Characteristics of Transmission Radio Waves in Undulating Coal Seams and a Topographic Correction Method For Its Tomography

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Case study

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Characteristics of transmission radio waves in undulating coal seams and a topographic correction method for its tomography

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Abstract

The transparency of coal seam working face is an important assurance for safe and accurate mining of coal mines. Mine geophysical prospecting is an important means for geological exploration of coal seam working faces, among which the mine radio wave tomography is one of the most common and effective methods. However, the undulating feature of the coal seam will greatly interfere the high-precision attenuation electromagnetic wave imaging. Through two-dimensional numerical simulation experiments, we identified that in a horizontal coal seam, the energy of penetrated radio wave showed an approximate linear attenuation law, while in an inclined coal seam, it showed a very different parabolic attenuation trend. To eliminate the influence of coal seam inclination on the accuracy of radio wave tomography, in this paper, we proposed a correction method for imaging undulating coal seams using radio wave tomography. Further, through three-dimensional numerical simulation experiments, we verified the validity and reliability of the correction method. Overall, both theoretical and numerical simulation experiments indicated that the method could basically eliminate the influence of coal seam inclination and improve the imaging accuracy.

Keywords: Undulating coal seam; radio wave penetration; tomography; undulating correction

Introduction

Coal is the main energy source of China and provides important support for the sustainable development of China's economy. Although the energy structure is constantly changing with the development of the social economy, coal consumption still accounts for 80% of China’s total energy consumption. Therefore, coal’s dominant position in the energy structure will not change in a short period of time (Peng et al., 2015). Nowadays, with the popularization of industrialization, the realization of precise and intelligent coal mining has become the only way for mining. This means that identification of geological anomalies in the working face and the transparency of the geological conditions of the mine working face are important foundations for intelligent and precise coal mining (Yuan et al., 2019; Cheng et al., 2019). The current methods used to explore the geological structures of the working face include the cross-well electromagnetic method, channel wave exploration, and seismic tomography. However, the current ordinary drilling and geophysical exploration methods can no longer meet the requirements for high-precision exploration and are unable to accurately detect some hidden structures as well as faults with a drop of less than 5 m (Hu et al., 2017). Accurate detection of geological structures in coal seam working faces urgently requires high-precision detection methods to improve the economic benefits and mining safety of the coal mine.

Radio wave tomography is one of the most effective and universal methods for detecting the geological structures of coal seam working face. Many scholars have theoretically explored the radio wave propagation laws and imaging algorithms. In terms of propagation laws, researchers proposed the layered geoelectric model and the single medium model, where the electrical changes of the top and bottom of the coal seam and the thickness of the coal seam will affect the phase of radio wave (Stolarczyk et al., 2003; Hussain et al., 2011). For complex coal mining faces, the ray

tracing-based radio waves propagation (RTRWP) law can effectively describe the radio wave propagation environment (Zhao et al., 2013). In terms of imaging algorithms, an improved Land Weber method was derived by improving the condition number of the weighting matrix and introducing new L1 norm and the objective function of the regularization term, which has better performance in typical modes and improves the space resolution (Han et al., 2018; Liu et al. 2019).

Among them, imaging with improved attenuation coefficient P can improve the detection accuracy in practical application (Liu et al., 2013), and phase tomography is considered as a rapid, effective new electromagnetic wave inversion method (Liu et al., 2013; Yu et al., 2011). In addition, determination of the initial field strength is also a useful attempt to improve the accuracy of radio wave tomography (Zhang et al., 2016), and the effective penetration width of the working surface can be determined from the initial field strength, absorption coefficient and background field strength (Xiao et al., 2017). Decades of research and application have proven that the electromagnetic wave method can effectively detect faults, collapsed columns, coal seam thinning areas, karst development, broken zones, and other geological hazards in coal seams (Hatherly et al., 2013; Li et al., 2015).

Radio wave tomography is advantageous in simple operation and good detection success. However, there are still issues such as incomplete understanding of radio waves propagation law in coal seams, simplicity of the collected electromagnetic parameters, and low imaging accuracy (Xiao et al. 2017; Zhang et al., 2017). The cause for the low accuracy of radio wave tomography is partly the influence of coal seam undulations. At present, in the studies on the geological structure of underground coal seam working face with different computed tomography techniques, the undulation degree of coal seam between roadways is rarely considered, making a great difference in the actual results (Hu et al., 2019). Fully analyzing the propagation characteristics and influencing factors of the radio waves in undulating coal seams is an effective way to improve the cognition and exploration accuracy of radio wave field in coal seams. Due to the inclination, there is a certain elevation difference between the radio wave transmitters and the receivers. Thus, it is necessary to propose a tomographic imaging method that can eliminate the influence of elevation difference to eliminate the influence of coal seam undulation on radio wave imaging data processing and interpretation. In this study, based on ray tracing, we proposed a quasi-three-

dimensional (3D) tomographic imaging technology to solve the deviation issue of imaging results caused by coal seam undulations to improve the accuracy of radio wave tomography.

