Research on Airborne Electromagnetic Whole-area Apparent Resistivity Imaging Algorithm in the Detection of Goaf in Rail Transit

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Abstract. Depth apparent resistivity imaging is an important process of data processing and analysis in the aviation transient electromagnetic method. It can provide reference value of conductor depth, vertical extension, and other information, and can accurately provide the measurement of each aviation transient electromagnetic measurement system. The structural section of the apparent conductivity of the one-dimensional layered medium on the line. As an advanced geophysical exploration technology, the aerial transient electromagnetic method has been applied significantly in the exploration of polymetallic minerals abroad in recent years. In this paper, based on the theory of ground-to-air transient electromagnetic method with multiple radiation sources, a corresponding multi-component global apparent resistivity definition method is established. The advantages of using the magnetic field strength to define the global apparent resistivity of the multi-radiation field source ground-air system are analysed. For each component of the magnetic field strength, respective global apparent resistivity algorithms are proposed to realize the multi-component, full-time, and full-space visual resistivity. The resistivity is calculated, and the influence of the offset on the global apparent resistivity is analysed. By adjusting the relative position of the source and the current direction and other parameters, the multi-radiation source transient electromagnetic ground-air system can not only strengthen the signal strength of different components, weaken random interference, but also better distinguish the location of underground anomalies.

Key words: Rail transit, goaf detection, aviation electromagnetic, resistivity imaging algorithm.

1. Introduction

Aviation Electromagnetic Method (AEM) is one of the commonly used measurement methods in aviation geophysical prospecting. It is widely used in various fields such as mineral resource exploration, rapid geological mapping, oil and gas exploration, groundwater, and environmental and engineering monitoring. The advantages of this method are high speed, low cost, and good accessibility. It can be applied to areas with complex terrain and geological conditions, such as desert
areas, mountainous areas, forests, swamps, and sea areas. It has an effect that is difficult to achieve by general exploration methods. The delivery vehicles of the aviation electromagnetic method are mainly fixed-wing aircraft and helicopters [1]. The application fields include metal mineral exploration, oil and gas resource exploration, environmental engineering, groundwater, and geothermal resources, etc. This method has high speed, large detection depth, high resolution ability, and low contrast. Advantages such as resistance to body sensitivity. The current domestic use is the VTEM aerial electromagnetic exploration system developed by Geotech, Canada. This system uses a coplanar centre loop vertical dipole transmitter and receiver device with the transmitter coil and the receiver coil coplanar.

The apparent resistivity depth imaging (RDI) is drawn by deconvolving the measured TEM data to quickly convert the electromagnetic response attenuation data into the resistivity depth profile information in the same sense. The RDI algorithm used for resistivity-depth conversion is based on Maxwell, Menu’s apparent resistivity conversion and TEM response principle of conductive half-space. This paper first systematically studies the frequency-domain airborne electromagnetic forward algorithm of the layered medium model under magnetic conditions, and realizes the solution of the kernel function of the integral equation of the commonly used frequency domain airborne electromagnetic response; then, the frequency domain airborne electromagnetic method is inverted for the strong magnetic region [2]. For the problem, the magnetic permeability factor is considered based on the traditional phase vector diagram, and the improved application is carried out to improve the accuracy of resistivity inversion under magnetic conditions.

2. Detection principle of transient electromagnetic method

The Nabothian sounding principle of the transient electromagnetic method can be clarified visually by the "smoke ring" effect. As shown in Figure 1. The late transient electromagnetic field is mainly produced by the induced current in the deep part, reflecting the electric distribution in the deep part [3]. Therefore, by observing and studying the changing laws of the earth's transient electromagnetic field over time, it is possible to detect the vertical changes of the earth's electrical properties.

\[ V(t) = -N \frac{d\phi(t)}{dt} = -q \frac{dB(t)}{dt} = -NS \cdot \frac{d\mu_0 I(t)}{dt} = -\frac{N^2 S}{I} \cdot \mu_0 \cdot \frac{dI(t)}{dt} \]  

(1)

Figure 1. Equivalent current loop

When a cylindrical solenoid coil with several turns of N and a cross-sectional area of S is placed in a time-varying magnetic field B(t), an induced electromotive force \( V(t) \) will be generated in the coil, which is:
Where $\phi(t)$ is the magnetic flux passing through the coil, $\mu_0$ is the vacuum permeability, $n$ is the coil density, $l$ is the solenoid length, and $I(t)$ is the induced current generated. The primary and secondary magnetic fields in the transient electromagnetic method can be reflected by the induced electromotive force of the coil [4].

