First International Symposium on Mine Safety Science and Engineering

Advanced forecast of coal seam thickness variation by integrated geophysical method in the laneway

Wang Bo\textsuperscript{a,b,*}, Liu Sheng-dong\textsuperscript{a,b}, Jiang Zhi-hai\textsuperscript{b}, Huang Lan-ying\textsuperscript{b}

\textsuperscript{a} State Key laboratory of deep geomechanics & underground engineering, China University of Mining and Technology, Xuzhou 221008, China
\textsuperscript{b} School of Resource and Earth Science, China University of Mining and Technology, Xuzhou 221008, China

Abstract

Coal seam thickness variation has a direct relationship with coal mine design and mining, and the mutation locations of the thickness are generally the gas accumulation area. In order to justify the feasibility and validity of advanced forecast about the thickness change, we carried out geophysical numerical simulation. Utilizing generalized Radon transform migration, coal-rock interface can be identified with an error of less than 2\%. By the calculation of 2.5D finite difference method, transient electric magnetic response characteristics of the thickness variation is conspicuous. In a coal mine the case study indicated that: the reflected wave energy anomaly offer interface information of the thickness change point; the apparent resistivity provide the physical index of the thick or thin coal seam area; synthesizing two kinds of information can predict the thickness variation tendency ahead of the driving face, which can ensure the safety of driving efficiency.

Keywords: advanced forecast; generalized Radon transform migration; 2.5D finite difference method; coal seam thickness

1. Introduction

Coal seam thickness variation mainly results from primary sedimentary environment and late tectonic deformation. The change indirectly affects mining deployment, arrangement and implementation of production plans, and the mutation locations are always rich in plenty of gas, so forecasting accurately the thickness variation is key problem related to the safety production in coal mine \cite{1-3}.

On the ground, there are lots of methods of predicting the thickness and its change, they mainly include:
geological analysis, drilling, geophysical well logging, seismic prospecting and electromagnetic prospecting. In the process of forecast, the ground methods may obtain efficaciously regional information, however they are lack of local information or the forecast accuracy is limited, which can’t meet actual need. So the underground methods are needed. On the underground, there are drilling and laneway prospecting which are direct means of detecting the thickness, but the detection efficiency is low and the construction of drilling may cause potential safety hazards. Therefore, it is very important to adopt geophysical methods which include the elastic wave method, the DC resistivity method, the transient electromagnetic method, and infrared detection, etc. However, each kind of geophysical exploration method has its own characteristic and applying condition, the single method is hard to forecast effectively geological anomalies, the mutation change of coal seam thickness especially. In this paper, analyzing the geophysical feature of the thickness change, combing with the response characteristics of seismic and electromagnetic detection, we adopted seismic reflected wave method to master interface information of the change point, utilized transient electromagnetic method to gain the physical index of the thick or thin coal seam area, so as to detect precisely the variation trend of coal seam.

2. Geophysical preconditions of coal seam thickness

Usually coal seam belongs to the weak medium which has the low speed and low density. According to the theory of wave impedance, the average density is 1800kg/m³ for the coal seam and 2600kg/cm³ for the surrounding rock. The average P-wave speed is 2000m/s for the coal seam and 3500m/s for the stratum. The reflection coefficient is around 0.46, so coal-rock interface is a strong reflection interface, which is beneficial to adopt the reflected wave method to predict the interface.

Generally in the coal measure strata, the resistivity of diverse stratum is different. The resistivity of the surrounding rock is about $100 \, \Omega \cdot m$, the resistivity of coal seam (bituminous coal) is approximately $300 \, \Omega \cdot m$. When the thickness of coal seam changes, in landscape orientation it mainly appears that the rate between coal and rock varies. If the rate increases, the regional resistivity will augment. Conversely, if the rate reduces, the resistivity will diminish. This is geophysical basis of obtaining the physical index of the thick or thin coal seam area by transient electromagnetic method.

Through the above mentioned analysis, in order to further justify the feasibility and validity, the numerical simulation was carried out.

3. Numerical simulation

3.1. Seismic Numerical simulation

In order to study elastic wave response of the coal-rock interface, based on the wave equation, forward model was computed by finite difference method, then the forward simulation results was calculated by generalized radon transform migration, which can guild the data acquisition, processing and interpretation. Owing to simulate mainly the response of the coal seam mutation interface ahead of the driving face, the design of model is simplified(Fig. 1). Under no circumstance of laneway influence, only considering the P-wave, two groups of interfaces is established in the uniform rock medium. Model length is 200 m and total depth of model is 40 m. The laneway floor is at depth of -20 m. One receiving point and thirty shot points are on the laneway floor. The receiver array extends from 22 m to 80 m. The shot interval is 2m and offset distance is 22m. The P-wave velocity and density of surrounding rock $(1)$ is 3500m/s, 2600kg/m³ respectively. Two coal seam interfaces whose P-wave velocity and density is both 2000m/s and 1800kg/m³ in the position of $x=90$ m, $Z=-15 \sim -27$ m $(2)$ and $x=160$ m, $Z=-15 \sim -27$ m $(3)$ respectively.

