All zone apparent resistivity of magnetic field source wide field electromagnetic method: study in uniform half-space model

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Abstract. By constructing the obtaining apparent resistivity in underground uniform half-space model and combining the expression of apparent resistivity in magnetic field source wide field electromagnetic method, apparent resistivity in the model is calculated by using the dichotomy iterative method. Compared with solving the apparent resistivity by wide field electromagnetic method in a direct way, the difficulty of acquiring apparent resistivity is reduced, and a more suitable method for calculating apparent resistivity is found. Investigate the different apparent resistivities under the different frequency of electromagnetic field, and contrast and analysis electric field components, all time apparent resistivities and absolute values of relative errors of apparent resistivities of magnetic field source wide field electromagnetic method and controlled source audio-frequency magnetotelluric method to detect advantages of wide field electromagnetic method in calculation and accuracy in underground uniform half-space model.

Introduction

The wide field electromagnetic (EM) method has abandoned the method of taking the approximate value by Cagniard apparent resistivity formula about the component value of the EM field. It adopts a simplified apparent resistivity formula, break through the limitation of the "far region" and expands the observation depth. By measuring only one components of the EM field, the apparent resistivity can be obtained. Meng Qingxin and others have researched the definition solution and interpretation method of apparent resistivity of TEM field in wells and concluded that apparent resistivity is a comprehensive reflection of all electric bodies in the range of EM field action at whole times. It is feasible to identify the radial and blowing electrical properties of the whole space medium from the apparent resistivity results of the whole time period. The apparent resistivity of each channel can be used as a basis for inferring geoelectric structure information [1]. Liu Chunming and others have compared and analyzed the field exploration results of wide field EM method, audio magnetotelluric method and controlled source audio-frequency magnetotelluric method (CSAMT), and compared the experimental results on the same profile. It is found that wide field EM method has the advantages of high shallow resolution, high exploration depth, strong anti interference ability and high working efficiency [2]. Wang Qi and others have studied E-Ex [3-6] and E-E\( \phi \) [6-7] wide area EM method, and proved that wide area EM method has the advantage of strong resolution. He Jishan proposed wide field EM method [8-11], inheriting the advantages of CSAMT [12-13] using artificial field source which can overcome the randomness of natural field sources. Meantime, it breaks through the limit of remote measure, retains the higher-order term in the formula, extends the appropriate scope of artificial field source EM method and improves observer accuracy and efficiency of field work.

The fundamental theory

\[ E_\phi = -\mathbf{M}_\rho \left[ 3 - e^{ikr} \left( 3 + 3ikr - k^2r^2 \right) \right]/(4\pi r^4), \]

in the form, \( E_\phi \) is electric field component produced by vertical magnetic field, \( k \) is the wave number of EM waves. \(-ikr\) can be expressed as:

\[ -ikr = (-1 - p), \]
\[ p = \frac{r}{\delta}, \quad (3) \]

\( p \) is electrical distance. It is essentially the distance between the observation points and the source in terms of skin depth \( \delta \). \( \delta \) is skin depth, \( \omega \) angular frequency of EM field, \( \rho_a \) apparent resistivity of underground, \( r \) observation radius, and \( \mu \) permeability of medium. Because there is no big difference between the permeability of the non-ferromagnetic earth and the air’s. In this paper, we use permeability of vacuum \( (\mu_0 = 4\pi \times 10^{-7} \ \text{H/m}) \) as permeability of the non-ferromagnetic earth.

\[ \delta = (2\rho_a / \mu\omega)^{1/2}. \quad (4) \]

Fig.1 Underground uniform half-space model diagram

By magnetic source CSAMT, ungrounded loop wires is used as the field source. The Cagniard apparent resistivity is calculated by measuring the tangential components of the EM field which are orthogonal to each other in far region. In this paper, we choose the scalar CSAMT and the expression of its own far-range vertical magnetic field to conduct the research. For same coordinate system:

\[ E_\phi = \frac{-3M\rho_a}{(2\pi r^4)}, \quad (5) \]

\[ H_r = 3M\rho_a^{1/2}e^{4\pi r^4/(2\pi(\omega\mu)^{1/2})}, \quad (6) \]