3. Transient electromagnetic response analysis

3.1. Transient electromagnetic response of a line source on the isotropic horizontal layered earth

In the electromagnetic sounding theory, the distribution of the electromagnetic field under the uniform conductive half-space model is generally studied first, and then introduced into the layered model for solution. The solution of the transient electromagnetic field is to obtain the harmonic field by the Helmholtz equation in the frequency domain, and then use the Fourier transform technique to transfer the harmonic electromagnetic response in the frequency domain to the time domain. The transient electromagnetic field is a transitional field generated by exciting the earth with a step wave or other form of pulse current source [5]. The step wave is widely used because of its simple excitation and practicality. From the negative step current $i(t) = u(-t)$, its Fourier transform $I(\omega) = -1/i\omega$, and the harmonic electromagnetic field amount $E_1(\omega)$, $H_1(\omega)$ in the frequency domain, which are the frequency characteristics of a linear system, the relationship between the corresponding transient electromagnetic response $E(t)$, $H(t)$ under the excitation of the negative step current in the time domain is:

$$H(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} H_1(\omega) e^{-i\omega t} d\omega$$  \hspace{1cm} (3)$$

$$\frac{\partial H(t)}{\partial t} = \frac{1}{2\pi} \int_{-\infty}^{\infty} F\left[ \frac{\partial H(t)}{\partial t} \right] e^{-i\omega t} d\omega$$  \hspace{1cm} (4)$$

$$E(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E_1(\omega) e^{-i\omega t} d\omega$$  \hspace{1cm} (5)$$

Generally, can be written as

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E_1(\omega) e^{-i\omega t} d\omega$$  \hspace{1cm} (6)$$

Generally, $E(t)$ is not studied in the transient electromagnetic detection of magnetic sources.

3.2. Transient electromagnetic field formed on the surface by a large loop source on a uniform earth surface

The source of the circular loop above the uniform ground is shown in Figure 2, where $k_0$, $k_1$ is the wave number of the air and the underground half-space, respectively [6]. The expression of the vertical component of the harmonic field formed by the large loop source on the surface of the uniform ground is:

$$Hz(\omega) = \frac{3I_0}{k_1^2a^3} \left[ 1 - \left(1 + k_1a + \frac{1}{3} k_1^2 a^2 \right) e^{-k_1a} \right]$$  \hspace{1cm} (7)$$
Figure 2. Source map of the layered earth surface circle loop

In the actual measurement, the ground transient electromagnetic field is usually measured by measuring the induced electromotive force \( e(t) = \frac{\partial H(t)}{\partial t} \) in the receiving coil, so that:

\[
F[\frac{\partial H(t)}{\partial t}] = -i\omega H_x(\omega) = \frac{3I_0\rho_1}{\mu_0 a^3} \left[ 1 - (1 + k_1 a + \frac{1}{3} k_1^2 a^2) e^{-k_1 a} \right]
\]  

(8)

In order to change the frequency domain expression into the transient field expression, using the inverse Fourier transform relationship, the above formula is transformed into

\[
\frac{\partial H_z(t)}{\partial t} = \frac{3I_0\rho_1}{\mu_0 a^3} \left[ \Phi(u) - \sqrt{\frac{2}{\pi}} u (1 + \frac{u^2}{3}) e^{-u^2/2} \right] = \frac{3I_0\rho_1}{\mu_0 a^3} \bullet f(u)
\]  

(9)

