Study on the Anisotropy of Formation Resistivity by Dual Controlled-source Electromagnetic Sounding

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Abstract. We proposed a method to obtain the anisotropy of formation resistivity by dual controlled-source electromagnetic sounding. The two field sources are arranged in two orthogonal directions outside the measuring area: the two grounded dipole sources excite two uncorrelated signals current step by step alternately, and record the current into time series; At sounding station of survey area, the orthogonal horizontal electric field response signals or the vertical magnetic field response signals were recorded into time series; according to the recorded current time series, as well as the time series of electromagnetic response signal, and the parameters of working layouts such as transceiver distance and so on, the whole zone apparent resistivity of the sounding station were calculated by circular cross-correlation system identification method, and then the anisotropy coefficient of the formation resistivity was calculated according to the whole zone apparent resistivity. This method has the advantages of fewer observation components, simple processing, strong anti-interference ability, and high working efficiency.

1. Introduction

The stratum structure under the surface has complex three-dimensional characteristics and obvious anisotropic characteristics. With the development of geophysical exploration technology, more and more attention has been paid to the study of formation anisotropy. The anisotropy of the shallow strata can be studied by using two orthogonal DC sounding sections. However, there are few methods to accurately obtain the anisotropy of deep earth resistivity. In the field of electromagnetic prospecting, the anisotropic characteristics of underground geological bodies can be obtained by observing electromagnetic field components on the surface, which can provide technical parameters for fine inversion of electromagnetic sounding data. Five-component magnetotelluric sounding (MT, AMT) estimates two orthogonal electrical principal axis apparent resistivity by observing the orthogonal horizontal electric field (Ex, Ey), horizontal magnetic field (Hx, Hy) and vertical magnetic field component (Hz), which can be used to analyze the anisotropic characteristics of earth resistivity. However, due to the weak natural field signal, the estimation accuracy at some frequency points is not enough.

In addition, the existing artificial source electromagnetic sounding methods need to use multiple field sources or controllable tensor source electromagnetic sounding worked in the frequency domain to acquire the anisotropic characteristics of ground resistivity. The processing process is complex, the work efficiency is low, and the anti-interference ability is not strong. Especially in the mining area, it is difficult to collect high-quality data.
In this paper, a dual-field source electromagnetic sounding method is proposed to obtain formation resistivity anisotropy.

2. Method

Outside the survey area, two field sources are arranged along the two directions of the orthogonal x-axis and y-axis: source X and source Y; two field sources work at the same time and emit two uncorrelated signals step by step alternately; source Y sends the second signal when source X transmits the first signal; source Y sends the first signal when source X transmits the second signal; The first signal can be a single-frequency square-wave signal and the second signal is a pseudo-random signal of inverse repeat m-sequence. The frequency of the single-frequency square-wave signal is higher than the lowest frequency of the pseudo-random signal of inverse repeat m-sequence. Record the time series $I_x(t)$, $I_y(t)$ of current emitted by source X, and source Y.

In the measuring area, the orthogonal horizontal electric field response signals $E_x$ and $E_y$, and/or the vertical magnetic field response signals $H_z$ at each measuring point are collected and recorded as time series $E_x(t)$ and $E_y(t)$, and/or $H_z(t)$.

According to the recorded current time series, working layout parameters and electromagnetic field response signal time series, the apparent resistivity of the stratum in the survey area is obtained by circular cross-correlation method, and the resistivity anisotropy coefficient is calculated.

The current time series $I_x(t)$ emitted by source X is matched with $E_x(t)$ or $H_z(t)$ time series, and the current time series $I_y(t)$ emitted by source Y is matched with $E_y(t)$ or $H_z(t)$ time series. The frequency response of the strata in the survey area is obtained by the circular cross-correlation method. The specific calculation method refers to patent literature [1].

According to the frequency response of the stratum in the survey area and the parameters of the working device, the excitation current and the time series of the received electromagnetic field components, the apparent resistivity of the stratum in the survey area can be obtained by iteration method.