CSAMT uses the Cagniard apparent resistivity expression to obtain the resistivity of the homogeneous earth or the non-uniform earth:

\[ \rho_a = \frac{1}{\omega\mu} \left| \frac{E_\phi}{H_r} \right|^2. \quad (7) \]

**Calculation and discussion**

First, verify and determine the electric field component produced by the vertical magnetic field source is a monotone function. In order to simplify the calculation method, the dichotomy method [14] is used to carry out the theoretical trial calculation: according to the expression of electric field component, iterating the apparent resistivity by dichotomy, the calculation of electric field component will gradually approach to the electric field component in the underground uniform half-space. Stop iteration when the error between the calculated value of electric field component and the value of electric field component in the model is less than that of the set precision of electric field component. A smaller precision value of electric field component can be set to obtain more accurate apparent resistivity value, thus reducing the relative error. In the uniform half-space model, the absolute value of the relative error of the iterative value of apparent resistivity obtained by the wide field EM method is not more than 0.1% in the homogeneous half-space. The points of red, orange, green, blue and purple curves are the iterative values of the electric field components generated by the iterative magnetic field at different frequencies of the EM field, respectively, when the apparent resistivity of the underground uniform half-space is 10Ω.m, 100Ω.m, 1000Ω.m, 10000Ω.m and 100000Ω.m, at different frequencies of the EM field. The iterative values of apparent resistivities and the absolute
values of relative errors of apparent resistivities obtained by dichotomy (for the ease of analysis, we choose the absolute values of relative error to study the relative errors).

Fig.2 Iterated values of $E\varphi$

Fig.3 Apparent resistivity by wide field EM method

Fig.4 Relative error of wide EM apparent resistivity

Fig.5 Iterated values of $E\varphi$ by CSAMT

Fig.6 Apparent resistivity by CSAMT

Fig.7 Relative error of CSAMT apparent resistivity

Based on the dichotomy principle, in the underground uniform half-space model, when the iterative value of electric field component is the same, the variation trend of the curve of the all time apparent resistivity obtained by wide field EM method is basically the same. All of the relative errors of apparent resistivities are small and in agreement at the whole frequency. In the apparent resistivity curve obtained by CSAMT, the smaller the apparent resistivity value, the more serious the distortion occurs in the non-distant region, and the greater the relative error of apparent resistivity will be.

The wide field EM method is not affected by the apparent resistivity and the frequency of EM field. When the frequency of EM field is 10Hz, it suggests that the apparent resistivity obtained by CSAMT method is accurate only in the far region where the frequency of EM field is very weak. According to the absolute value images of the relative error of apparent resistivity, it is obvious that the smaller the apparent resistivity in the underground uniform half space, the greater the relative error of apparent resistivity will be. It shows that the larger apparent resistivity is, under the condition of the same precision value of EM field component, the smaller relative error.

And the iteration of dichotomy can make the relative error curves of apparent resistivity of CSAMT method to be "multistage", especially when the apparent resistivity is 100000Ω/m in underground uniform half space. By observing the variation law of relative error curve of apparent resistivity.
resistivity under different apparent resistivity, it is found that the greater the apparent resistivity value is, the "multistage" more obvious, but all values of the relative error curves give significant reduction. If the precision value of EM field component is reduced, that means increasing the precision and the relative error curve will be more smooth, such as the red curve.

Conclusions

(1) The magnetic field source wide field electromagnetic method can obtain the unique apparent resistivity value in the whole region under the different frequency of the electromagnetic field.
(2) The iterative method is easier to solve the apparent resistivity of wide field electromagnetic method than directly calculating the wide field electromagnetic apparent resistivity.
(3) In the underground uniform half space, when the precision of the electric field component is the same, the appropriate frequency range of wide field EM method is wider than the CSAMT, and keeps the obvious advantage in the precision: the apparent resistivity can be obtained at the whole frequency of the EM field, the relative error of the apparent resistivity is quite small and basically consistent.

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