Application of Magnetic Resonance Detection in Goaf Water in Wuhai

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Abstract. The mine water disaster in our country has always been the key factor restricting the development of coal production. Due to the unreasonable small coal mine development, mining in some mining area, the destruction of the waterproof coal pillar, lead to the formation of the mined-out area, and goaf water. Because the goaf water does great harm to coal field exploration and development, the prevention and control of goaf water disasters are very important. In this study, aiming at a large area of exploration space, the method of magnetic resonance can be used to detect groundwater, and two magnetic resonance instruments are used to work together. In order to ensure the accuracy and effectiveness of the data collected by the two instruments, improve the efficiency of exploration work and save field exploration time, the basic model of detecting groundwater with magnetic resonance sounding (MRS) method instrument is established, the influencing factors of MRS are analyzed, and the effective signal value of detecting groundwater with MRS instrument is calculated. Through numerical simulation, the optimal distance between the coils laid on the ground when the two MRS instruments are working at the same time is determined. Furthermore, the practicability of the method is verified via a field case performed in a mining area in Wuhai, China. This method can be used as a guide for large-scale field exploration in the future.

1. Introduction
The impact of coal mine water disaster is increasingly serious in China, which brings many hidden dangers to the construction of mining engineering, labor environment and coal production [1]. Therefore, we must use advanced technical methods to understand the causes of mine water disaster more clearly, strengthen prevention and take corresponding measures to solve the unsafe factors of mine water disaster. Magnetic resonance method can be used to detect groundwater directly, which improves the accuracy of groundwater resource detection [2]. The application of magnetic resonance method provides a broader prospect for the advanced detection of goaf water and other disaster water sources, which has important practical significance for the collection of groundwater data under special geological conditions [3].

Magnetic resonance method has unique solution for detecting groundwater and no harm to the surface, but it takes a lot of time to measure each measuring point in the process of detection. In order to ensure the measurement quality and improve the working efficiency of a certain measurement area, it is proposed to use two sets of instruments to work together, which can shorten the construction period
and survey the existing state of groundwater in the area in the most effective time. However, there is mutual interference between any two working coils. Through the simulation calculation, the reliable distance between the two instruments in the region without mutual interference is obtained, which improves the efficiency of the magnetic resonance detection method in the region, and better guides and serves the practice of the magnetic resonance instrument in detecting groundwater.

In this study, the influencing factors of MR signal include water content, depth of water content and thickness of water content. The above influencing factors are forward calculation, and the effective signal value of magnetic resonance instrument detecting groundwater when the model parameter is the limit value is obtained. According to the analysis results, the model of the magnetic resonance antenna is established, and the finite element method is used to simulate the induced electromagnetic field in the software. Compared with the effective signal value obtained through forward calculation, the optimal distance between the working coils of the two magnetic resonance instruments is analyzed. Based on the simulation of the actual exploration situation in Wuhai Mining Area, the basic model of the two instruments is established, and the electromagnetic field is simulated and calculated. According to the effective signal value of the magnetic resonance instrument detecting groundwater, the reliable distance between the two coils is calculated when the two instruments are working at the same time. Finally, the effectiveness and accuracy of this method are verified by field test in Wuhai comprehensive physical exploration area.

2. Algorithm

2.1. MRS Method

The magnetic resonance method uses artificially generated magnetic fields to excite hydrogen nuclei in groundwater to form macroscopic magnetic moments. When the excitation pulse moment field stops and then the excitation field stops, the relaxation of the hydrogen atomic nucleus spins due to the excitation at this time. Then, the receiving coils laid on the ground are used to record the MRS signal generated by the macroscopic magnetic moment precession, and the existence of groundwater can be determined. The time domain expressions of magnetic resonance signals with different emission pulse moments q are shown in the following formula (1).

$$E(t,q) = E_0(q)\exp\left(-t/T_2^*\right)\cos(\omega_0t + \phi_0)$$

Among them, $E_0 (q)$ is the initial amplitude of the MRS signal at different transmission pulse moments, $T_2^*$ is the average lateral decay time, and $\phi_0$ is the initial phase of the signal. The three are the key parameters of magnetic resonance signals, which represent the water content per unit volume, porosity, and the conductivity of the aquifer, as shown in Table 1.