1 Introduction to the principle of radio wave tomography

Radio wave tomography is a detection method by emitting radiofrequency electromagnetic waves. It has also been named as radio wave penetration method and electromagnetic wave tomography (Liu et al. 2020). Fullagar et al. collectively refer to it as the radio imaging method or RIM for short (Fullagar et al., 2000). Its main theoretical basis is energy attenuation tomography based on ray tracing, which uses sinusoidal electromagnetic waves as the emission source to obtain the distribution of the absorption coefficient of the medium. At present, the commonly used frequencies of mainstream electromagnetic wave penetration instruments are 88 kHz, 158 kHz, 365 kHz, and 965 kHz (Xiao et al., 2017). The essence of the radio wave penetration imaging of the working face is to solve an ill-conditioned linear equation system (Liu et al., 2017). The intensity H of the electromagnetic wave in the coal seam at any point is expressed as:

$$H_m = H_0 \frac{e^{-\beta r}}{r} \sin\theta \tag{1}$$

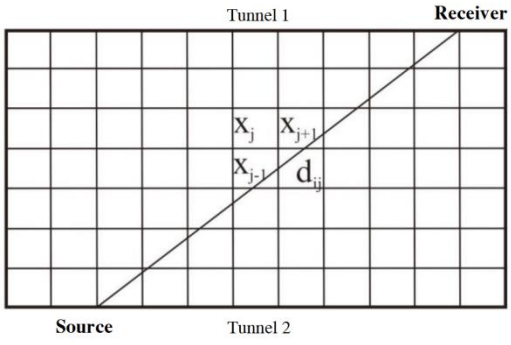


Fig.1 Schematic diagram of tomography grid (Liu et al., 2013)

The imaging space in the working surface is gridded. In this area, a ray y_i passes through the pixels with the field strength attenuation coefficients being $x_1, x_2, ..., x_n$, and the intercepts on these

pixels being d_{i1}, d_{i2},..., d_{in}. In this way, the electromagnetic wave energy attenuation value $\mathrm{V}H_i$ on the i-th ray path can be expressed as:

$$\mathrm{V}H_i = \sum_{j=1}^{n} d_{ij} x_j \tag{2}$$

The energy attenuation value $\mathrm{V}H_i$ can be obtained from the measured value and the correction value $8.68 \ln r_i$ (Xiao et al. 2017):

$$\sum_{j=1}^{n} d_{ij} x_j = H_0 - 8.68 \ln r_i - H_i \tag{3}$$

In the coal seam working face, the radio wave is emitted from multiple points, and the coal mining face is covered multiple times. By performing multi-point receiving measurement on each source, one can get the matrix equation of the following large sparse matrix:

$$\begin{bmatrix} d_{11} & d_{12} & \mathrm{L} & d_{1n} \\ d_{21} & d_{22} & \mathrm{L} & d_{2n} \\ \mathrm{M} & \mathrm{M} & \mathrm{L} & \mathrm{M} \\ d_{n1} & d_{n2} & \mathrm{L} & d_{nn} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \mathrm{M} \\ x_n \end{bmatrix} = \begin{bmatrix} \mathrm{V}H_1 \\ \mathrm{V}H_2 \\ \mathrm{M} \\ \mathrm{V}H_n \end{bmatrix} \tag{4}$$

2. Principle of radio wave tomography correction method for undulating coal seams

2.1 The impact of coal seam undulation

3D penetration tomography is a more feasible method to overcome the influence of coal seam inclination on radio wave tomography. But this method still has some unsolved difficulties in the inversion of the radio wave computed tomography in coal mines. Jackson et al. used boreholes on the ground construction to perform cross-hole velocity tomography for inversion to obtain the 3D structural characteristics of coal seams (Jackson et al. 1995). Due to the limited numbers of boreholes, the data density in the horizontal direction is not enough, which in turn causes the underdetermined problem of the velocity equation. The same problem also presents in the 3D radio wave tomography between two roadways. Since the signal source and receiver are both arranged

in the roadway, the data in the depth direction is not enough. Therefore, the underdetermined problem of the absorption coefficient equation is more serious.

When performing radio wave penetration tomography of coal seam working surface, the data volume of radio wave penetration field strength is often insufficient due to the limitation of the test space. When performing 2D imaging inversion, because the coal seam undulation is not considered, the number of grids required for inversion is small, and the amount of data is just enough, as shown in Fig.2-1a. Therefore, when switching from 2D inversion to 3D inversion, multiple grids must be set in the Z direction, as shown in Fig.2-1b. Due to the lack of data, the rays can only pass through a part of the grids. For example, in Fig.2-1b, only grids 1 and 2 have data lines passing through, while grids 3 and 4 do not. This phenomenon will greatly aggravate the under-determinism of the matrix equation.

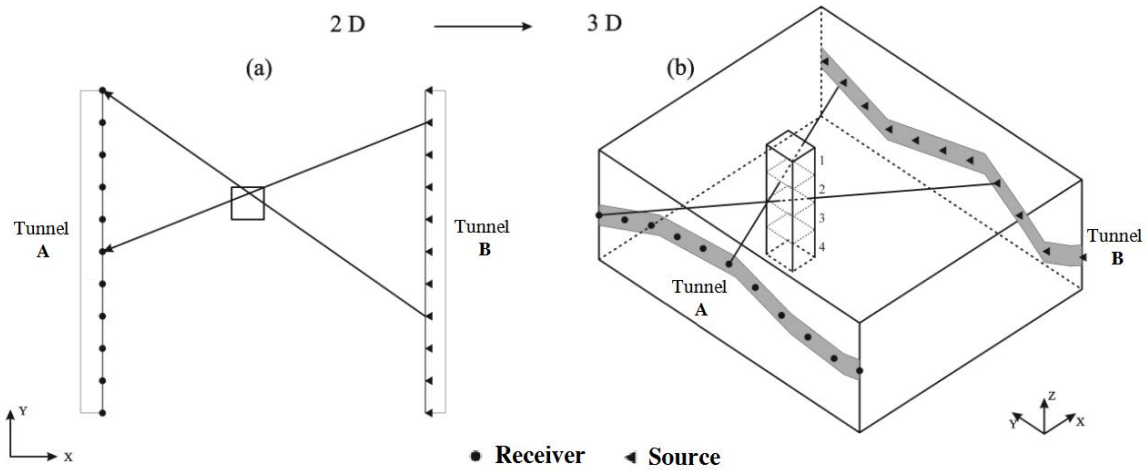


Fig.2 Schematic diagram of the underdetermined equation of 3D tomography of coal seam working face

2.2 The method to solve the influence of coal seam undulation

3D penetration tomography requires sufficient data in the vertical direction. But the measurement conditions of the coal seam working face are unable to meet the requirement. Based

148 on the current technical conditions, we proposed a technical scheme similar to the 3D attenuation
149 coefficient electromagnetic penetration tomography. The essence of this scheme is a simplified 3D
150 inversion model, that is, a plate-shaped inversion model with only one large grid in the vertical
151 direction. The solution adds an elevation parameter to make the ray tracing travel path more
152 accurate. Meanwhile, the number of grids in the Z axis direction is 1, making the electrical model
153 essentially 2D, thereby solving the problem of an underdetermined 3D attenuation coefficient
154 equation.

