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Innovative technology for estimating water content of water-holding construction in coal mine tunnels

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ABSTRACT

The estimation of water content in water-bearing structure of coal mine tunnel directly affects the progress and quality of coal mine tunnel construction. Therefore, in order to accurately estimate the water content of water-bearing water in coal mine tunnels, this experiment innovatively applies nuclear magnetic resonance detection technology to advanced geological prediction. The research first explains the principle of water detection of nuclear magnetic resonance technology, and then optimizes and improves it to be more suitable for water detection in coal mine tunnels. In addition, in order to realize the numerical simulation of water exploration in coal mine tunnels, particle swarm optimization and wavelet transform are also applied to the inversion of nuclear magnetic resonance data. The emission energy and the sensitivity of the received signal of the optimized nuclear magnetic resonance water detection technology are improved, and the noise of the overall model is also reduced. Finally, the laboratory test of nuclear magnetic resonance water detection in coal mine tunnel was carried out. The experimental results show that the water volume value obtained from the NMR response is basically consistent with the water volume value in the actual water-holding construction; Compared with the set water content (0, 0.167, 0.333, 0.5, 0.667), the water content in the water-holding construction of the coal mine tunnel measured by nuclear magnetic resonance detection under five working conditions is basically consistent, which verifies the reliability of the technology.

Keywords: Water-bearing structure; Water content; Inversion; NMR response

1. Introduction

Although China is rich in coal resources, human demand for coal mines is increasing, so coal resources also play an increasingly important role in social production activities. The construction of coal mine tunnels is the necessary way for coal mine development, so the construction of coal mine tunnels is very important. The traditional coal mine tunnel construction takes a long time and the construction method is inefficient. With the rapid development of science and technology, modern machinery has been widely used, and the construction of coal mine tunnels has gradually moved towards modernization. There are usually water-bearing structures along the construction of coal mine tunnels, such as fault fracture zones, karst caves and underground rivers, which seriously threaten the quality and safety of coal mine tunnels. Therefore, it is very necessary to carry out the estimation model of water content in the coal mine tunnel [1]. In the estimation of water-bearing structure in coal mine tunnels, there is a large improvement area in the existing

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technology. The advanced geological prediction method adopted at this stage focuses on the evaluation of the adverse geological problems faced in the construction of coal mine tunnels. Although this method can estimate the water content structure, it has insufficient judgment on the spatial location of the structure that holds water and the corresponding water content estimation, and lacks the technology of direct quantitative prediction of the water content [2,3]. In nuclear magnetic resonance technology, the response signal obtained on the receiving coil is directly related to the water content in the water body, that is, nuclear magnetic resonance technology can directly detect the water content in the coal mine tunnel [4,5], which has great application potential in this field. Therefore, in order to improve the progress and quality of coal mine tunnel construction, this study attempts to apply nuclear magnetic resonance technology to the detection of water content in coal mine tunnel. The experiment classifies the aquifer information and screens the available information by increasing the emission energy. In addition, the research also reveals the NMR response characteristics of water content in different water-bearing structures through laboratory tests.

1.1. Related work

In the existing research, many scholars have studied the detection of water content in water-bearing structures. From the perspective of ecological protection, Shi et al. [6] used a combination of macro and micro methods to predict the water bearing capacity of surface aquifers. After determining the micro-pore parameters and water absorption of sandstone, an index weighting method is constructed to comprehensively evaluate the volume index of sandstone. The final experimental results show that this method can estimate the bearing capacity of coal mine aquifer. Ma et al. [7] found that the occurrence rate of mine accidents has a great relationship with the water content of coal seams, so they carried out research on the detection of water-bearing rocks. The experiment uses high-frequency electromagnetic wave to detect water-bearing rocks, and simulates and analyzes the effectiveness based on the numerical value of theoretical research. The final simulation results show that this method can play a greater role in the detection of aquifer in coal mine tunnels, and is of great significance to avoid the occurrence of mine accidents. According to the difference of chemical composition of water sources in the mine, Li et al. [8] selected 14 indicators as sample variables for identifying water inrush. The experiment combined principal component analysis and Fisher discriminant analysis to build a water inrush recognition model. The final experimental results show that the proposed method can significantly improve the recognition accuracy of mine water inrush, and has strong practical significance for the prevention and control of water inrush accidents. In order to prevent and control mine floods, Zhang et al. [9] have adopted hydrochemical analysis, Fisher discriminant analysis and geothermal verification analysis methods to identify and verify the water source of the multi-groundwater system in the coal mine. The experimental results show that the accuracy rate of water source identification can reach 97.3% by combining the three analytical methods, and can reasonably explain the reasons for misjudgment of water samples. The method described in the experiment can play a greater role in the prevention and control of mine flood. Yan et al. [10] used ground penetrating radar to detect the water content of groundwater. By analyzing the time domain and frequency spectrum characteristics of the electromagnetic signal of the aeolian sand samples, the technology tests the aeolian sand samples with different water contents. The experimental results show that the method can accurately estimate the water content of windblown sand, and can provide reference value for the management and decision-making of effective water in semi-arid areas.