**Table 1. Key parameters of magnetic resonance instruments**

| MRS signal characteristic parameters | Hydrogeological parameters from inversion interpretation |
|--------------------------------------|--------------------------------------------------------|
| Initial amplitude of the MRS signal $E_0$ (nV) | Water content (effective porosity) |
| MRS signal relaxation time $T_2^*$ (ms) | Pore size (permeability) |
| Initial phase of MRS signal $\phi_0$ (degree) | Electrical conductivity (resistivity) of the aquifer |

2.2. Numerical simulation results and analysis of MR signals

There are natural factors and other factors that affect the change of MR signal. This paper mainly simulates and analyzes the influence of other factors on MR signal, mainly including the change of water content, the change of depth of water content and the change of thickness of water content on MR signal.
It is defined that the detection antenna is a $100 \times 100$ m square transmitting antenna, the number of turns is a single turn, and the Larmor frequency is 2326 Hz. The aquifer with different water content, different burial depth and different aquifer thickness are calculated forward respectively, and the corresponding initial amplitude $E_0$ and transmitting pulse moment $q$ are obtained. The $E_0$-$q$ curve of the calculation results is drawn in MATLAB, as shown in Figure 1, Figure 2 and Figure 3 \cite{4-7}.

![Figure 1. E0-q curve with different water content](image1)

![Figure 2. E0-q curves at different water depths](image2)

![Figure 3. E0-q curves for different aquifer thicknesses](image3)

Through the analysis of different water content, burial depth and thickness of aquifer, it is found that the larger the water content is, the larger the value of $E_0$ will be. The deeper the water is, the smaller the value of $E_0$ will be. The thicker the water is, the larger the value of $E_0$ will be. According to the above conclusion, when the parameters of the theoretical model are the minimum, the effective signal value of the magnetic resonance instrument for detecting groundwater can be obtained. That is to say, when the water content of aquifer is 10%, the buried depth is 100m, and the thickness of aquifer is 5m, the maximum amplitude of MRS signal is 46.64nv, which is the effective signal value of magnetic resonance instrument for detecting groundwater.

3. Finite element method

3.1. Modeling of electromagnetic field of magnetic resonance antenna by finite element method

The experimental model of two magnetic resonance instruments simultaneously detecting groundwater is shown in Figure 4\cite{8,9}. Two magnetic resonance instruments and their detection antennas are laid on the same plane. The side length of the antenna is $100 \times 100$m, the number of turns is single turn, the excitation frequency is 2326Hz, and the distance between the two antennas is defined as $L$. 

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The text is formatted to include figures and tables as described, with proper references and a logical flow of information.
When two or more magnetic resonance instruments work together to detect groundwater, the emission current changes from small to large with the increase of excitation pulse moment. According to Faraday's law of electromagnetic induction, it can be known that the magnetic induction intensity $B_1$ generated in the transmitting antenna 1 also changes accordingly. When the component of the magnetic induction $B_1$ in the $B_{1z}$ direction acts on the receiving antenna 2, a change in magnetic flux is caused, and an induced electromotive force $E$ is generated. The induced electromotive force $E$ generated by the coil 2 is compared with the effective signal value of the measurement signal recognized by the magnetic resonance instrument, and the interference condition of the induced electromotive force $E$ on the detection of groundwater by the magnetic resonance instrument is evaluated.

We use the finite element method and COMSOL MULTIPHYSICS software to carry out simulation of magnetotelluric exploration. The finite element model is created, and the spatial simulation model is established as shown in Figure 5[10,11]. The meshing result is shown in Figure 6, and the obtained magnetic field distribution is shown in Figure 7.