155 2.2.1 Ray tracing

156 Ray tracing is a common forward modeling method with very concise and intuitive
157 calculation. It is often used to indicate the ray propagation path in complex geological conditions.
158 These methods are mostly based on the least attenuation between 3D adjacent grid nodes. For
159 example, the 3D finite difference ray tracing method calculates and selects the minimum
160 attenuation between seven adjacent grid nodes. Because the pseudo-3D model has only one grid in
161 the Z direction, the 3D finite difference ray tracing is obviously not applicable. To this end, we first
162 performed a 2D ray tracing on the XY plane of the model and brought in the even elevation
163 difference between the source points and the receiving points to calculate the ray length in each 3D
164 grid. The finite difference method first requires the numerical model to be meshed discretely. The
165 equation is then constructed through the dB value of the known grid nodes. Solving the equation
166 can obtain the dB value of other nodes in the grid. So, the dB value of adjacent nodes is obtained
167 according to the above method, and the dB value of all grid nodes in the model is calculated by
168 repeating the above process. According to the smallest change direction of the dB value, that is,
169 the smallest attenuation coefficient, the propagation path of radio wave penetration in the model
170 can be obtained. Further, according to the known relative position relationship between the source
171 and the receiver, the length d_{ij} of the i-th ray in the j-th grid can be obtained in 2D condition.
172 Knowing the elevation difference h_i of the i-th ray, by adding the average of the total elevation
173 difference to the passing M grids, one can get the ray length D_{ij} in 3D condition.
174
175
$$D_{ij} = \sqrt{d_{ij}^2 + (\frac{h_i}{M})^2} \tag{5}$$

176

177 2.2.2 Construction of the inversion equation and related calculation

178 Based on the above ray tracing results, the expression of radio wave energy attenuation is

179 $$\mathrm{V}H_i = \sum_{j=1}^{M} D_{ij} x_j \ (i = 1, ..., N) \tag{6}$$

180 where x_j is the electromagnetic wave energy attenuation coefficient in the j-th grid, D_{ij} is the length
181 of the j-th grid on the i-th ray, N is the total number of rays, and M is the number of grids.

182 At this time, a grid matrix A($N \times M$) can be established in the detection area, forming the
183 following matrix equation:

184 $$x = A^{-1}\mathrm{V}H \tag{7}$$

185 Solving the coefficient matrix of Eq.7 can obtain the distribution information of the attenuation
186 coefficient in the detection area. Many methods have been proposed to obtain the coefficient
187 matrix. Of them, the most commonly used methods include the algebraic reconstruction technique
188 (ART), simultaneous iterative reconstruction technique (SIRT), least square QR decomposition
189 (LSQR), and singular value decomposition (SVD). Because SIRT has advantages such as better
190 convergence speed, good calculation efficiency, and solution stability, it is adopted in the inversion
191 calculation in this study.

192 **3. 2D numerical simulation experiments**

193 3.1 Theoretical basis of GprMax forward simulation

194 GprMax software was used to carry out the numerical simulation calculation of the radio
195 wave tomography. GprMax software is a 2D and 3D numerical simulation software for
196 electromagnetic waves based on finite difference time domain (FDTD) algorithm and perfectly
197 matching layer (PML) absorbing boundary conditions (Giannopoulos 1997; Yee 1966). The
198 software can simulate the field distribution of electromagnetic waves in different relative
199 permittivity media and anomalous body models to obtain electromagnetic wave response signals
200 of underground layers and anomalies.

3.2 Forward simulation of the horizontal coal seams

To fully understand the propagation law and wave field characteristics of radio waves in coal seams, it is necessary to construct a 2D electrical property model of coal-measure formation and analyze the factors affecting radio wave propagation through electromagnetic wave simulation data. Table 1 shows the lithology of the coal seam as well as its roof and floor and the typical electrical parameters of non-magnetic conventional media (Jol 2011).

Table 1 Parameters of media used in the model

Items	Relative permittivity ε_r	Relative conductivity σ ($ms.m^{-1}$)
Coal	3	0.0001
Sandstone (wet)	20	0.1
Limestone	7	0.5

The simulation model is 250 m × 100 m in size and symmetrical along the middle layer of the coal seam with a thickness of 10 m. The simulation grid step length is $\Delta x=\Delta y=0.5$m, and the simulation time window $t_w=30$ μs. A continuous sinusoidal wave with a frequency of 1 MHz and an amplitude of 10^5 is emitted in the coal seam. The initial position of the emission source was set at the position (50m, 50m), and 30 receivers were set within the position (55 m-200 m) with a spacing of 5 m. The schematic diagram of the numerical model is as follows:

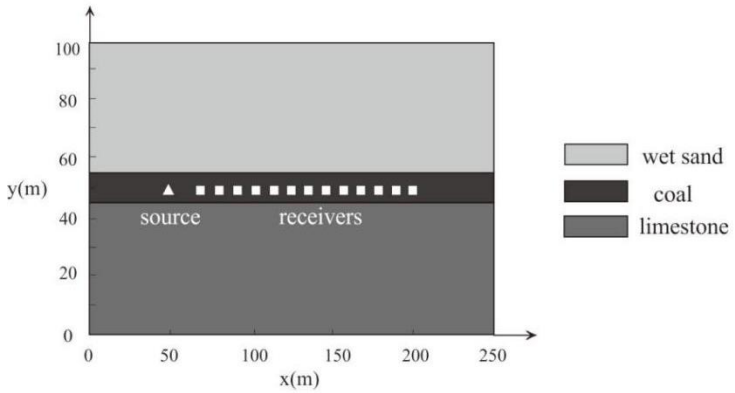
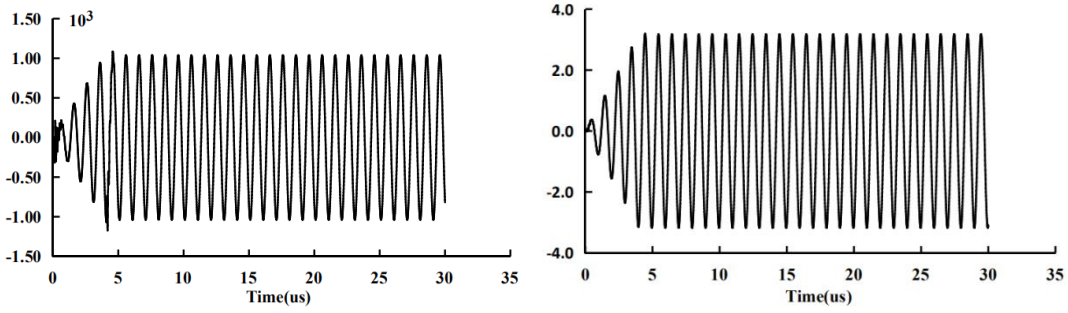


Fig.3 Numerical model for forward simulation of horizontal coal seam

Based on the above 2D model, the corresponding two-component numerical simulation signals are obtained. Fig.4 shows the ez component of the electric field and hx component of the magnetic field at the receiver at 70 m.

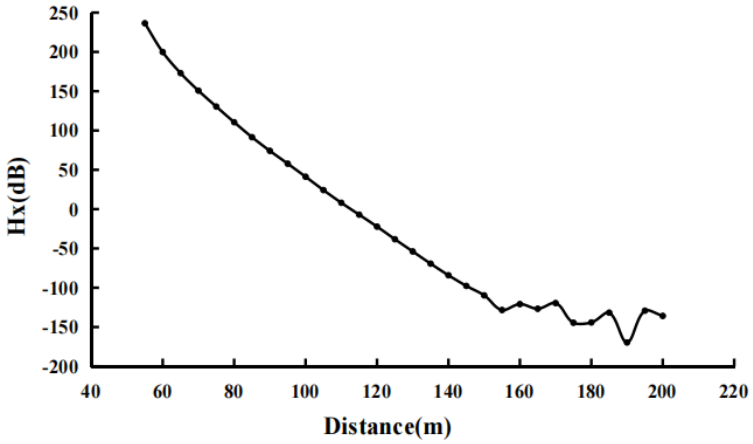


(a) ez component diagram of the electric field (b) hx component diagram of the magnetic field

Fig.4 Signal diagram at 70 m of the horizontal model

The numerical simulation results generally show the characteristics of the sine wave. At the first cycle of the sine wave, the waveform's amplitude is modulated, which has a slight influence on the simulation results. Further, the hx component signals of each receiver in the same time period are transformed by fast Fourier transform. The amplitude A corresponding to the frequency of 1MHz in the transform result was selected to calculate the dB value of each received signal according to Eq.(8):

$$dB = 20 \times \log A(f) \tag{8}$$



232

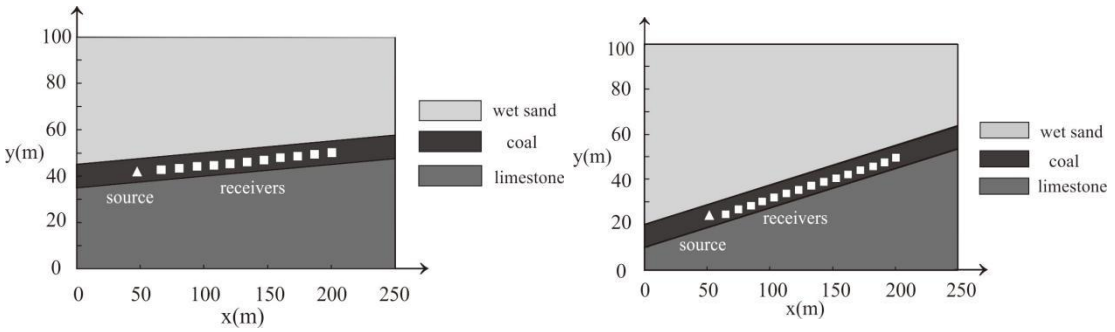
233 Fig.5 Energy attenuation curve of hx component of the radio wave

234

235 It can be seen from the curve of dB value with distance changing (Fig.5) that with the
236 propagation of electromagnetic waves, the dB value of the hx component signal shows a regular
237 attenuation trend before 150 m, which proves that the energy attenuation of radio waves
238 propagating in the coal seam within the distance between the source and the receiver of 5 m-100
239 m is in line with the approximate linear attenuation law: the fitting attenuation coefficient of the
240 hx component is about 5.4 dB/m. After 150 m, the energy is too small. Thus, the calculation error
241 leads to a decrease in the data signal-to-noise ratio. But in general, dB attenuation of the hx
242 component signal of the radio wave in the coal seam shows an approximately linear relationship
243 with the propagation distance. This law lays the theoretical foundation for radio wave penetration
244 tomography.

