

A study of the frequency characteristics of downhole penetration by Audio electric perspective method

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Abstract. There are many factors affecting the safe production of coal mines, and mine water damage is the most prominent one. In the field operation, we should find out the old air water, water-rich aquifer and geological structure of the mining face and its surroundings, so as to eliminate the hazards of mine water damage to the people's lives and properties. At present, there are many mature and effective methods for underground anomaly detection, and this paper adopts the audio electro-optical perspective method for early warning detection of mine water-bearing areas. First of all, through the reasoning research on the basic theory of electromagnetic field, the equivalent principle of low-frequency alternating current (AC) and direct current (DC) is deduced, which provides the theoretical basis for the research of audio electro-optical perspective; then, through the COMSOL simulation experiments, the penetration frequency characteristics of the downhole are investigated, and the optimal penetration frequency is found in different depths by comparing the strength and stability of the signals. The results of the study have promoted the significance for the improvement and development of the audio electro-penetration method, and have greater reference value for the prevention and control of water damage in coal mines.

Keywords: Audio electric perspective method; electric dipole; optimum frequency.

1. Introduction

With the increase in the depth of coal mining, the underground geological structure, especially the hydrogeological structure, is becoming more and more complex, and mine water hazards often plague mine safety and coal production [1]. The detection of water-rich anomalous area in front of the tunneling roadway by underground direct current method and transient electromagnetic method has achieved obvious results [2]. However, the detection of water-rich anomalous zone on the top (bottom) plate inside the coal mining face is still a difficult problem [3]. At present, there are many kinds of physical exploration methods can be used for mine anomalous water-rich zone detection [4], among which the electric method exploration is the most commonly used detection method, which utilizes the propagation characteristics of the electric field in the underground rock to detect the electrical properties and structure of the underground medium, and it is a non-destructive method, which can effectively detect the underground water, mineral resources, engineering geological conditions and so on. At present, electric exploration mainly includes artificial field source exploration and natural field source exploration, artificial field source exploration can be divided into DC electric exploration and AC electric exploration. DC electric method, has the advantages of simple operation, small amount of data calculation, but its anti-interference ability is poor, detection depth is not big; In contrast, AC electric method has strong penetration, detection depth, signal stability and other characteristics, but its data volume is huge, and the difficulty of data processing increases.

In foreign countries, Gao et al. in order to detect in the water-rich roof area, the use of a dipole device using the two-bit ETR method to determine the resistivity of water-rich areas, in order to stop the roof of the sudden water to provide a basis [5]. Su et al. in order to prevent the karst from entering the coal mine and causing serious coal mine disasters, used DCR technology coal mining process of fissure detection and developed a set of DCR observation system for actual coal mines, and the results show that the resistivity changes are obvious, and the location and movement of karst water can be better predicted [6]. Xie used DC bathymetry to establish a coal-rock rich-area identification model, predicted the degree of coal-rock region of the water-rich degree, and with the

subsequent borehole water influx data, and the results showed that the prediction results were highly consistent with the borehole water influx data^[7]. However, in general, in recent years, Japan and Europe and the United States have done less work in the application of mine electric method than China and Russia, which is related to their energy structure, and in recent years, Europe and the United States and Japan have mainly done research work in numerical simulation and instrumental research.