3.2. Finite element model analysis of measured water data in goaf based on Wuhai
Define the detection antenna as a $100 \times 100$ m square transmitting antenna with a single turn. The local Larmor frequency is 2355 Hz. The receiving antenna is a $100 \times 100$ m square antenna with a single turn. The maximum current emitted by the magnetic resonance instrument is 250 A. This model is established in COMSOL MULTIPHYSICS software, and the different distances between the two coils and the impeded emission current are simulated. The result is that when the distance between the two transmitting antennas is 1900 m and the maximum transmitting current is 250 A, the induced electromotive force across the receiving antenna is 46.464 nV. This value is the closest and smaller than the effective signal value of groundwater detected by magnetic resonance instruments. The simulation results of the relationship between induced electromotive force and distance are shown in Figure 8. The transmitting antenna transmits different currents and the induced electromotive force $E$ at the receiving antenna is shown in Figure 9.
By analyzing the influence of other factors on the magnetic resonance signal, the effective signal value of the magnetic resonance instrument for detecting groundwater is 46.64nV. The simulation results show that when the distance between the two transmitting coils is 1900m and the maximum transmitting current is 250A, the induced electromotive force across the receiving antenna is 46.464nV. Therefore, in order to improve the working efficiency and use multiple magnetic resonance instruments to work together in the field, when the distance between the two antennas is 1900m, it is a reliable distance. As long as the distance is exceeded, the data obtained by detecting groundwater with a magnetic resonance instrument can be considered accurate.

4. Analysis of actual exploration results

In order to verify the feasibility of this method, tests were carried out in Wuhai Pinggou Coal Mine. By cooperating with the magnetic resonance inversion software, the groundwater information such as the depth, water content and permeability of the groundwater layer in the tested area can be quickly obtained. According to the record of the exploration site, the detection point ML73-6 and the detection point ML65-1 work at the same time. The detection records are as follows: the laying detection antennas are all 100 × 100m square coils, the number of turns is single, the local Larmor frequency is 2355Hz, and the number of superimpositions is 32 times. The distance L when the two detection antennas are laid is 2097.339m. The fitting curve E0-q curves obtained from the inversion results of the excitation pulse moments of the two detection points and the detection signals are shown in Figure 10 and Figure 11.

The detection point ML73-6 was calculated through inversion, and the maximum amplitude of the acquired signal is 1229nV, and the average value was 409.71nV. The detection point ML65-1 was calculated through inversion, and the maximum amplitude of the acquired signal was 1102nV, and the average value was 397.94nV. The water cuts obtained after inversion calculation at the two detection points are shown in Figure 12 and Figure 13. The aquifer at detection point ML73-6 is buried at a depth
of 10-30m underground, and the water content of the aquifer is 30%. The aquifer at detection point ML65-1 is buried at a depth of 5-20m, and the water content of the aquifer is 32%.

Simulate the antennas laid at these two detection points using the model previously established in COMSOL MULTIPHYSICS software. Because the two detection antennas work at the same time, when the excitation pulse moment reaches the maximum value, that is, the emission current is 250A, the induced electromotive force at both antennas at this time is 5.5015nV. The value of the induced electromotive force is much smaller than the effective signal value of 46.64nV for detecting groundwater by magnetic resonance instruments. The distance at which the instruments at the above two detection points perform detection work at the same time is 2097.339m, which does not affect the accuracy of the groundwater detection results. The detection results are valid.

5. Conclusions
This paper studies a method for improving the efficiency of field exploration for large-scale exploration space. A basic model of groundwater detection by magnetic resonance instruments was established, and the factors affecting the magnetic resonance signals were analyzed to obtain the effective signal value of groundwater detection by magnetic resonance instruments. The finite element method is used to simulate the induced electromagnetic field, and a model of the magnetic resonance antenna is established. The reliable distance between the two coils when the two magnetic resonance instruments work together is obtained according to the effective signal value of the groundwater detected by the magnetic resonance instrument. In addition, the data collected from the groundwater detection in the Wuhai survey area by magnetic resonance instruments were inverted, and a set of data was used to verify the simulation calculation results. Further verifying the conclusion that two instruments beyond a reliable distance can be used to simultaneously detect groundwater in actual exploration work. This method can guide future large-scale exploration space exploration work. However, it is necessary to further study the working mode of two or more instruments in the field and the working mode between coils of different specifications in order to improve the efficiency of large-area exploration space.
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