The nuclear magnetic resonance detection technology has strong practicability and has been widely used by scientists in various fields. Zhou et al. [11] used nuclear magnetic resonance technology to study the evolution characteristics of meso-damage of unloading rock. The experimental results show that the nuclear magnetic resonance technology can accurately dynamically indicate the development process of microcracks and cracks in rock samples, and verify that the technology has good operability. From the perspective of food quality control, Balthazar et al. [12] used nuclear magnetic resonance technology to detect whey, urea, hydrogen peroxide and synthetic urine in milk raw materials. The experimental results show that NMR technology can detect the water mobility in milk drinks, and then effectively evaluate the water retention capacity of milk. In addition, the technology is also non-destructive and is a powerful tool to ensure product quality in dairy processing and storage. Crow et al. [13] applied nuclear magnetic resonance technology to the geological field. The experiment mainly evaluated the ability of nuclear magnetic resonance technology to measure volume water content in geological disasters and hydrogeology. The experimental results show that the thin NMR tool with multiple frequencies can provide signals to penetrate rocks with different diameters around the tool. Experiments have proved that this technology can provide more useful information. Lin et al. [14] applied surface nuclear magnetic resonance technology to the detection of groundwater. They proposed a new transmission method based on the untuned constant pressure clamp technology to optimize the surface nuclear magnetic resonance technology for the disadvantage of signal loss in this technology. The experimental results show that this method can control the turn-off process of the transmission current and avoid the delay of the response. In addition, the optimized nuclear magnetic resonance technology has also improved the detection performance of groundwater. Zhu et al. [15] found that nuclear magnetic resonance technology can be used to detect the chemical structure of products. Therefore, the team used this technology to detect the excess water in the polymer gel system. The experimental results show that NMR technology can evaluate the water control performance of polymer gel in porous media. Therefore, the experiment verifies the strong practical value of NMR technology in polymer gel system.

To sum up, the current academic community has explored and studied the detection technology and nuclear magnetic resonance technology of water content in aquifer, and has obtained relevant research results. However, although the methods mentioned above are innovative, their overall limitations are still large. Therefore, this experiment further applies nuclear magnetic resonance technology to the detection of water content in coal mine tunnels, aiming at improving the progress and quality of coal mine tunnel construction.

2. Research on water exploration model based on nuclear magnetic resonance detection technology

2.1. Research on nuclear magnetic resonance water exploration technology model

Magnetic resonance sounding (MRS) is the technical basis for nuclear magnetic resonance water exploration, which belongs to single-channel detector. The working principle of MRS is shown in Fig. 1.

Fig. 1 shows that a single hydrogen atom is affected by the static magnetic field B_0 and continues to precess at a fixed frequency of wl. Fig. 1b shows that the atoms in the excited electromagnetic field B_1, after being affected by the excitation pulse, the spin direction of some atomic nuclei changes, and the angle deviates, causing the chamfer θ appear. Fig. 1c shows that after the end of an excitation pulse, the hydrogen atom will continue to precess at the angular frequency wl. Fig. 1d shows the equilibrium state of atomic nucleus under static magnetic field. This process is called relaxation process, and the whole process is accompanied by the release of free induction attenuation signal. Normally, the experiment will collect the attenuation signal to obtain the existence position of hydrogen atom nucleus, and then detect the water content in the coal mine tunnel [16]. When the same coil is selected for both transmitting and receiving coils, the expression of free induction attenuation signal related to the coil is:

$$V(q,t) = -4w_L M_0 \int \sin\left|\gamma B_{1\perp}^{+}(r)\cdot q\right| \times \left|\gamma B_{1\perp}^{-}(r)\right| e^{i2\xi(r)} \\ w(r,T_2^*)\cdot e^{-t/T_2^*}\cdot d^3r\cdot d^3T_2^* \tag{1}$$

where w_L, M_0, w and ξ are angular frequency, magnetic purification intensity, water content ($w \in [0,1]$) and phase parameters. When the components of the excited electromagnetic field B_1 and the static magnetic field B_0 are perpendicular to each other, the amplitude of the reverse and co-rotating components of the circularly polarized field can be expressed by $B_{1\perp}^{-}(r)$ and $B_{1\perp}^{+}(r)$, respectively, and this value is related to the coil sensitivity. When the relaxation time is T_2*, the water content at that time is $w(r,T_2^*)$.

$$M_0(r) = M_0 \cdot w(r)$$
$$V = \int K(q,r)\cdot w(r) d^3r$$
$$K(q,r) = w_L M_0 \sin\left(-\gamma_p \frac{q}{I_0}\left|B_T^{+}(r,w_L)\right|\right) \\ \times \frac{2}{I_0}\left|B_R^{-}(r,w_L)\right|\cdot e^{i\left[\xi(r,w_L)+\xi_R(r,w_L)\right]} \\ \times\left[\hat{b}_R(r,w_L)\cdot\hat{b}_T(r,w_L) + i\hat{b}_0\cdot\left(\hat{b}_R(r,w_L)\times\hat{b}_T(r,w_L)\right)\right] \tag{2}$$

Eq. (2) contains the expression of response kernel function $K(q,r)$ of MRS. When the water content is measured as a one-dimensional space, the depth variable z index can be used to measure the spatial position γ Instead, the kernel function K can be used to excite the pulse distance q (q = current I × Excitation time τ) and z [17]. When laying the nuclear magnetic resonance coil in the coal mine tunnel, it is necessary to optimize the surface nuclear magnetic resonance water finding method in combination with the actual situation. Assuming that the conductivity of the excavated part of the coal mine tunnel is 0, there is no electromagnetic wave eddy current phenomenon, and the electromagnetic wave has no loss [18]. Place the transmitting and receiving coils on the construction surface of the coal mine tunnel, and connect the alternating current with a certain frequency to the transmitting coil, and detect the free attenuation signal on the receiving coil through time control.