Domestically, as early as in the early 1990s, China began the research of the DC method, and in recent years, both the high-density DC method and the audio electro-optic fluoroscopy method have made great progress. Lu Jingjin et al. used the audio electro-permeability method to carry out physical simulation tests of water tanks and verified the accuracy of the audio electro-permeability method^[8]. Zhang Ruirui focused on analyzing the effect of audio-electric perspective on the detection of water-free structures in the working face, and proved that the use of audio-electric perspective can be used to detect the water-free structures on the roof plate in the working face through the analysis of examples^[9]. Liu used audio-electric perspective and mine high-density electric bathymetry two physical exploration methods corroborate each other, combined with the later drilling results, proved the accuracy of the audio-electric perspective method, and has a guiding significance for the water exploration and discharge in the air-sealed area^[10]. Zhang Haonan et al. pointed out that the DC resistivity method and the transient electromagnetic method have limited detection depth for aquifers, and there is a blind zone in the detection of water-richness of the roof plate of the ultra-wide working face, while the audio-electric perspective method has high reliability in the detection of water-richness of the roof plate of the ultra-wide working face, and it has a value of wide popularization and application^[11-12]. Li Zhilong et al. applied the audio-electric perspective method in the address exploration of coal mines, which fully proved that the audio-electric perspective method has high accuracy in the detection of geological structure and water-richness of coal seam roof, and it is worth to be popularized and used on a wide scale^[13-17]. In order to solve the problem of environmental influence of audio electro-perspective method, Zhang Jun et al. proposed a method to correct the interference of low-resistance body of the roadway surrounding rock for the audio electro-perspective data of mines, studied the principle and method of audio electro-perspective in mines, and verified the validity of the correction method through the analysis of the measured data, so as to improve the accuracy of the audio electro-perspective method^[18]. It can be seen that the current research on the audio electro-penetration method is mainly focused on the principle and feasibility of the program, and there is no in-depth study on the detailed penetration frequency characteristics.

For the research on the frequency characteristics of underground penetration of audio electro-optic see-through method, this paper, on the basis of the theoretical investigation of audio electro-optic see-through method, simulates the geological conditions and construction environment conditions of different mines, transmits low-frequency signals of different frequencies with the same current value, and compares the size of the received value, stability and other data under the same receiving conditions, to investigate the effect of penetration of different frequencies. Through the statistical comparison of the collected data to find out the penetration characteristics of different frequencies and the choice of transmitting frequency for different environments, to provide a theoretical basis for the frequency selection of the audio electro-telemetry method.

2. Principle analysis of AEPM

2.1 Low Frequency AC and DC Equivalence Principle

According to the knowledge related to electromagnetic field, the potential of time-varying electromagnetic field can be written as:

$$\begin{aligned}\vec{E} &= -\nabla\varphi - \frac{\partial}{\partial t}\vec{A} \\ \vec{B} &= \nabla \times \vec{A}\end{aligned}$$

Then the d'Alembert equation for φ and \vec{A} under the Lorenz norm is:

$$\begin{cases} \nabla^2 \vec{A} - \frac{1}{c^2} \frac{\partial^2 \vec{A}}{\partial t^2} = -\mu_0 \vec{J} \\ \nabla^2 \varphi - \frac{1}{c^2} \frac{\partial^2 \varphi}{\partial t^2} = -\frac{\rho}{\varepsilon_0} \end{cases}$$

Assuming a point of charge at the origin, the scalar potential d'Alembert equation above becomes:

$$\nabla^2 \varphi - \frac{1}{c^2} \frac{\partial^2 \varphi}{\partial t^2} = -\frac{1}{\varepsilon_0} Q(t) \delta(\vec{x})$$

Solving the above equation in the spherical coordinate system using the method of separated variables yields the solutions except the origin as:

$$\varphi(r, t) = \frac{f\left(t - \frac{r}{c}\right)}{r} + \frac{g\left(t + \frac{r}{c}\right)}{r}$$

For the solution at the origin is:

$$\varphi(r, t) = \frac{Q\left(t - \frac{r}{c}\right)}{4\pi\varepsilon_0 r}$$

Since the magnetic field is excited by a current element (analogous to a charge-excited electric field), and considering the superposition of fields there:

$$\begin{cases} \varphi(\vec{x}, t) = \int_V \frac{Q\left(\vec{x}', t - \frac{r}{c}\right)}{4\pi\varepsilon_0 r} dV' \\ \vec{A}(\vec{x}, t) = \int_V \frac{\mu_0}{4\pi} \frac{\vec{J}\left(\vec{x}', t - \frac{r}{c}\right)}{r} dV' \end{cases}$$

It is not the charge density $\varphi(\vec{x}, t)$ or $\vec{A}(\vec{x}, t)$ current density vector at the same time t that contributes to the potential or but the charge density value at an earlier time t . In other words, the effect of the charge density or current density vector on the electromagnetic field in space propagates at the speed of light c . In other words, the effect of the charge or current density vector on the electromagnetic field in space propagates through space at the speed of light c . Therefore, the electromagnetic field measured at the field point at time t is the result of the charge-current distribution. Therefore, the electromagnetic field measured at moment t at the field point is excited by the charge-current distribution at different moments.