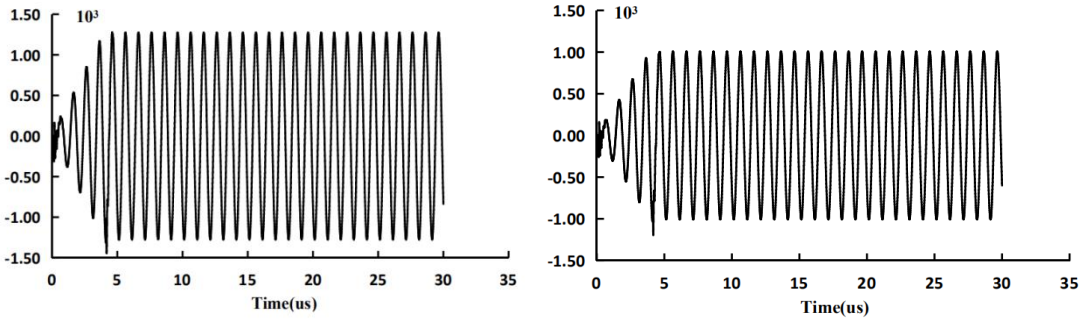
245 3.3 Forward simulation analysis of the inclined coal seam

246 Several 2D models were constructed using the same medium material for the horizontal coal
247 seam model to simulate the inclined coal seams of different inclinations. These models were 250
248 m × 100 m in size and had a coal seam thickness of 10 m (Table 1). During the experiment, the
249 grid step length is set at $\Delta x=\Delta y=0.5$ m, time window $t_w=30$ μs, and the inclination as 1.1°, 3.4°,
250 5.6°, 7.8°, 10°, 11.1°, 12.2°, 14.3°, and 16.4°, respectively. Fig.6 shows two numerical simulation
251 models of coal seam with an inclination of 3.4° and 11.1°, in which the electromagnetic wave was
252 emitted at 50 m and the distance between receivers was set at 5 m (55 m - 200 m).



a) The model with an inclination of 3.4° (b) The model with an inclination of 11.1°

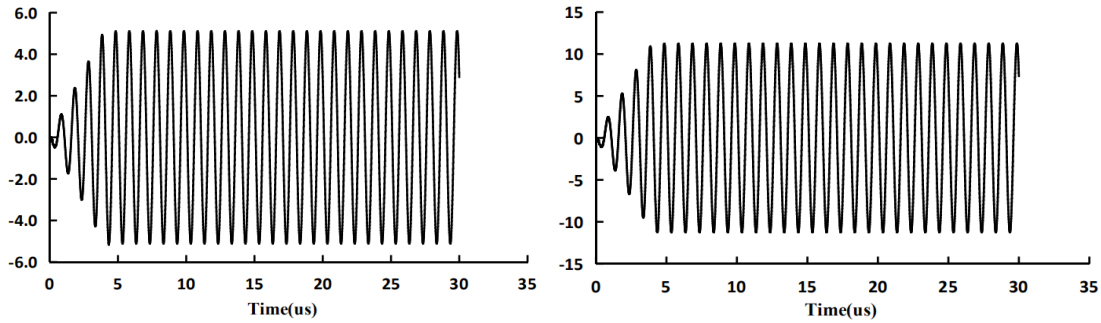
Fig.6 2D numerical simulation model of coal seams with different inclinations



a) The electric field component (ez) in the coal seam with an inclination of 3.4°

b) The electric field component (ez) in the coal seam with an inclination of 11.1°

Fig.7 Electric field in coal seams with different inclination at 70 m



a) The magnetic field component (hx) in the coal seam with an inclination of 3.4°

b) The magnetic field component (hx) in the coal seam with an inclination of 11.1°

Fig.8 Magnetic field component in coal seams with different inclination at 70 m

Based on the 2D numerical model of the inclined coal seam (Fig.6), the numerically simulated electric field ez distribution (Fig.7), as well as magnetic field hx distribution (Fig.8) of the inclined coal seams can be obtained. Compared with the electric field component of the horizontal coal seam in Fig.4(a), the inclination of the coal seam causes the reduction of the electric field component. As the inclination of the coal seam increases, the electric field component decreases, while the magnetic field component continuously increases. Therefore, it is more suitable to use radio wave magnetic component data for inversion in the exploration of coal seams with great inclination.

Compared with the magnetic field component diagram of the horizontal coal seam in Fig.4(b), the inclination of the coal seam also affects the amplitude of the hx component. To facilitate the comparison with the 3D numerical simulation results, we selected the hx component signal at 100 m in the numerical simulation result to calculate the dB value of the hx component of coal seams with different inclinations and analyzed the influence of changes in the inclination on the hx component. It can be seen from Fig.9 that at a position of 50 m from the horizontal source, as the inclination of the coal seam increases, the dB value of the hx component gradually decreases.