$$\theta = 0.5\gamma_p B_{1\perp} q \\ E(t) = E_0(q) e^{\frac{-1}{T_2^*}} \sin(w_L t + \varphi_0) \tag{3}$$

In Eq. (3), when the excitation field B_1 is perpendicular to the geomagnetic field B_0, its vertical component $B_{1\perp}$ is related to the pulse distance q, atomic nuclear magnetic rotation ratio γ_p, and the flip angle θ are connected. In the expression of the corresponding electromotive force $E(t)$ of nuclear magnetic resonance obtained by the receiving coil (in the attenuation state), the initial amplitude set by the nuclear magnetic

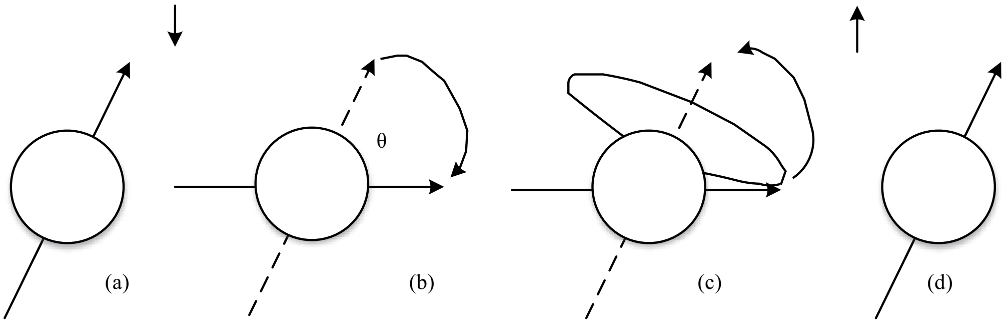

Fig. 1. Schematic diagram of nuclear magnetic resonance sounding.

resonance signal is E_0 (representing water content); The corresponding mean decay time (indicating permeability) and relative initial phase (indicating conductivity of aquifer) of MRS signal are expressed by T_2* and ($A\varphi_0$), respectively.

2.2. Detection of water-bearing structure in coal mine tunnel based on nuclear magnetic resonance detection technology

In order to improve the accuracy of nuclear magnetic resonance detection in estimating the water content of water-bearing structure in coal mine tunnels, the experiment will improve the forward and inverse process of nuclear magnetic resonance response in combination with the actual situation of coal mine tunnels. Based on the optimization of the resolution of the nuclear magnetic resonance response, the experiment designed a new prediction technology of water volume in the coal mine tunnel [19].

Fig. 2 is the calculation model of nuclear magnetic resonance response. The geomagnetic field strength B_0=52,000 nT, geomagnetic inclination 60°, coil radius and current are respectively 3 m and 1 A. Ensure that the continuous power supply time is 1,000 ms and the formation conductivity is 0.01 S/m. The coal mine tunnel water-bearing structure is located 2 m above the coil, and its true water content is 80%. When performing the inversion calculation of NMR response, convert $V=\int K(q,r)\cdot w(r)d^3r$ into matrix form E = An. Meanwhile, $E = (E(q_1), E(q_2), \ldots, E(q_I))^T$, $A_{ij}=K(q_i,z_j)\Delta z_j, j\in 1,2,\ldots,M$, $n = (n_1, n_2, \ldots, n_M)^T$. After that, divide the front of the coal mine tunnel equally to make it a 0.2 m aquifer M, and M = 50. The inversion calculation of NMR response is carried out by singular value decomposition algorithm.

$$A_{M\times I}=U_{M\times M}\Lambda V_{I\times I}^T \tag{4}$$

where $A_{M\times I}$, $U_{M\times M}$ and $V_{I\times I}{}^T$ are arbitrary matrices and $M\times M$-order orthogonal matrix, $I\times I$-order orthogonal matrix.

$$\Lambda=\begin{bmatrix}\sum r\times r & 0\\ 0 & 0\end{bmatrix}M\times I,\sum r\times r=\begin{bmatrix}\sigma_1 & 0 & 0 & 0\\ 0 & \sigma_2 & 0 & 0\\ 0 & 0 & \ldots & 0\\ 0 & 0 & 0 & \sigma_r\end{bmatrix} \tag{5}$$

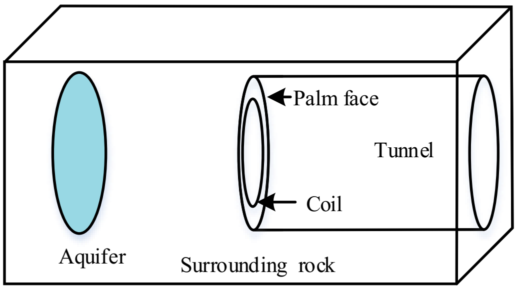

Fig. 2. Calculation model.