In the full space electric field, for an electric dipole, there is:

$$\begin{aligned} \vec{p} &= Q\Delta\vec{l} \\ \vec{p} &= I\Delta\vec{l} = \int_V \vec{J}(\vec{x}') dV' \end{aligned}$$

The radiation of an alternating current dipole can be regarded as simple harmonic motion, and therefore the solution of the d'Alembert equation for the magnetic vector potential can be written as:

$$\vec{A}(\vec{x}) = \frac{\mu_0}{4\pi} \int_V \frac{\vec{J}(\vec{x}') e^{ikr}}{r} dV'$$

Therefore, the vector potential expression for the electromagnetic field of the electric dipole in spherical coordinates in the spherical coordinate system is given by:

$$\vec{A} = \vec{e}_R A_R + \vec{e}_\theta A_\theta + \vec{e}_\phi A_\phi$$

By Helmholtz's theorem, the vector magnetic potential \vec{A} satisfies:

$$\vec{B} = \nabla \times \vec{A} = \vec{e}_\phi \frac{\mu_0 I \Delta \vec{l} \sin \theta}{4\pi} \left(-\frac{i}{kR} + \frac{1}{k^2 R^2} \right) e^{ikR}$$

$$\vec{E} = \frac{i}{\omega \epsilon_0 \mu_0} \nabla \times \vec{B} = \vec{e}_R \vec{E}_R + \vec{e}_\theta \vec{E}_\theta + \vec{e}_\phi \vec{E}_\phi$$

At lower frequencies as well as smaller pole distances, this corresponds to near-field radiation, so that we have $|kR| \ll 1$, and further, under seemingly stable conditions, ignoring the displacement current, the above equation can be simplified to:

$$\begin{cases} E_R = \frac{1}{4\pi\epsilon_0} \frac{2p \cos \theta}{R^3} \\ E_\theta = \frac{1}{4\pi\epsilon_0} \frac{p \sin \theta}{R^3} \end{cases}$$

The above equation is in perfect agreement with the expression for the full-space electric field strength of a DC dipole, thus showing that it is possible to explain the field strength characteristics of low-frequency AC in terms of DC.

2.2 Principles of AEPM

Since all kinds of rock and coal seams have different resistivities, these different resistivities affect the distribution of the artificial electric field. AEPM is based on the theory of electric field distribution in the whole space, and for the uniform whole space, the electric field distribution generated by the point power source is characterized as follows:

$$\begin{cases} U_m = \frac{I\rho}{4\pi R} \\ E_m = \frac{-I\rho}{4\pi R^2} \\ J_m = \frac{I}{4\pi R^2} \end{cases} \quad (1)$$

In equation (1), U_m is the potential, unit mV; I is the strength of the supply current, unit mA; E_m is the electric field strength, unit N/C; J_m is the current density, unit A/m²; ρ is the uniform spatial medium resistivity, unit $\Omega\cdot\text{m}$; R is the distance from the observation point to the point power supply, unit m.

From equation (1), it can be seen that when an anomalous resistivity occurs in underground rock or coal seams, it will change the distribution of the electric field; the larger the resistivity change of the anomaly, the larger the change in the amplitude of the electric field affected. Meanwhile, for the local anomalous conductor downhole, when the current flows through the conducting anomalous body, this anomalous body can also be approximated as an anomaly of the electric dipole with the expression:

$$U = \frac{\rho_0 I}{4\pi} \left(\frac{1}{r_2} - \frac{1}{r_1} \right) = \frac{\rho_0 I}{2\pi} \frac{r_2 - r_1}{r_2 r_1} \quad (2)$$

In equation (2), ρ_0 is the resistivity of the anomalous body, I is the current flowing through the anomalous body, r_1 , r_2 is the distance from the point power source to the electric dipole, it can be seen that the anomalous curve is an axisymmetric curve with the axis of symmetry of the extension of the line connecting the point power source A with the geologic body. The anomaly amplitude and width are related to the size of the anomaly body, the electrical difference of the surrounding rock and the distance from the transceiver surface. The larger the range of the anomaly body, the larger the electrical difference with the surrounding rock, the smaller the distance from the transceiver, the larger the anomaly amplitude; conversely, the smaller.

