast.

MMR data are interpreted using a normalized parameter H_n that represents the ratio of the measured field H_{meas} to the normal field H_{norm} (calculated for a particular array, if necessary, based on topography): $H_n(\%) = (H_{\text{meas}}/H_{\text{norm}}) \times 100$. Values of H_n over 100% indicate an "excess" of current, i.e., the presence of a conducting "channel," and its values below 100% indicate a "deficit" of current, i.e., a body or a zone of increased resistivity.

Another parameter, MMR, is believed to provide better resolution. It is calculated by the formula: MMR $(\%) = 100 \times (H_{\text{meas}} - H_{\text{norm\_b}})/H_{\text{norm\_b}}$, where $H_{\text{norm\_b}}$ is the normal field calculated for some "basic" or "reference" point. Usually, the middle of the straight line connecting the transmitter electrodes is chosen as such a point.

Like any other methods, the MMR and MIP methods have not only advantages, but also advantages, which are rarely mentioned by those who "promote" or "propagate" these methods. Apparently, the main factor limiting the sensitivity of these methods is that, along with the anomalous field, on the surface there is a magnetic field that does not contain information on the medium being studied.

This field has several components. The first is the geomagnetic field, which exceeds the anomalous magnetic field by many orders of magnitude. Usually, this problem is solved by exciting the medium by a low-frequency alternating current and using an induction reception coil. The second component is the field of the wire connecting the transmitter electrodes, which in the context of this article can be called the primary field. In flat country, it is directed vertically. Its intensity is much higher than the vertical component of the anomalous field. Therefore, it is common to measure the horizontal component of the magnetic field or its derivative. And the final component is the "normal" ground field, which is directed horizontally. If the terrain is not flat, this must be taken into account when calculating the field of the wire and the normal field. In the calculation of the anomalous field, the errors in the determination of the geometry of the system are transformed into a "useful" signal, which is not such in fact. Since the anomalous field is much smaller than the field of the wire and the ground field, the error of the anomalous signal can be very large. This situation is similar to that in the study of frequency-dependent magnetic susceptibility (Kozhevnikov et al., 2014).

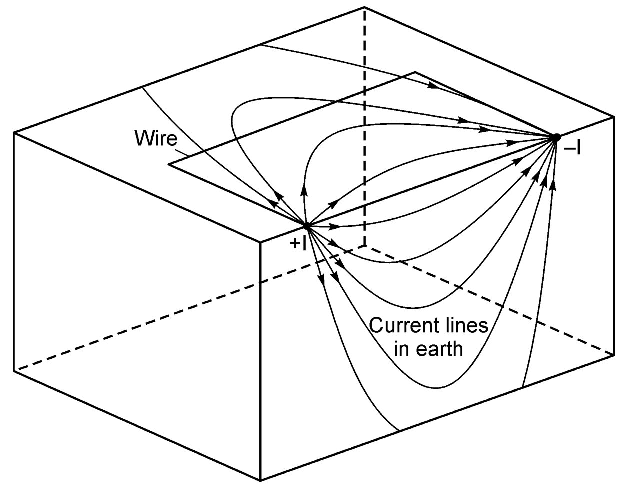

Fig. 1. General view of the array used in the MMR and MIP methods.

Usually, the above problem is noted in publications, but in practice everything depends on quantitative relationships. We propose a rather radical solution involving the use of a source that allows the introduction of the same current into the earth as the line, but does not have its own magnetic field. Such a source exists—it is a circular electric dipole (CED). CED theory and electrical prospecting methods, based on its application are described in many publications. Here we will only mention (Mogilatov and Zlobinsky, 2014) and the final work (Mogilatov, 2014). In these papers, the frequency-domain and transient modes are considered. The only exception is the early work (Mogilatov and Zlobinsky, 1995), which analyzes the constant electric field of a CED. In the present paper, the possibility of using a CED in direct current methods involving magnetic field measurements is investigated for the first time.

CED: definitions

By a circular electric dipole we mean an azimuthally uniform distribution of surface (in A/m) extraneous radial current grounded along circles of radii *a* and *b* used in theory (Fig. 2, left). For example, (Mogilatov, 1996):

$$j_r^{\text{ext}}(r) = \frac{I}{2\pi r} \cdot [U(r-b) - U(r-a)], \tag{1}$$

where $U(x)$ is a Heaviside function. Obviously, of the greatest practical importance is the case where $a \to 0$, i.e., the inner