In the formula, \( f(u) = \left[ \Phi(u) - \sqrt{\frac{2}{\pi}} u (1 + \frac{u^2}{3}) e^{-u^2/2} \right] \), \( u = a \frac{\mu_0 \omega}{2\rho_1} = \frac{2ma}{\pi \tau} \{ \tau \}_{m} = \sqrt{2\pi \times 10^7 \{ \rho \} \Omega \bullet m \{ \tau \}} \), \( \Phi(u) = \sqrt{\frac{2}{\pi}} \int_{0}^{u} \mu(t) e^{-t^2/2} dt \) are called probability integrals. When measuring the rate of change of magnetic induction intensity over time, it is obtained after sorting

\[
B_z(t) = \frac{u_0 I_0}{2a} \left[ 1 - \left( \frac{3}{u^2} \right) \Phi(u) - \frac{2}{\pi} \left( \frac{2}{\pi} \right) e^{(-u^2/2)} \right]
\]  

(10)

Through analytical calculations and numerical calculations such as Hankel integral and cosine integral, a set of thin lines shown in Figure 3 are obtained to represent the response curves of different resistivities.
Figure 3. Time characteristic curve of electromotive force of two layers of earth

In the late stage of the induced electromotive force $\varepsilon(t) \propto t^{-2/5}$, the response curve on the double logarithmic coordinate is a 68.2° descending straight line [7]. The greater the resistivity, the shorter the early and mid-term periods, and the greater the amplitude, the smaller the resistivity, the longer the early and mid-term periods.

4. Experimental detection

The model parameters are as follows: the length of source 1 and source 2 are both 1000 m, and the current direction is as shown in the figure. As shown by the arrow, the angle between the two sources is 30°, the current is 500A, the observation point is at a flying height of 100m, and the offset from source 1 is 500m. The corresponding coordinate in the x1y1z1 coordinate system is (300m, 400m, -100m), the resistivity of the first layer of the two-layer model $\rho_1 = 100\Omega m$, layer thickness $h_1 = 20m$, change the resistivity of the second layer $\rho_2 = 2, 5, 10, 30, 80, 200, 800 \Omega m$. It can not only gradually approach the first and last layer resistivity of the model in the early and late stages, but also can reflect the complete gradual smoothly [8]. Changes in electrical information out of the model. In order to illustrate the influence of offset on the global apparent resistivity of the multi-radiation source ground-air system, the following model is designed: the length of source 1 and source 2 are both 1000m, the direction of current is shown by the arrow in the figure, and the angle between the two sources It is 30°, the current is 500A, the observation point is located at the flight height of 100m, and the offsets from the source 1 are 500m, 1500m, 3000m and 5000m, respectively. The corresponding coordinates in the x1y1z1 coordinate system are (300m, 400m, -100m), (1060m, 1060m, -100m), (2121m, 2121m, -100m) and (3000m, 4000m, -100m), the resistivity of the three-layer model $\rho_1 = 500\Omega m$, $\rho_2 = 100\Omega m$, $\rho_3 = 500\Omega m$, $h_1 = 800m$, $h_2 = 800m$. It can be seen from Figure 4 that the global apparent resistivity definition method is applicable to both large and small offsets. The curves can completely and gradually reflect the changes in electrical information in the ground. They are approaching in the early and late stages respectively [9]. Based on the resistivity of the first layer and the bottom layer of the model, the problem of the apparent resistivity definition distance of the ground-air system with multiple radiation sources is solved, and the difference of the apparent resistivity curve of each component can be seen by comparison. The difference is small.
5. Conclusion
Aiming at the problem of strong magnetic regions, the classic apparent resistivity conversion method—the shortcomings of the phase vector method is discussed. Based on the traditional two-dimensional phase vector diagram, the calculation of the permeability parameter is added and drawn into different resistivity, Three-dimensional phase vector diagrams with different relative magnetic permeability and different flying heights, and then slice this three-dimensional graph according to the aircraft flying height, you can get a two-dimensional phase vector diagram with resistivity and permeability as parameters at a certain altitude. Thus, the values of apparent resistivity and apparent relative permeability corresponding to the real and imaginary components of the measured magnetic field can be obtained by bivariate interpolation. For strong magnetic regions, the accuracy of apparent resistivity inversion can be improved, and it is beneficial to the analysis of the physical properties of underground geological bodies.

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