According to this principle, when water is contained in a uniform rock or coal seam, the resistivity is lower due to the better conductivity of water, which further reduces the resistivity value of the water-bearing location of the rock or coal seam, which reacts to the electric field as a

reduction in the electric field strength, and then the existence as well as the scope and scale of the underground anomalous area can be deduced based on the magnitude and range of changes in the measured data. Figure 1 shows that when there is a water-rich area under the ground, the measured potential change curve, according to the curve can be seen in the location of the anomalous area and the amount of water content, the greater the change in the peak potential, indicating that the water-rich area of the water content of the larger.

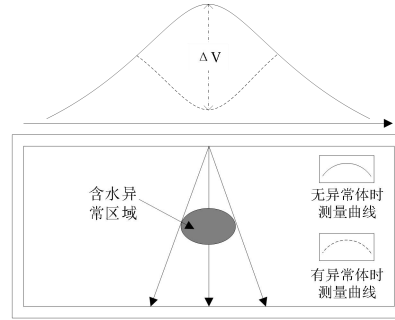


Fig. 1 Schematic diagram of potential simulation of water-bearing anomalous area

AEPM has a variety of construction methods during construction, such as monopole-dipole device, dipole-dipole device, etc. However, in actual construction, the monopole-dipole device with simple construction method, sensitive abnormality detection and strong signal penetration is often selected, as shown in Figure 2. This device form will transmit electrodes and measurement electrodes were arranged in the coal mine working face on both sides of the roadway, that is, in one side of the roadway arrangement of the power supply point pole, in the other side of the roadway in the corresponding fan-shaped range of reception. During measurement, the power supply electrodes are moved sequentially along the roadway to ensure that the receiving sectors of adjacent power supply electrodes have sufficient overlap to complete the measurement of a single side of the roadway; then the transmitting and receiving roadways are interchanged, and the working face is probed point by point sequentially to further increase the number of observation coverage and complete the double-roadway measurement.

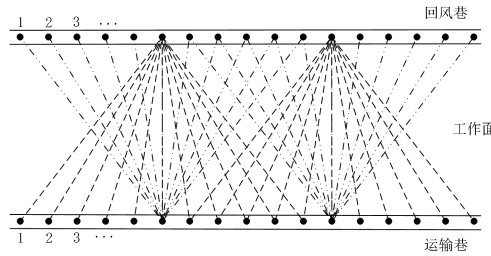


Fig. 2 Schematic diagram of the AEPM data acquisition methodology

3. Downhole Penetration Frequency Simulation

In order to find the optimal AEPM frequency, simulation experiments were carried out using COMSOL simulation software. A two-dimensional physical model is set up in the simulation software as shown in Fig. 3, and in order to simulate the underground environment of the real mine, the two-dimensional model is divided into three layers, the first and the third layers are the soil layer, which simulates the soil environment of the earth, and the second layer is the coal-rock layer, which contains a water-bearing region with abnormal resistivity. A point is taken at each of the upper and lower positions of the model and set as the power supply electrode A electric and probe B point.