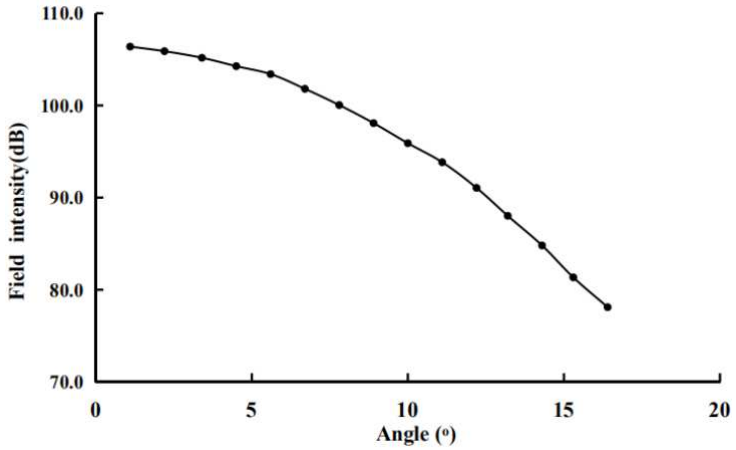
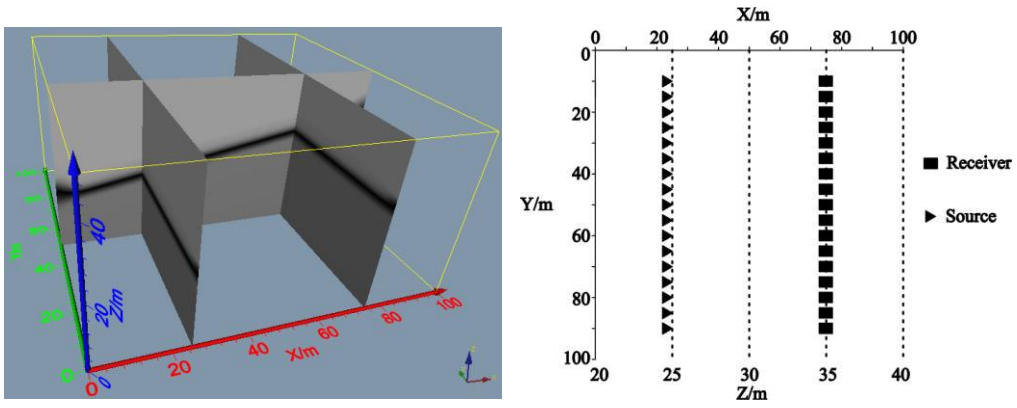


Fig.9 Energy attenuation of hx component at 100 m with different inclinations

3.4 3D numerical simulation experiment

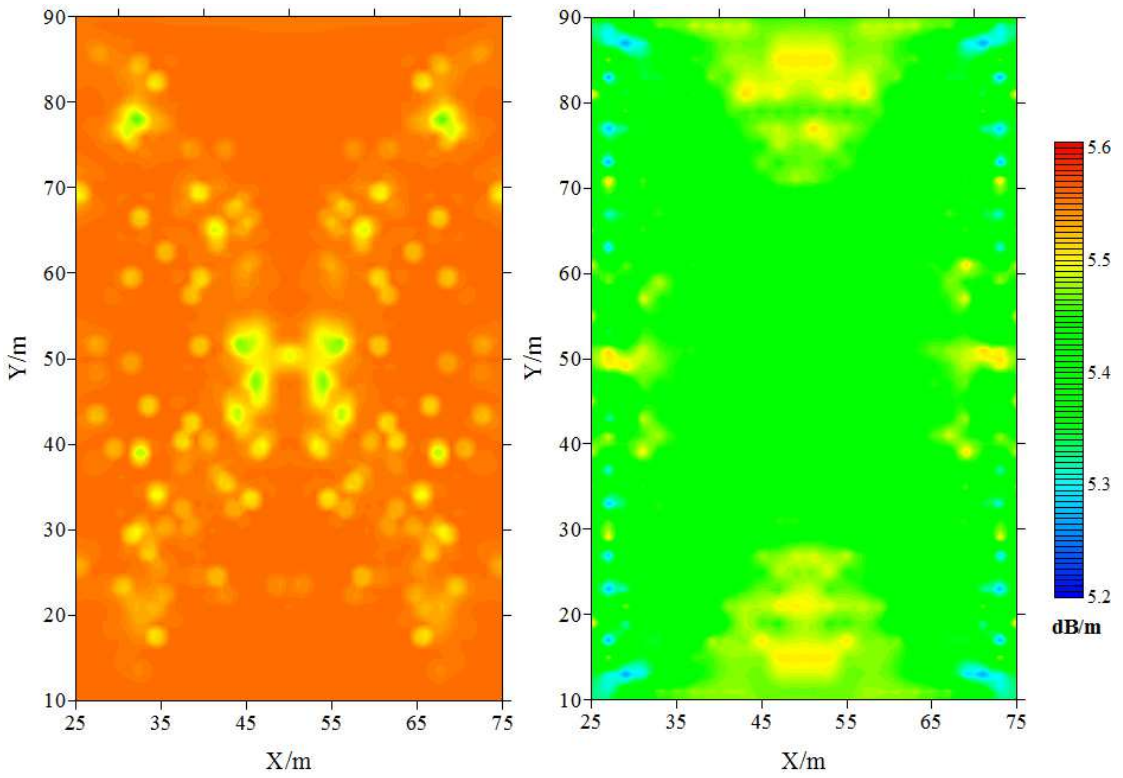
The parameters of the 3D simulation model are determined based on the 2D numerical simulation results with comprehensive consideration of other factors such as the effective propagation distance of radio waves, the influence of the inclination, and the coal seam thickness. The size of the 3D electrical model is 100m×100m×50m, and the coal seam is inclined 11.1° and 10 m thick. Table 1 lists the parameters of the surrounding rock and coal seam. The mesh size is 1m×1m×1m. The radio wave sources and receivers are set on the two lines with positions of x=25m and z=25m as well as x=75m and z=35m, respectively. The source spacing and the receiver spacing are both 5m. Thus, there are a total of 17 sources and 17 receivers. Fig.10 shows the 3D numerical simulation model of the inclined coal seam and the observation system. Consistent with the 2D simulation, a continuous sinusoidal wave with a frequency of 1 MHz and an amplitude of 10^5 is emitted in the coal seam. The simulation time window t_w is 30 μs. We performed Fourier transform on the hy component signal of each receiving point and selected the amplitude A corresponding to the frequency of 1MHz in the transform result to calculate the dB value of hy at each received signal according to Eq.(8). The component dB value is used for imaging calculation after azimuth correction. Based on the conventional 2D attenuation imaging method and the method described in Section 2.2, the conventional 2D attenuation imaging results and the imaging results with coal seam undulation correction are obtained, respectively (Fig.11).