where $\sigma = (j = 1, 2, \ldots, r)$ and Λ represent $M\times$ for diagonal matrix of order I, σ_j represents r singular values of A, and r is the rank of A. Then the solution of An = E equation is $n = V\Lambda^{-1}U^TE$. Use the least square method to obtain Eq. (6):

$$n_{\text{is}}=\sum_{i=1}^{r}\frac{u_i^TE}{\sigma_i}v_i \tag{6}$$

Eq. (6) is the singular decomposition expression of the water content of the water-bearing structure in the coal mine tunnel. Where, u_i is the column vector numbered i; v_i is the column vector with V number i; σ_i is the element with number i existing on the main diagonal of $\Sigma r\times r$. Because the half-space response algorithm is easy to reduce the resolution of nuclear magnetic resonance detection technology, this study introduces particle swarm optimization algorithm into the inversion calculation of nuclear magnetic resonance water exploration to improve the interpretation accuracy and resolution [20]. Consider the research object as a point, and only consider its spatial position vector $X_i = (x_1, x_2, \ldots, x_N)$ and motion velocity $V_i = (v_1, v_2, \ldots, v_N)$, then there is Eq. (7):

$$\begin{aligned}v_I^{k+1}&=v_I^k+c_1\times\text{rand}(\ )\times\left(\text{pbest}-x_I^k\right)+c_2\\&\quad\times\text{rand}(\ )\times\left(\text{gbest}-x_I^k\right)\\x_i^{k+1}&=x_i^k+v_i^{k+1}\quad ;i=1,2,\ldots,M\end{aligned} \tag{7}$$

The function of Eq. (7) is to continuously update the optimal solution (pbest, gbest). The total number of particles is; When the particles are in position X_i, the speed of each particle is expressed in V_i. Let the learning factor represent a random number between 0 and 1 with rand(). The inertia weight factor is used to improve the particle swarm optimization algorithm, as shown in Eq. (8):

$$\begin{aligned}v_i^{k+1}&=\omega\times v_i^k+c_1\times\text{rand}(\ )\times\left(\text{pbest}-x_i^k\right)+c_2\\&\quad\times\text{rand}(\ )\times\left(\text{gbest}-x_i^k\right)\\\omega&=\omega_{\max}-\frac{\omega_{\max}-\omega_{\min}}{\text{iter}_{\max}}\cdot\text{iter}\end{aligned} \tag{8}$$

where ω is the inertia factor; $\omega_{\max}$, $\omega_{\min}$ is the maximum and minimum value of inertia factor; The current iteration number is expressed in iter; The maximum number of iterations is expressed in $\text{iter}_{\max}$. Generally, $\omega_{\max}$=9, $\omega_{\min}$=0.4.

$$F=\frac{1}{n}\sum_{i=1}^{n}\left[\frac{E_0(i)-E_1(i)}{E_0(i)}\right]^2 \tag{9}$$

In Eq. (9), the measured value and calculated value of the i-th sampling channel are represented by $E_0(i)$ and $E_1(i)$, respectively. Wherein, $E_1(i)$ is calculated by numerical model inversion. Make the number of particles and the maximum number of iterations in the particle swarm optimization algorithm 40.

3. Estimation model and performance verification of water-bearing structure water volume in coal mine tunnel based on nuclear magnetic resonance technology

3.1. Water content estimation model and performance verification of water-bearing structure based on nuclear magnetic resonance technology

After combining the calculation model in Fig. 2 with Fortran language programming, nuclear magnetic resonance (NMR) is introduced into the advanced prediction of coal mine tunnels for numerical simulation, and the approximate relationship between the water-bearing structure of coal mine tunnels and nuclear magnetic resonance is obtained. Make the current pulse intensity excited to 20, and the maximum current pulse intensity is 2,000 A/mS. Fig. 3 shows the inversion calculation results of the theoretical model based on singular value decomposition.

Fig. 3a shows that the smaller the equivalent area of the coil, the weaker the induced electromotive force generated, and the maximum value of the induced electromotive force is 7.14 nV. The comparison between Fig. 3b and c shows that the theoretical model based on singular value decomposition has high inversion accuracy in inversion calculation; The location of the aquifer in the water-holding construction of the corresponding coal mine tunnel and the calculation results of the water content at the corresponding location are consistent with the actual situation of the original model. When the singular value decomposes and inverts the NMR data, it is found that the water content at 2 m of the coil is more than 80%. The inversion process has multiple solutions, resulting in differences between the relative theoretical value and the inversion results of the spatial location and water content of the aquifer. Fig. 3d shows that the observed value curve is basically fitted with the results of inversion calculation, which verifies the feasibility of inversion of NMR data by singular value decomposition [21,22].

Fig. 4 shows the NMR inversion results based on particle swarm optimization algorithm. It is not difficult to find from Fig. 4a that the observed value is basically consistent with the calculated value after the inversion of NMR data by particle swarm algorithm. Fig. 4b shows that the fitting error of the model gradually decreases during the inversion process. After the inversion is completed, the calculated water content at 2 m directly in front of the coil is 78%, while the actual water content is 80%. It can be seen that the NMR inversion results based on particle swarm optimization algorithm are basically consistent with the actual situation, and reflect the physical characteristics of the original model well, indicating that particle swarm optimization algorithm has a relatively good inversion effect. Because the nuclear magnetic resonance detection technology is extremely susceptible to noise, this study will use wavelet transform to denoise the nuclear magnetic resonance signal. It is found that the closer the wavelet function of the instantaneous waveform of the NMR signal is, the more effective it is to transform the NMR signal. In view of this, DB4 wavelet will be selected for the analysis of NMR signals in this study.

$$\lambda_{\text{hard}} = \begin{cases} \chi(t) & |\chi(t)| > \lambda \\ 0 & |\chi(t)| \le \lambda \end{cases} \tag{10}$$