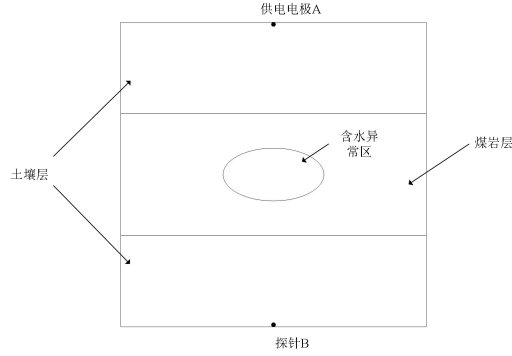


Fig. 3 Schematic diagram of physical simulation model

Next, the model is created, this experiment in order to explore the optimal frequency at different depths, in the software were created specifications for 100m * 100m, 200m * 200m, 400m * 400m two-dimensional graphics, the entire area is divided into three layers, the upper, middle and lower three layers, set the ratio of its thickness is 3:4:3. in the upper and lower layers filled with a customized soil material, set the resistivity of the soil, relative dielectric constant and other material properties; in the middle layer filled with coal bed material and set the coal bed properties; at the same time, set an elliptical water resistivity anomaly area and set the anomaly area attributes, relative dielectric constant and other material properties; fill in the middle layer with coal bed material and set coal bed properties, and at the same time, set an elliptical water-bearing resistivity anomaly in it and set anomaly properties.

Add a frequency-adjustable current source at the power supply electrode A, which is responsible for transmitting low-frequency current signals with different frequencies. In the selection of current signals, in order to ensure that the values of the current signals are the same each time, each experiment transmits current signals with different frequencies at the same current value, so the simulation experiment adopts a bipolar square-wave signal as the transmitting electrode, and its expression is:

$$A = \begin{cases} 10 \left(\frac{k}{f} < t < \frac{2k+1}{f} \right) \\ -10 \left(\frac{2k+1}{f} < t < \frac{k+1}{f} \right) \end{cases} (k \in \mathbb{Z})$$

where f is the frequency of the square wave signal in Hz.

According to equation (1), the smaller the distance R from the probe point to the power supply electrode, the larger the value of the electric field obtained, and the more obvious the phenomenon is, so the probe B should be placed directly under the power supply electrode A. The probe B is responsible for recording the value of the electric field strength at the point B, and judging the magnitude of the signal strength at the point B based on the value of the field strength. After setting the relevant parameters, the relevant charge conservation conditions, electric insulation conditions and boundary conditions are set according to the distribution of the electric field, and the boundary conditions are automatically satisfied in the software, which can be automatically loaded according to different situations.

After completing the above work, the model is solved for transients, and the auxiliary scan is selected in the research expansion option to scan the frequency in the current source A. Because it is a low-frequency alternating current (AC), its frequency should not be too high, but it should not be too low either, so that there is no significance of AC. So the frequency is set to vary from 10Hz to 100Hz in steps of 1Hz, and then the value in the probe B is extracted, and the size of the value in the probe B is compared with different frequencies to determine the best penetration frequency under the preset conditions. Then the model was modified by setting the depth to 200m and 400m to repeat the above experimental operation.

4. A study of downhole penetration frequency characteristics

The field strength distribution of the experimental model at different depths and frequencies is roughly the same, and the potential at the location of the anomalous region is obviously increased, indicating that the detection of the anomalous region is more obvious. The schematic diagram of the field strength at 100m depth is shown in Fig. 4, and the average maximum signal strength at point B is shown in Fig. 5, which shows that the best AEPM frequencies are 49 Hz and 97 Hz.

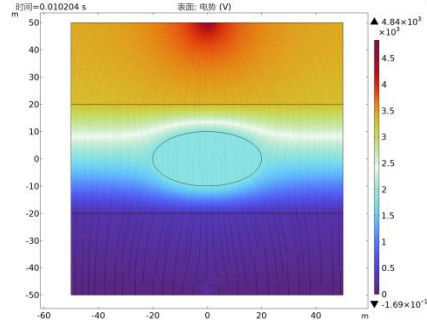


Fig. 4 Field strength distribution at 100m depth

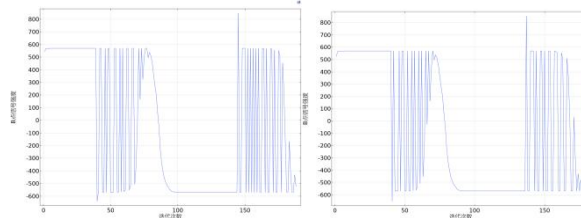


Fig. 5 Maximum signal strength at point B at 100m depth with different frequencies