The synthetic seismogram parameters are: sampling frequency is 0.2 ms; record length is 150 ms; the wavelet main frequency is 300Hz; the frequency band range is $1 \sim 500$Hz. After F-K and $\tau - p$ apparent
velocity filtering, direct wave and interference wave are removed and the effective reflection wave is extracted, then the depth section (Fig. 2) is obtained by using the generalized radon transform migration. Generalized radon transform migration \(^{[6-8]}\) considers the angle between the ray from the source to the image point and the ray from the receiver to the image point, and calibrates the phase and amplitude by Hilbert transform. The inversion formula is

\[
\langle f(x) \rangle = \frac{4}{v^3} \int dx \left( \frac{p - s}{p - r} \right)^{1/2} \cos \alpha_r + \left( \frac{p - s}{p - r} \right)^{1/2} \cos \alpha_s \right) \times \cos^2 (\alpha_r - \alpha_s) Hu_{sc}(r, s, t = \tau_0)
\]

Where \( \tau_0 = (|p - r| + |p - s|)/v \); \( p \) is the image point; \( r \) is the receiver; \( s \) is the source. \( H \) is Hilbert transform.

From Fig. 2 there are two energy abnormal interfaces in 90m and 156m. There exist the error between the calculation and the reality, and maximum error rate of interface position is 2% (4/200*100%), which illustrate that the coal seam mutation interface can be judged from the reflected wave energy anomaly.

3.2. Numerical simulation of transient electromagnetic method

According to the characteristics of coal measure strata, electrical change is low at the direction of the vertical detection, so it can be treated as the two dimension geoelectric structure. Because the dipole source belongs to 3D source, 3D numerical simulation can be simplified by 2.5D method. Because the
response amplitude of high resistance coal seam is low \cite{9-10}, the longitudinal grids magnify one time. Model length and depth is 240m and 200m respectively. When the resistivity of surrounding rock is $100 \, \Omega \cdot m$, three models (Fig. 3) are: 1) No coal seam model: 100~200m (X direction), -123~-117m (Z direction), the resistivity is $100 \, \Omega \cdot m$; 2) Normal coal seam model: 100~200m, -123~-117m, the resistivity is $300 \, \Omega \cdot m$; 3) Localized thickening coal seam model: 100~200m, -123~-117m, the resistivity is $300 \, \Omega \cdot m$; 110~180m, -123~-135m, the resistivity is all $300 \, \Omega \cdot m$.

Mesh size of forward modeling is 1m×1m. The excitation source situates in the geometric center of the model, and it excites with parallel bedding. Based on diffusion equation of transient magnetic field (Formula 2), wavenumber domain diffusion equation (Formula 3) is transformed by Fourier Transform. Finite difference method is adopted to compute. According to the principle of unidirectional wave
absorbing boundary conditions, the absorbing boundary condition is installed. Inverse Fourier transform is applied by using the piecewise fitting exponential function so that wavenumber domain is transformed back to space domain to achieve results of forward modelling.

\[
\nabla^2 H - \mu\sigma \frac{\partial H}{\partial t} = 0
\]

(2)

\[
\frac{\partial^2 \hat{H}_x}{\partial x^2} + \frac{\partial^2 \hat{H}_x}{\partial z^2} - \lambda^2 \hat{H}_x = \mu\sigma \frac{\partial \hat{H}_x}{\partial t}
\]

(3)

From Fig. 4 it can be observed that, there are three response curves of transient magnetic field over time at the source point. The curves show different response characteristics of the above mentioned three models. On account of the diffusion of electromagnetic field, and there exist obvious electrical difference between surrounding rock and coal seam, starting from 0ms the space distribution of transient electrical field change, so at the source point response amplitude of the no coal seam model is about 0.0003A/m higher than the normal and localized thickening coal seam models. Before 0.0025ms the transient magnetic field isn’t transmitted to the thickening area, high resistance coal seam can’t have an effect on the response of the source point, which leads to the coincidence of response amplitudes between the normal and localized models. As the transient magnetic field diffuse, the thickening coal seam start to affect the space distribution of transient electrical field. The response amplitude of the localized thickening model is lower than the normal model, which shows that the response amplitude is inversely related to the thickness of coal seam. Combing with the electromagnetic induction theory, we can infer that, when the recording response amplitude lessens, the electromotive force reduces accordingly, and the appear resistivity increases, so coal seam may thicken, which is the theoretical basis of detecting coal seam variation by means of MTEM.