Eq. (10) is the hard threshold $\lambda_{\text{hard}}(A)$ of wavelet denoising. Among them, the wavelet transform function of the signal is represented by $\chi(t)$, and the selected threshold is represented by $\lambda(A)$.

$$\lambda_{\text{soft}} = \begin{cases} \left(|\chi(t)| - \lambda\right)\text{sgn}\left(\chi(t)\right) & |\chi(t)| > \lambda \\ 0 & |\chi(t)| \le \lambda \end{cases} \tag{11}$$

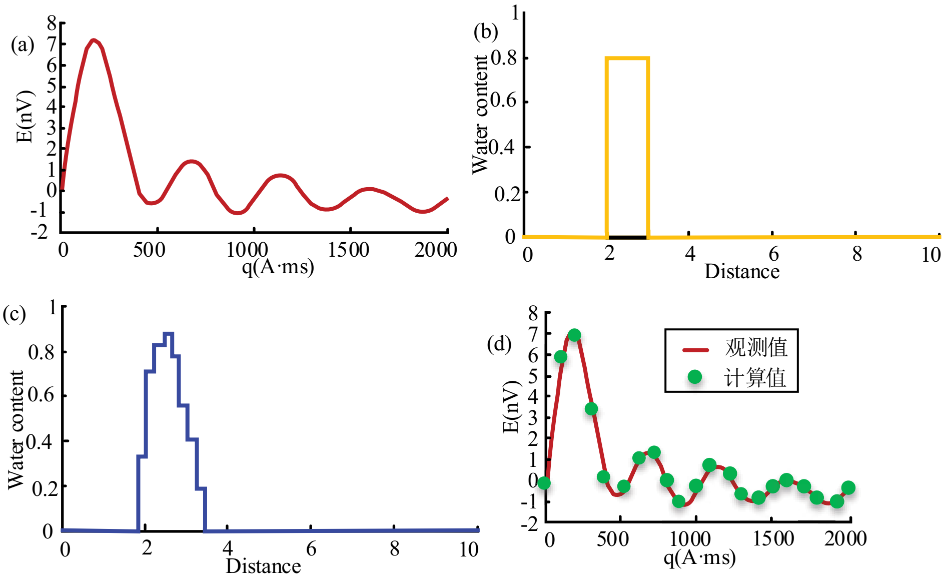

Fig. 3. Inversion calculation results of theoretical model based on singular value decomposition. (a) NMR response initial signal amplitude curve, (b) theoretical observation data and (c) inversion results of theoretical observation data and theoretical observation value and its corresponding inversion and forward modeling value.

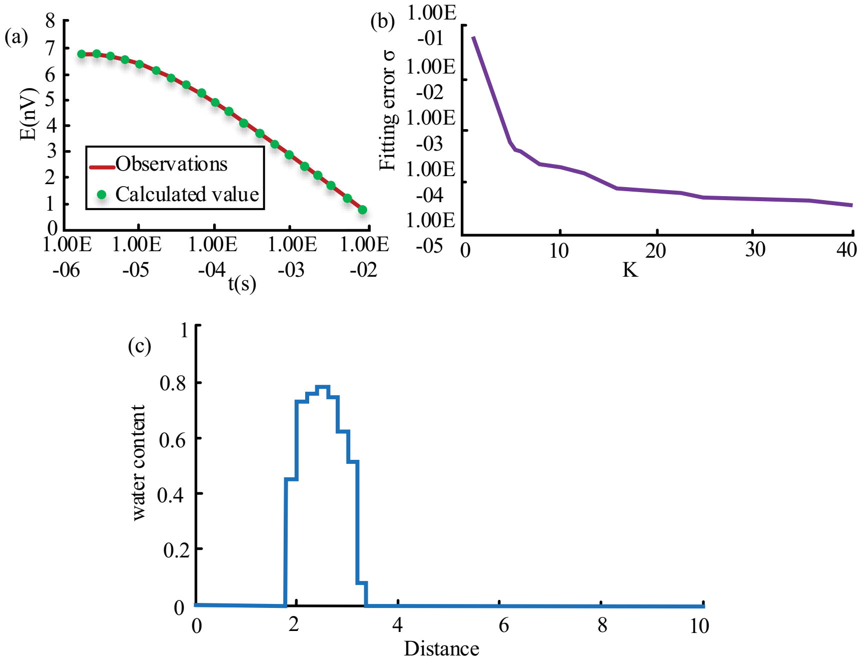

Fig. 4. NMR inversion results based on particle swarm optimization algorithm. (a) Calculated value and actual value, (b) fitting error and (c) inversion results.