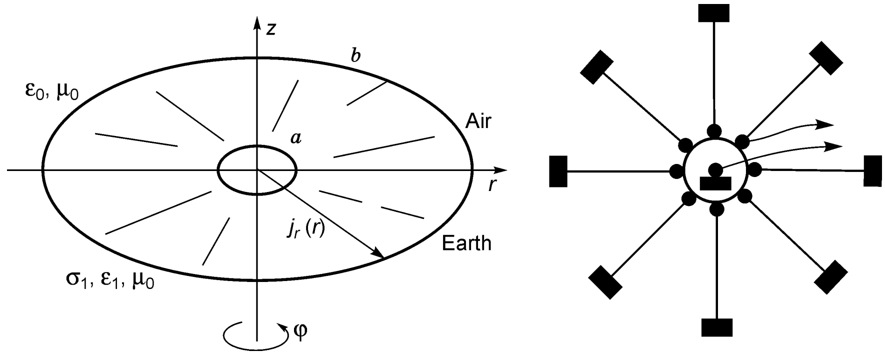

Fig. 2. Ideal and real circular electric dipoles.

circle "degenerates" into a central ground contact. In practice, a CED is implemented using a finite set of lines (Fig. 2, right).

Magnetic field of an ideal circular electric dipole

When a CED is located on the surface of a horizontally stratified conducting half-space, there is no magnetic field in the air and on the surface. We will show this using a cylindrical coordinate system. According to the integral representation of one of the Maxwell equations, the circulation of the vector **H** along any closed loop L is equal to the total current through an arbitrary surface S bounded by this loop:

$$\int_L \mathbf{H}\, d\mathbf{l} = \int_S \mathbf{j}\, d\mathbf{s}. \qquad (2)$$

From general considerations with the axial symmetry of the ideal source and medium taken into account, it follows that the magnetic field has only the component H_φ. Therefore, assuming that the loop L in (2) is a circumference of radius r coaxial with the CED, and as S is a circle bounded by this circumference, we obtain

$$2\pi r H_\varphi = \int_S \mathbf{j}\, d\mathbf{s}. \qquad (3)$$

Because there is current in the air, it follows that $H_\varphi = 0$. In other words, in the air and on the surface, the magnetic fields of the central ground, external ground, and the radial current are mutually compensated. We note that this conclusion remains valid in the case of an axisymmetric inhomogeneity coaxial with a CED. Obviously, to detect such an inhomogeneity, it is necessary to separate the centers of the CED and the inhomogeneity.

Thus, unlike the magnetic field of a loop or a line, the field of an ideal CED on the surface is zero. This is a unique feature of a CED and its value to the magnetometric resistivity (MMR) method. We can expect that the use of a CED will make it possible to measure low-level anomalous fields and hence increase the sensitivity and resolution of the resistivity method based on magnetic field measurement.

3D modeling of the field of a local body using an ideal CED as a source

Figure 3 shows a local body with dimensions of 200 × 100 × 80 m and an electrical resistivity of 5 Ohm·m. The body is located at a depth of 100 m in a host rock layer with a resistivity of 100 Ohm·m underlain by a conducting base rock. The medium and the body are excited by a circular electric dipole of 100 m radius with a current of 1 A.

Figure 4 shows maps of isolines for two magnetic induction components. The calculations were performed by the finite element method using the GeoPrep program (Persova et al., 2011). It is easy to see that the body is clearly visualized due to the absence of a direct source field. The maximum absolute values of the magnetic induction components (B_φ and B_z) are about 10^{-9} mT. The vertical component (B_z) gives a bipolar anomaly on the isoline map.

Once again, we emphasize that this result cannot be obtained in the case of using a grounded line as a source. Since the primary field of the line is three orders of magnitude larger than the anomalous field, insignificant errors in determining the parameters of the line and the measuring system lead to very large errors in determining the anomalous field.

Residual magnetic field of a real CED

As the above example shows (Fig. 4), the application of an ideal circular electric dipole basically solves the problem of a direct source field. However, real CEDs differ from the ideal one. A small array in the form of a metal disk or mesh with a central ground contact and with uniform ground at the edges can be close to ideal. However, if a large-sized source is needed, for its layout use some (usually eight) radial lines. Obviously, a CED with a finite number of radial lines has a residual (direct) magnetic field. We estimate the difference between a source composed of eight current lines and the ideal one.

Figure 5 shows the results of calculation of the residual magnetic field of an 8-beam CED along the profile along the Y coordinate at X = 300 m (the coordinate system and the CED are shown in Fig. 3*a*). The horizontal component of the residual field does not exceed 30×10^{-9} mT; the vertical