a) 3D model of a coal seam with an inclination of 11.1°

b) Observation system of 3D radio transmission simulation model

Fig.10 3D numerical simulation model and observation system



a) Results of conventional 2D electromagnetic wave attenuation coefficient imaging

b) Results of the improved electromagnetic wave attenuation coefficient imaging

Fig.11 Comparison of hy component numerical simulation imaging using different tomographic methods

Fig.11a shows the results of the conventional 2D electromagnetic wave energy inversion using 3D inclined coal seam numerical simulation data. The inversion results show that the energy attenuation coefficient of the model is mainly concentrated at 5.55 dB/m, which is higher than 5.4 dB/m of the horizontal coal seam. In the 2D imaging calculation, the distance between the source and receiver is a horizontal distance, which ignores the influence of the elevation on the propagation distance. The existence of the elevation difference enlarges the actual propagation distance between the source and receiver, so the inversion coefficient is larger than the actual attenuation coefficient. When the elevation difference is constant, the smaller the distance between the source and the receiver is, the greater the impact on the inversion results. The closer the

horizontal distance between the source and the receiver is, the greater the calculated attenuation coefficient and the more the deviation from the real value.

Fig.11b shows the electromagnetic attenuation imaging result after elevation correction. Because this inversion method takes elevation into consideration, the inversion result is closer to the real value, which indicates that the approximate 3D tomographic inversion method basically eliminates the influence of the coal seam inclination on the tomographic inversion of electromagnetic wave attenuation coefficient. Numerical simulation experiments further verify the feasibility and effectiveness of the inversion method described in this study.

4. Field Test

4.1 Experiment site overview

A coal mining face in Xieqiao mining area, Anhui Province, China, was selected as the experimental site. The coal seam mined at this working face is No. 8 coal seam with the thickness stabilized at 2.5 m and thinner local coal thickness due to structural influence. The overall shape of the working face is a monoclinic structure with the coal (rock) layer inclination angle being 15° on average, the elevation difference between the two detection roadways stabilized at about 50 m, and a simple geological structure. In the actual measurement experiment, the transmission radio wave energy attenuation coefficient in the coal seam is relatively small, which is more suitable for the verification of the imaging method described in this study.

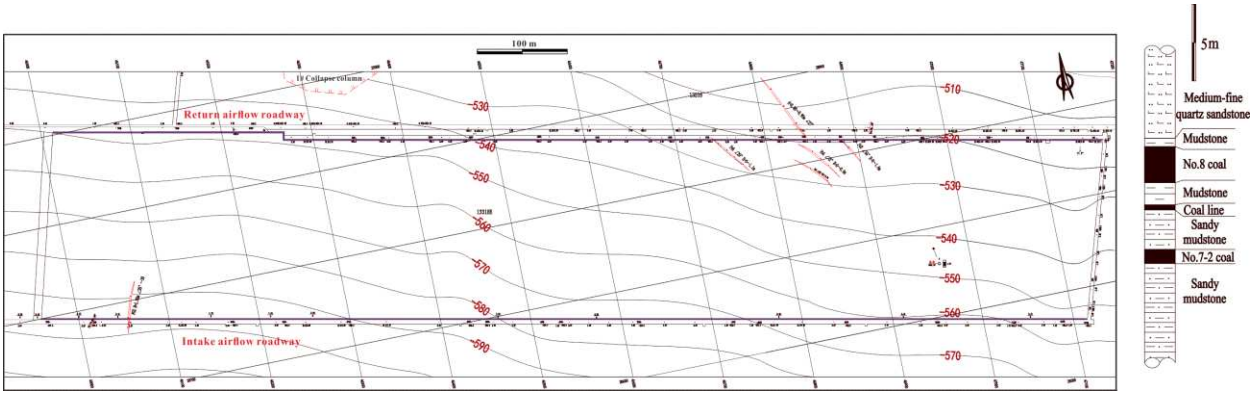


Figure 12 Contour map and comprehensive columnar shape of the measured coal seam working face floor

4.2 Detection method and construction layout

In the experiment, WKT-6 radio wave tunnel perspective instrument was used, and the transmitting source and receiving antenna with a frequency of 0.365 MHz were selected for detection. The detection method adopts the fixed-point intersection method. A total of 33 emission points were arranged every 80 m in the air inlet and return lanes. On the other side of the roadway, receiving points were arranged every 10m, corresponding to each emission point. In addition, in the fan-shaped symmetrical section of another roadway, 21 receiving points were set up to ensure that each physical measurement point in the roadway was covered more than twice.