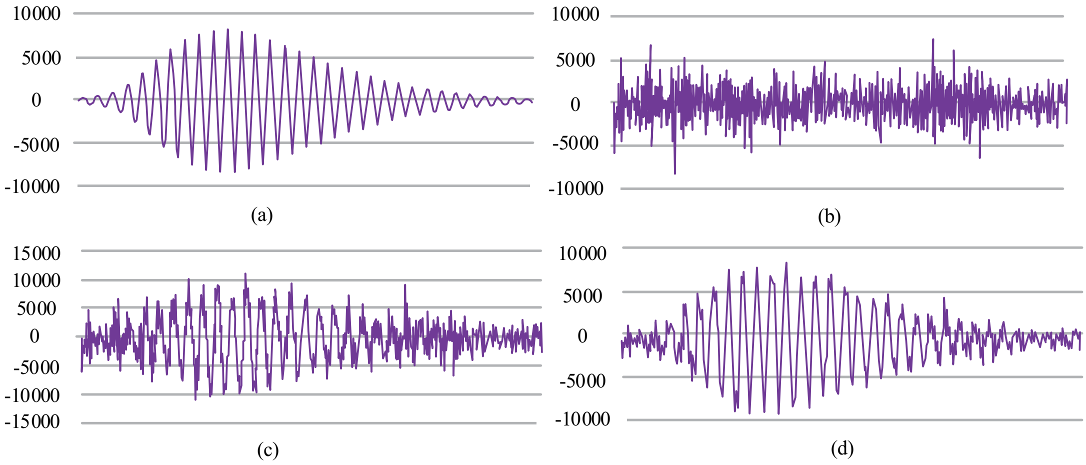

Fig. 5. NMR noise reduction results based on wavelet transform processing. (a) Original NMR waveform curve, (b) random noise curve, (c) single-channel NMR curve after adding random noise and (d) reconstructed single-channel NMR curve after drying.

Eq. (11) is the soft threshold (A) λ_{soft} of wavelet denoising, where sgn(A) is a symbolic function. Because of the hard threshold in the process of processing, it is very easy to appear a series of effects, including the pseudo Gibbs effect. Therefore, it is more appropriate to use the method of combining soft and hard thresholds for processing. Although the soft threshold is relatively smooth, at the same time, the soft threshold may cause unclear edges. The more the number of wavelet decomposition layers, the greater the computational pressure, and the less obvious the benefit of noise reduction effect. Usually, 3 or 4 layers are selected. The specific results of wavelet transformation are shown in Fig. 5.

Fig. 5 shows the reconstructed image closest to the original signal obtained by selecting three decomposition levels in DB4 wavelet. It is not difficult to find from the figure that applying wavelet transform to nuclear magnetic resonance noise reduction can reduce the noise in the environment and improve the signal-to-noise ratio, thus optimizing the accuracy of nuclear magnetic resonance technology in estimating the amount of water in the water-holding construction of coal mine tunnels.

3.2. Verification and analysis of indoor experimental results based on nuclear magnetic resonance detection of water-bearing water in coal mine tunnels

In the experiment, the equivalent area is increased by increasing the return line, and the intensity of the excitation magnetic field is increased by increasing the current. 44-turn 1 m × 1 m^2 wire frame is used as the size of the transmission coil, and 128 turns of 1 m are used × the 1 m^2 wire frame is used as the size of the receiving coil. Then, the two were placed vertically on the face of the coal mine tunnel in the experiment, and the nuclear magnetic resonance instrument was placed at the coal mine tunnel portal. The magnetic field was measured by the magnetometer to calculate the Lamor frequency of the coal mine tunnel location. The final available geomagnetic field strength is: B_0 = 52,539 nT; Lamor frequency is 2,237 Hz. In the experiment, the coil inductance is 4.40 mH by measuring the coil inductance with an electric meter; Configure instrument capacitance $C = 1/[(2\pi F)2L] = 1.15$ μF. In addition, the experiment sets the stacking times to 64 times, and uses the instrument control software to start the nuclear magnetic resonance detection system, and uses the system data inversion software to predict the amount of water in the water-holding construction of coal mine tunnels. Under the same water content condition, the average value of the amount of water in the water-holding construction of coal mine tunnels measured by three detection experiments is the measured value under this water content condition.

Fig. 6a shows the system structure of the advanced geological prediction physical experiment in the coal mine tunnel, and 6b shows the overall device of the water-bearing geological structure. Among them, the coal mine tunnel model is made of glass. The length, width and height of coal mine tunnels are 6.3, 1.6 and 2.2 m, respectively. The water-bearing geological structure is composed of water-bearing shell, water inlet and outlet pipe and water pump. The length, width and height of water-bearing structures are set at 1.1, 2.2 and 2.2 m, respectively.

The main index parameters involved in nuclear magnetic resonance technology are shown in Table 1. This technology can detect groundwater directly, and the collected aquifer information is more comprehensive and the data interpretation is more reliable. In addition, nuclear magnetic resonance technology has the advantages of short detection time, wide prediction range and high detection accuracy, and has a good application prospect in the field of groundwater detection.

Fig. 7 shows the prediction results of water content in water-bearing structures of coal mine tunnels based on nuclear magnetic resonance detection technology. Fig. 7a shows the detection results without water; Fig. 7b–7 show the estimated water content obtained by nuclear magnetic resonance detection technology when 1, 2, 3 and 4 m^3 of water are added to the water-holding construction. When measuring the amount of water in the water-holding construction with different water content, it is necessary to test three times. Then, collect the measured water content values for three times, and take the average of the measured water content values for three times as the collected data. It can be seen from Fig. 7 that the change trend of the amount of water in the water-holding construction of coal mine tunnels calculated by the nuclear magnetic resonance detection technology is basically consistent with the actual water content, but there are certain differences in the specific values. Considering the detection range of the nuclear magnetic resonance detector, the water content under five working conditions is set in the experiment, which are 0, 0.167, 0.333, 0.5 and 0.667, respectively. The results of detecting water content under different working conditions are shown in Fig. 8.