By extracting and analyzing the data of probe B, the variation curves of signal strength with frequency at point B at different depths were plotted separately as shown in Fig. 6. The optimum AEPM frequencies at 200m depth are 24Hz and 96Hz. The optimum AEPM frequencies at 400m depth are 16Hz and 77Hz. The longitudinal comparison at different depths shows that the frequency corresponding to the maximum signal strength decreases gradually with the increase of depth. Therefore, when the frequency is higher the penetration is worse, and the frequency is lower the penetration is stronger. Therefore, a dual-frequency transmitting system can be used as an AEPM detection scheme, i.e., transmitting two frequencies at a time, namely, lower frequency and higher frequency, the lower frequency is responsible for detecting the deeper areas of the underground, and the higher frequency is responsible for detecting the shallower areas of the underground, and the dual-frequency can achieve the best detection effect by cooperating with each other. From the overall trend, with the increase of depth, the corresponding point B detected signal strength decreases, so to achieve better detection results in the detection of ultra-wide working surface, it is inevitable to increase the working current of the audio power.

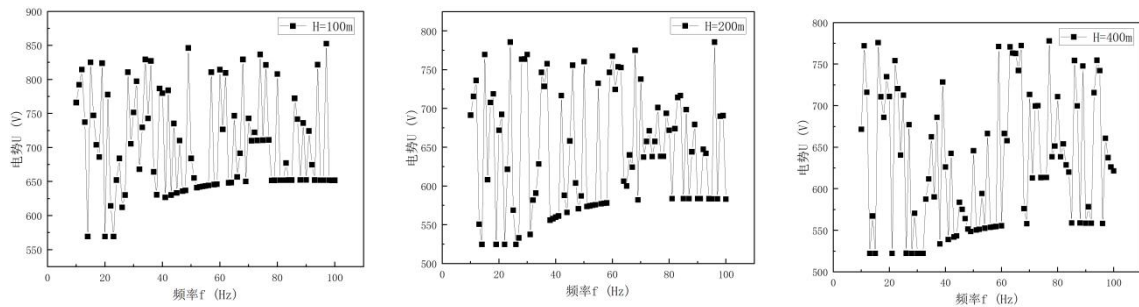


Fig. 6 Distribution of signal strength at point B at different depths and frequencies

Through this simulation experiment, it provides the theoretical foundation for the research of AEPM, lays the experimental foundation for the research of AEPM equipment, and provides a reference for the further improvement and innovation of AEPM. AEPM as an efficient, convenient, non-destructive method of physical exploration has great application prospects and development

space, through this simulation experiment, for the future development of AEPM provides a new way of thinking, the future can be in the detection process, the implementation of dual-frequency detection or even multi-frequency detection, so that each specific frequency detection of a specific depth, which can improve the detection accuracy, so that AEPM This will improve the detection accuracy and make the audio electro-optic fluoroscopy method to be further developed.

5. Conclusion

(1) In this paper, from the perspective of electromagnetic radiation of full-space electric dipole, the equivalent principle of low-frequency alternating current (AC) and direct current (DC) is derived through mathematical theory under the constraints of near-field and seemingly stable, which provides a theoretical basis for the data processing of AEPM and strongly supports the research of AEPM.

(2) The investigation of the optimal penetration frequency of AEPM, through the comparison and analysis of the simulation experimental data, the optimal audio penetration frequency under different depth conditions was obtained, and from the overall point of view, when the depth is bigger, the frequency of AEPM should be lowered to improve the signal strength of the detection point, which provides a reference for the subsequent selection of the frequency of the transmitter of the audio electro-optical penetrometer.

(3) Through this simulation experiment on the frequency characteristics of AEPM, it provides design ideas for the future design of AEPM transmitter. In the selection of the transmitting source, a dual-frequency transmitter should be selected; for the coal seams in the oversized working face, the detection current of the transmitter should be increased, and at the same time, in order to reduce the difficulty of the data processing, the transmitter's current transmission should be a constant-current transmitter.

(4) The investigation of the best penetration frequency of AEPM shows that AEPM reflects the electric field characteristics of the areas with abnormal resistivity in the coal seam very obviously, and it can quickly and accurately identify the water-rich anomalous areas in the coal seam, which provides technical support for the physical prospecting in the "two probes" strictly required by the "Rules on Water Control in Coal Mines". Technical support.

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