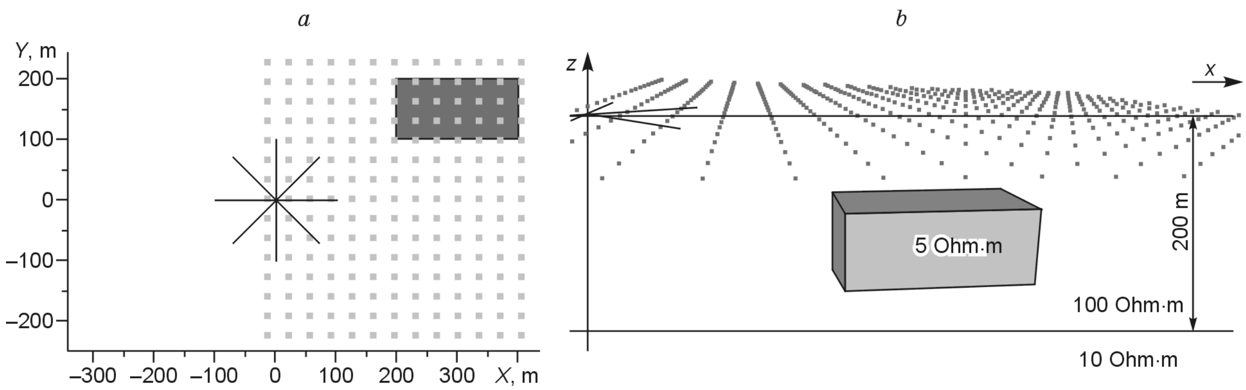

Fig. 3. 3D model: plan (*a*) and section (*b*).

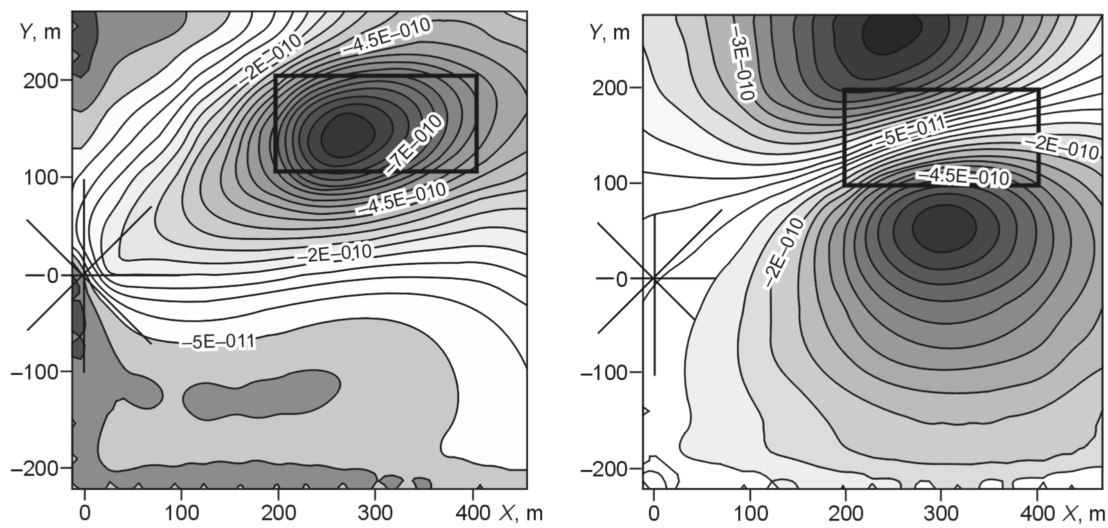

Fig. 4. Maps of isolines of B_φ (left) and B_z (right) over a local body from the results of three-dimensional modeling of the CED magnetic field. The isolines are in mT.

component is several orders of magnitude smaller, and its values cannot be shown on the scale of the graphs in Fig. 5.

Obviously, the residual magnetic field of a real CED depends not only on the number of lines forming it, but also on the errors arising from the layout of the lines on the ground. Suppose that one of the electrodes (the upper one in Fig. 4) is shifted right by 1 m. According to the calculations, in this case, the horizontal field remains practically the same as in the absence of error; the vertical field changes, but its absolute values remain small (Fig. 6).

Comparison of the CED and line fields

Obviously, to compare the capabilities of a CED and a grounded line as applied to magnetic (MMR, MIP) measurements, it is necessary to estimate the normal and anomalous magnetic fields of the grounded line.

The horizontal component of the normal field line can be estimated using the expression of the magnetic field of a point ground in the air (the coordinate origin at the ground point, DC) (Zaborovskii, 1963):