Fig. 8 shows the detection results of water content after placing nuclear magnetic resonance detector within 2.5 m in front of the coal mine tunnel. It can be seen from Fig. 8 that after the detection, there are relatively obvious NMR responses under different working conditions, that is, the NMR detection technology has a relatively accurate positioning of water-bearing structures. In addition, the amount of water in the water-holding construction of coal mine tunnels measured by nuclear magnetic resonance detection under five working conditions is basically consistent with the set water content (0, 0.167, 0.333, 0.5, 0.667). Therefore, under the same water content condition, the water content measured by three experiments is very similar, which shows that the technology has certain reliability.

Fig. 9 shows the relationship between the amount of water in the water-holding construction of coal mine tunnels detected by nuclear magnetic resonance and the actual water content in the water-bearing structure. The overall detected water content is basically consistent with the actual water content. In addition, when the amount of water in the water-holding construction gradually increases, the signal intensity received by the NMR response also increases, and there is a close linear relationship between the two. When

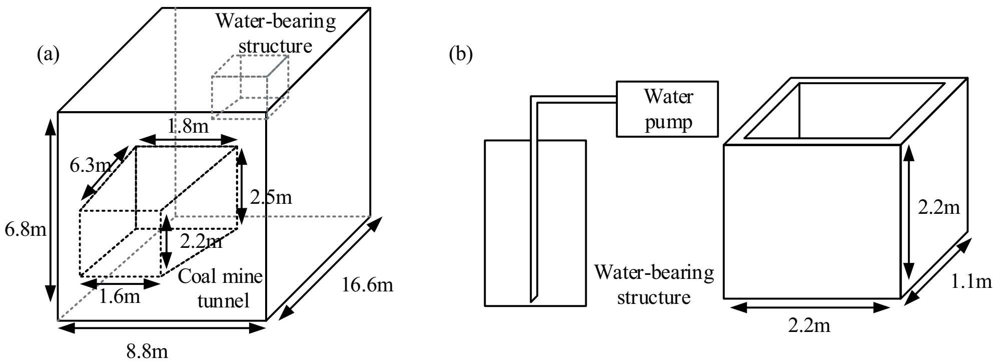

Fig. 6. Structure diagram of experimental system. (a) System structure diagram of advanced geological prediction physical experiment in coal mine tunnel and (b) integral device of water-bearing geological structure.

Table 1
Main index parameters of magnetic resonance

Index	Parameter	Index	Parameter
Maximum emission voltage (V)	450	Energy storage capacity (F)	0.132
Maximum emission current (A)	500	Filter bandwidth (Hz)	10–122
Transmission frequency (kHz)	1.2–3.5	Amplifier gain	103–107
Pulse distance (A ms)	100–20,000	Maximum detection depth	150