The anisotropy coefficients are calculated according to the apparent resistivity ratio of two directions obtained by the dual-field source electromagnetic sounding method.

$$
\lambda = \frac{\rho_x(w_i)}{\rho_y(w_i)}
$$

(1)

Figure 1. Schematic Diagram of Working Arrangement of Dual Field Source Electromagnetic Sounding Method
This workflow is divided into six basic steps:

1. Outside the survey area, two field sources, source X and source Y, are arranged along the orthogonal x-axis and y-axis.

2. The two field sources alternately excited two uncorrelated signals step by step.

3. Record the current into time series \( I_x(t) \), \( I_y(t) \) emitted by source X and source Y.

4. In the measuring area, the orthogonal electric field response signals \( E_x \) and \( E_y \) on each measuring point are collected, and / or the vertical magnetic field response signals \( H_z \) on each measuring point are collected, and the collected response signals are recorded as time series \( E_x(t) \) and \( E_y(t) \), and / or \( H_z(t) \).

5. According to the current time series, working device parameters and electromagnetic field response signal time series, the apparent resistivity of the whole area of the stratum in the survey area is obtained by the method of cyclic cross correlation.

6. Calculate the anisotropic coefficient of formation resistivity in the survey area according to the whole zone apparent resistivity of the stratum in the survey area.

**Figure 2.** The workflow of dual-source CSEM for

In the observation, the distance between source X and the center of the measurement area is approximately equal to the distance between source Y and the center of the measurement area, and the distance between each field source and the center of the measurement area ranges from 4 km to 30 km.

### 3. Simulation calculation

Two signal sources are used to excite a known system model at the same time (formula 2) to simulate the electromagnetic response characteristics of the geoelectric system excited by two field sources. One signal waveform uses the pseudo-random signal of inverse repeat m sequence, and the other uses the single frequency square wave signal. The pseudo-random signal of inverse repeat m-sequence is generated by the 6-bit register, the shift clock frequency \( f_c = 4 \text{Hz} \), the sequence period is 63s, and the single frequency square wave frequency is 2Hz. Both of them are generated into time series with the sampling rate of \( F_s = 1000 \text{Hz} \). The simulation results show that changing the frequency band of pseudo-random signal and the frequency of single frequency square wave can make the two signal sources completely uncorrelated, that is, the correlation function sequence has a small value. For example, when the single frequency square wave frequency is 64Hz, 128Hz, or higher, the correlation function sequence of the pseudo-random signal generated with the above parameters is 0.

\[
H(s) = \frac{0.2909 + 1.5949s + 0.3418s^2}{0.3193 + 3.5228s + 5.5228s^2} \quad (2)
\]

The frequency response of two signals acting on the system is obtained by the circular cross-correlation method, as shown in Figure 3. The response of a wide-band system from 0.0159 Hz to 42 Hz is obtained by using a dual signal source excitation system model. The frequency response of 0.0159 Hz to 10Hz is identified by the 63s period inverse repeat m-sequence, while the frequency response of
2 Hz to 42 Hz is identified by a 2 Hz square wave. The identification results of the two signal waveforms are very consistent in this frequency band and have higher frequency resolution. If two signal sources are used as the excitation signals of two field sources as shown in Figure 1, and the vertical magnetic field or two orthogonal horizontal electric fields which are responded by the geoelectric system are observed, two orthogonal apparent resistivities of the whole zone can be obtained, which provides the possibility for the study of the anisotropy of the formation resistivity.

Figure 3. The frequency response of the system identified by two signal sources

4. Conclusions
The dual field source electromagnetic sounding method proposed in this paper uses the characteristics of the inverse repeated m sequence and the square wave signal which are not related to excite the geoelectric system at the same time and uses the two field sources to excite alternately step by step to obtain the apparent resistivity of different frequencies in two directions, which provides a technical advance for the study of the formation anisotropy. Because the power spectrum of the pseudo-random signal of the inverse repetitive m-sequence is linear, the frequency band is wide and not related to the power frequency interference, the method has strong anti-interference ability, high measurement accuracy, rich frequency points of the obtained apparent resistivity in the whole area, high resolution to the formation, and can improve the work efficiency. In addition, the method can simultaneously excite the field source from two orthogonal directions, which is more conducive to obtain the electromagnetic response of deep formation. It can be used in the electromagnetic exploration of land and sea.

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References
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