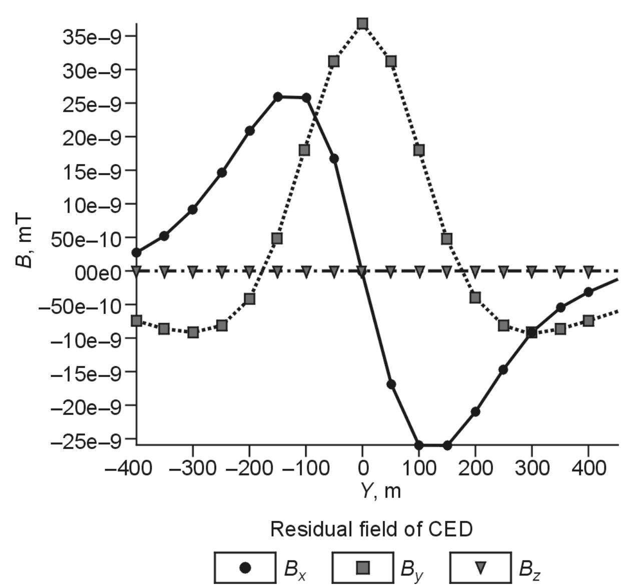

Fig. 5. Residual magnetic induction of the 8-beam CED along the line X = 300 m (Fig. 3). The radius of the CED is 100 m; the total current in the lines forming the CED is 1 A.

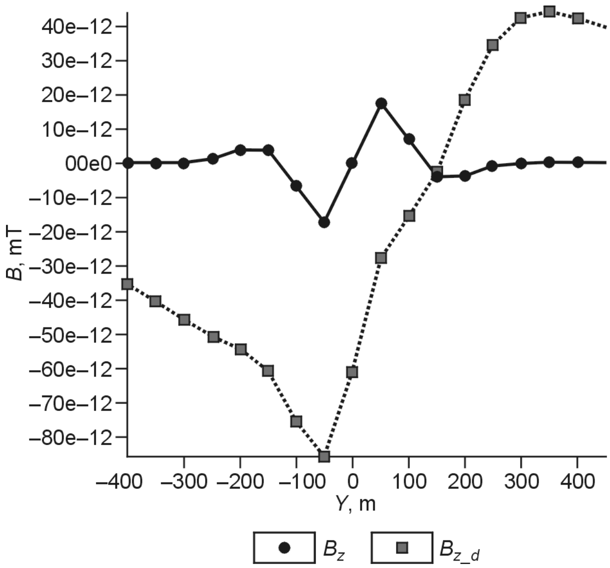

Fig. 6. Residual magnetic induction B_Z along the line X = 300 m of an 8-beam CED for the exact (B_z) and shifted (B_{z_d}) positions of one of the electrodes.

$$H_\varphi = \frac{I}{4\pi r}. \tag{4}$$

In the calculations, we will use an offset distance of 300 m and a current of 1 A. To evaluate the vertical component, we use the following formula for the magnetic field of an infinitely long straight wire, which is easily obtained from (2):

$$H_z = \frac{I}{2\pi r}. \tag{5}$$

To evaluate the anomalous magnetic field from a grounded electrical line, it is desirable to carry out a comprehensive three-dimensional simulation similar to that made above for a CED. However, it can be assumed that for the same body (at the same distance from the source), the anomalous magnetic field depends mainly on the current passing into the earth through the ground electrodes and to a lesser extent on the position of the ground electrodes. Therefore, taking into account the above results, we will use an estimated value of 10^{-9} mT for the vertical and horizontal components of the anomalous CED field and the line.

The magnetic field inductions (normalized to a source current of 1 A) produced by the ground electrodes, line, CED, and conducting inhomogeneity. For comparison, Table 1 also shows the geomagnetic field induction value typical of mid-latitudes.

As follows from Table 1, the application of an 8-beam CED leads to a 10-fold decrease in the direct horizontal field of the source and a 10,000-fold (!) decrease the direct vertical field. As in the case of a line source, when studying the horizontal component of the magnetic field with the aid of the CED, it is necessary to subtract the normal field from the observed field. However, the ratio of the anomalous field to the normal one is improved by an order of magnitude due to the use of the CED. When studying the vertical component, the normal CED field is approximately two orders of magnitude smaller than the anomalous one, whereas in the case of a line source, the normal field exceeds the anomalous by almost three orders of magnitude! Obviously, when using the CED, the signal-to-noise ratio can be increased by increasing the number of radial lines forming the CED.

Conclusions

In principle, the use of a circular electric dipole solves the main problem of the resistivity method with the measurement of the constant magnetic field. Although, in practice, a CED can only be implemented with an error, its use in the MMR method substantially increases the ratio of the anomalous field to the normal one. It should be noted, that everything said above about the MMR method remains valid for the MIP method.

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Table 1. Magnetic field induction

Magnetic field of the Earth (B_z), mT	Horizontal magnetic field of the ground (B_φ), mT	Vertical magnetic field of the line (B_z), mT	Horizontal magnetic field of the CED (B_φ), mT	Vertical magnetic field of the CED (B_z), mT	Anomalous magnetic field of the inhomogeneity (B_φ and B_z), mT
6×10^{-2}	300×10^{-9}	600×10^{-9}	30×10^{-9}	0.02×10^{-9}	1×10^{-9}

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