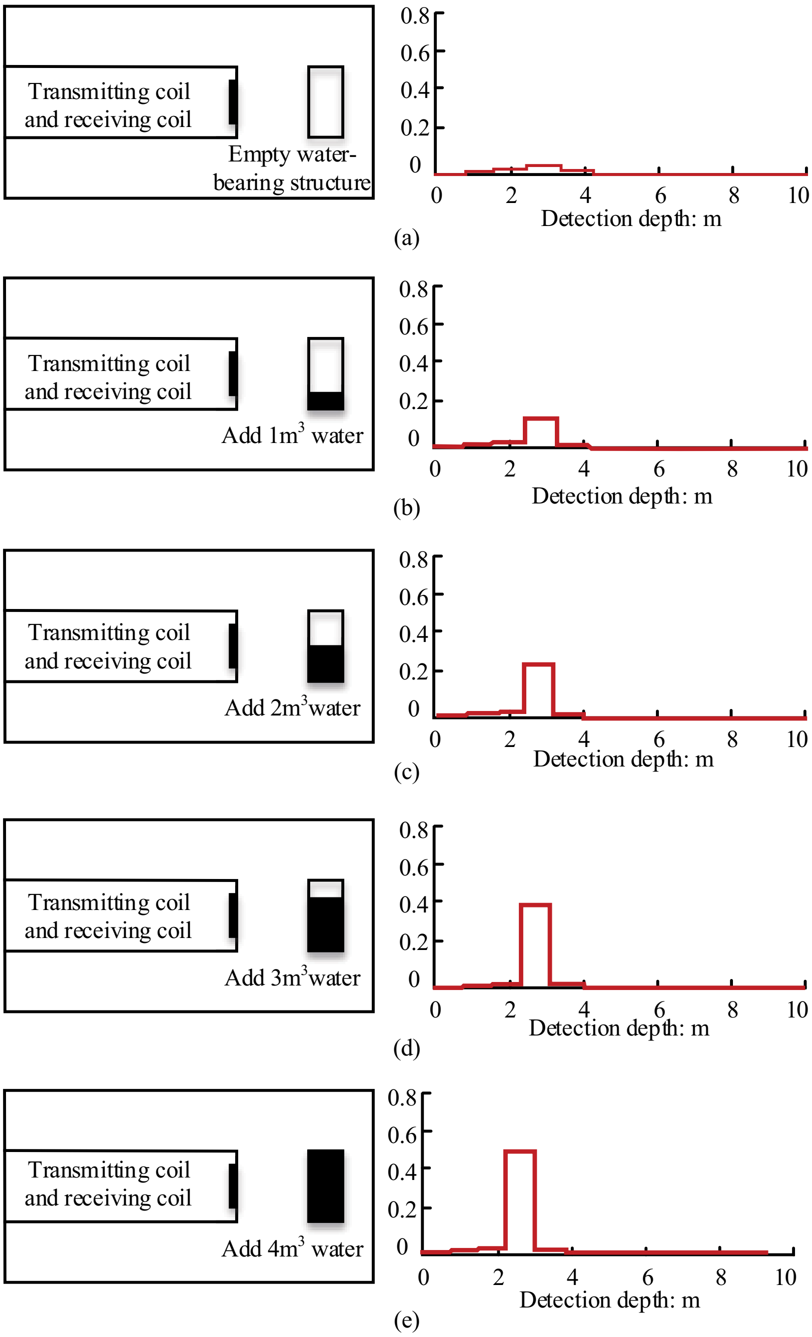

Fig. 7. Prediction results of water content in water-bearing structure of coal mine tunnel based on nuclear magnetic resonance detection technology. (a) Schematic diagram of detection with water, schematic diagram of detecting water content when adding (b) 1 m^3, (c) 2 m^3, (d) 3 m^3 and (e) 4 m^3 water.

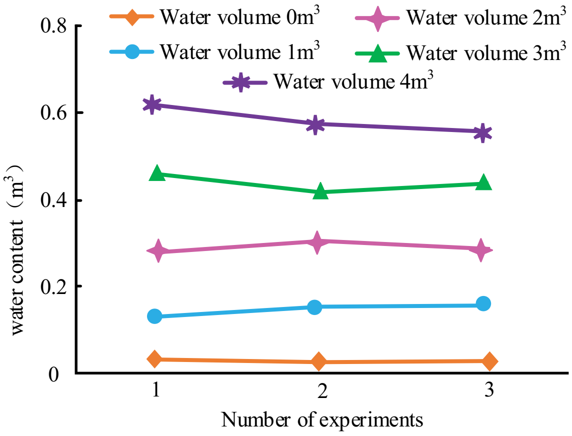

Fig. 8. Results of water content detection by nuclear magnetic resonance.

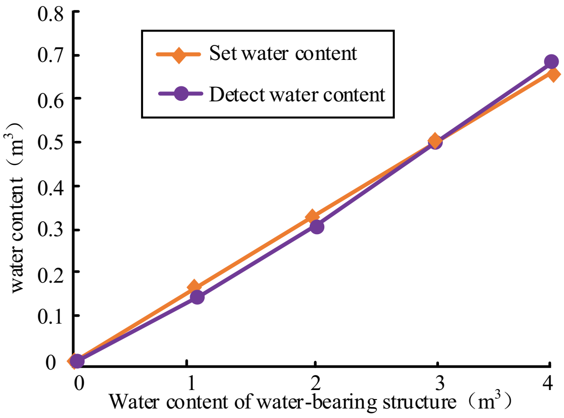

Fig. 9. Water volume change results detected by nuclear magnetic resonance.

the water-bearing structure is anhydrous, there will still be weak nuclear magnetic resonance response. At this time, the nuclear magnetic resonance response mainly comes from the water contained in the building materials of the coal mine tunnel. When 1 m^3 water is added to the water-bearing structure, there will be no water in front of the receiving coil and the sending coil, but the NMR response can be more obvious. The result shows that within a certain range, the hydrogen atom in water is affected by the magnetic field generated by the pulse current, forming a flip angle, and then stimulating the NMR response. Therefore, the value of water content obtained by inversion mainly reflects the overall water content of the water-bearing structure within a certain range centered on the coil. In addition, it can be seen from Fig. 9 that, on the whole, with the increase of water content in water-bearing structure (1–4 m^3), the increase of water content measured by nuclear magnetic resonance detection technology is relatively uniform.

4. Conclusion

The prediction of water content in coal mine tunnels is an important work before the construction of coal mine tunnels. At present, the prediction method of water inflow in coal mine tunnels usually uses the advanced geological prediction method, but this method has shortcomings in water volume prediction. In order to accurately detect the location of water-bearing structures in coal mine tunnels and calculate their specific water content, nuclear magnetic resonance technology is introduced into the advanced geological prediction method of coal mine tunnels in this study. The findings of the study demonstrate that the use of a singular value decomposition technique may increase the model's inversion accuracy, and the location and volume of water found in the coal mine tunnel aquifer retrieved are compatible with the original model's real condition. The observed values calculated from the inversion of nuclear magnetic resonance data based on particle swarm optimization algorithm are basically consistent with the calculated values, indicating that this method can reduce the fitting error. In addition, DB4 wavelet with three decomposition levels has the function of noise reduction, which can improve the accuracy of nuclear magnetic resonance technology in estimating the water content in the water-bearing structure of coal mine tunnels; The variation trend of the amount of water in the tunnel for a coal mine's water-holding construction calculated by the nuclear magnetic resonance detection technology is basically consistent with the actual water content, but there are certain differences in the specific values; The nuclear magnetic resonance detection technology has a relatively accurate positioning of the water-holding construction, which is mainly reflected in the amount of water in the tunnel for a coal mine's water-holding construction detected by nuclear magnetic resonance under five working conditions, which is basically consistent with the set water content; There is a close linear relationship between the amount of water in the water-holding construction and the signal intensity received by the NMR response. In this experiment, the nuclear magnetic resonance detection technology was innovatively introduced into the water content estimation technology in the water-holding construction of the coal mine tunnel, which basically achieved the experimental purpose, but still can be further improved. For example, there are some problems in the feedback of NMR signal to the change of water volume. It can only estimate the water volume in front of the coil, which has certain limitations. Therefore, the future research direction can start from here.

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