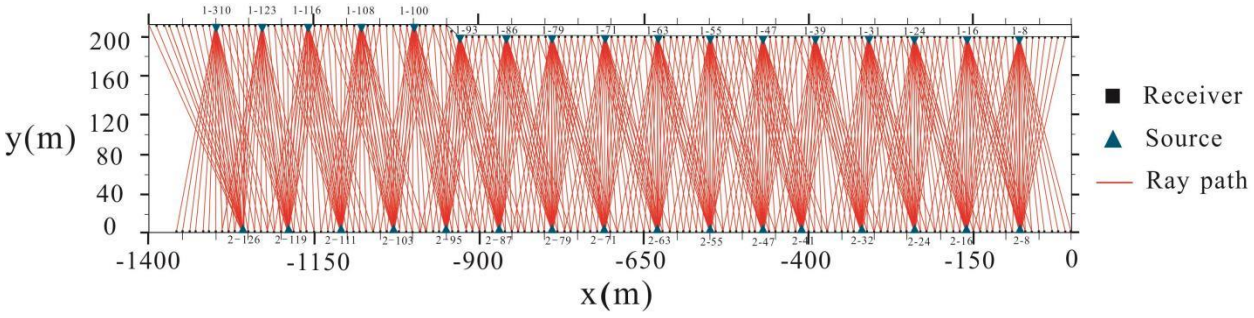
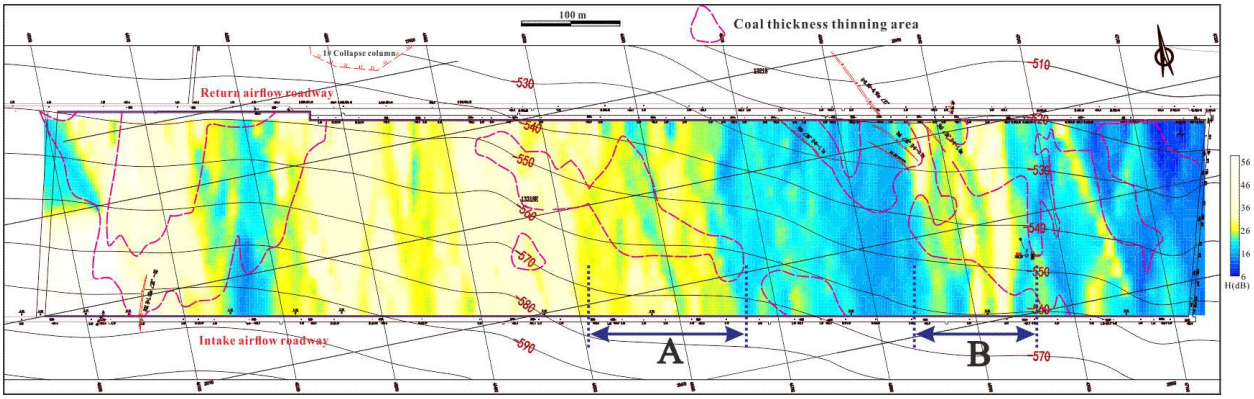


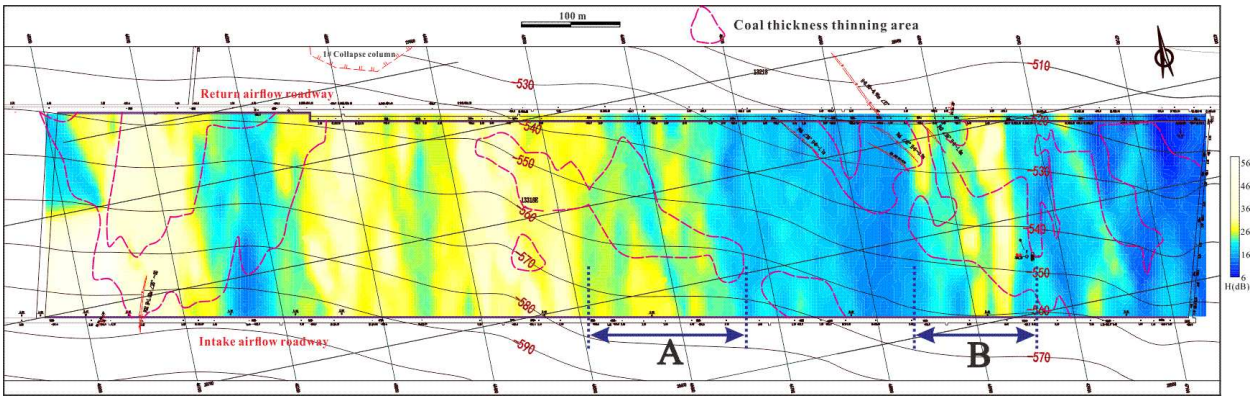
Figure 13 Observation system and ray path of the actual experiment

4.3 Test result comparison and analysis

According to the results of the measured transmitted radio wave field strength, the parameter distribution in the coal seam working face was obtained by inversion. The higher the parameter is, the more stable the coal seam; the lower the parameter is, the greater the possibility of abnormality. The area delineated by the magenta dashed circle is the area where the coal thickness became thinner after mining the work face. The blue area in Figure 14a generally corresponds well to the coal thickness thinning area, indicating that radio wave exploration is highly sensitive to abnormal coal thickness. But at the same time, there are two areas that do not correspond well, namely A and B. The coal thicknesses in both A and B sections have become thinner, but the inversion parameter values appear to be high values, which are inconsistent with the actual situation. Figure 14b shows the inversion result after terrain correction. The parameter values in the figure are slightly reduced as a whole. In areas A and B, the inversion value decreases significantly and coincides with the area where the coal thickness becomes thinner. The actual measurement experiments show that the terrain correction method has achieved good application effects.



(a) Inversion results of the measured field strength values using the conventional two-dimensional method



(b) Inversion result of the measured field strength values using the improved method

Figure 14 Comparison of the inversion results of the measured field strength using two different methods

5. Conclusion

1) The dB value of radio electromagnetic waves in the coal seam attenuates in an approximately linear manner, and the linear tomographic inversion is suitable for electromagnetic wave attenuation imaging. The inclination of the coal seam has a great influence on the energy attenuation of radio waves. As the inclination increases, the electric field component decreases gradually, and the magnetic field component increases gradually.

2) This study proposes to use an approximate 3D inversion method to eliminate calculation errors caused by coal seam undulation. 3D numerical simulation experiments and field test verified the feasibility and effectiveness of the inversion method to eliminate the error caused by the influence of the coal seam inclination on the tomographic inversion of electromagnetic wave attenuation coefficient.

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