4. Case study

In a coalmine in Yima mining area, the minable is only No.II 1 coal seam which is at the bottom of Shanxi Formation. The coal seam thickness changes dramatically (0.3-15.9m), which has caused great difficulties in the aspect of security and high-efficiency production. Therefore, it has a great practical significance that the thickness information is timely mastered before laneway excavation.

4.1. Practical detection in the laneway

At times of actual detection, coal seam mutation interfaces about 100m ahead of laneway were controlled by MSP, and the thick or thin coal seam area were controlled individually by MTEM. On July 18, 2009, with a point +128m in the belt conveyor laneway for zero we finished detection disposal.

Two receiving points were installed in MSP, each point adopted perpendicular X, Y, Z three-component velocity type seismometer, and X-direction was arranged parallel with laneway and was pointed to driving face direction. It utilized instantaneous cap and 110g emulsion explosive to blaze. According to the frequency difference between P-wave and S-wave, P-wave was extracted by high pass filtering and S-wave was extracted by low pass filtering. After desquamation of wave field at the back of the face with adaptation \(\tau - p\) Transform, in the light of direct S-wave 3100 m/s uniform speed, diffraction stack migration was operated, anterior reflected energy homing chart is gained (Fig.2).

From Fig.5, 0m is the position of last receiving point, and it is seen that from 62m to 162m (0~100m ahead of driving face), there exist two group main reflected abnormity interfaces, naming R1 and R2 respectively, 10m and 78m calculated with the face.
Advanced detection observation system of “11 points method” was adopted in MTEM. Two transient electromagnetic measured points whose interval was 3m were disposed in the left and right of laneway respectively, and seven measured points whose interval was 0.5m were arranged in the driving face. The detection device was designed as an overlapped loop line, with multi-turns of 1.5 m×1.5 m. The raw data was processed with apparent resistivity calculation and time-depth conversion[5], and detection result is shown in (Fig. 6). Because the early transient electromagnetic signals are usually distorted, the range of blind detection is 0~8m ahead of the face. Within 8~100m, it is easy to find that there is a relatively high-resistivity area in the section of 12~79m, apparent resistivity is over 60 Ω·m.

Combing with the geological data, collapse column, goaf and fault are not developed in the detection zone, and it is mainly that coal seam thickness change drastically. Therefore, integrating results of MSP and MTEM, according to the conclusion of the numerical simulation, there are abnormal interfaces in the position of 12m and 78m, moreover there appears high-resistivity response in the range of 12~78m ahead of the face, so we interpret that the section of 12~78m is the thick area of coal seam, 12m and 78m are sharp change points of the thickness. The measured profile data in Fig.7 shows that in the position of 10m the thick of coal seam abruptly increases from the normal 3.3m, while in the location of 80m coal seam thickness reduces to 3.0m rapidly. Within scope of 10m~80m, the average coal seam thickness is about 7.5m which increase by 127% compared with the normal, and extreme thickness is 8.9m. Error rate of interface position is 2%. Meanwhile, two mutational sites of coal seam thickness are rich in plenty of gas, so the forecast has guided effectively the safety production of driving.

![Fig.5 MSP seismic wave energy migrated section](image)

![Fig.6 MTEM advanced detection apparent resistivity section](image)

![Fig.7 Measured section of the laneway](image)
4.2. Verification results in other laneways

Meanwhile, we adopt the seismic and transient electromagnetic method to forecast the thickness of coal seam in other laneways of the same coal mine. The detection conditions are shown in Table 2.

<table>
<thead>
<tr>
<th>Laneway Name</th>
<th>Number</th>
<th>Strong reflected energy (yes or no)</th>
<th>High or low resistivity</th>
<th>Interpretation</th>
<th>Actual reveal and validation</th>
<th>Qualitative evaluation / Error rate of interface position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Railway laneway of 11011 working face (the position of driving face: +542.4m)</td>
<td>R1</td>
<td>Yes/High resistivity</td>
<td>Coal seam thicken in the position of +572.4m</td>
<td>Coal seam thicken (6.0m increase 9.5m)</td>
<td>Yes/0%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>Yes/Low resistivity</td>
<td>Coal seam thin in the position of +597.4m</td>
<td>Coal seam thin (9.3m reduce 5.4m)</td>
<td>Yes/8%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>Yes/High resistivity</td>
<td>Coal seam thicken in the position of +602.4m</td>
<td>Coal seam thicken (5.5m increase 7.7m)</td>
<td>Yes/5%</td>
<td></td>
</tr>
<tr>
<td>Railway laneway of 12011 working face (the position of driving face: +337.5m)</td>
<td>R1</td>
<td>Yes/High resistivity</td>
<td>Coal seam thicken in the position of +372.5m</td>
<td>Coal seam thicken (1.5m increase 3.9m)</td>
<td>Yes/0%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>Yes/Low resistivity</td>
<td>Coal seam thin in the position of +417.5m</td>
<td>Coal seam thin (4.0m increase 2.0m)</td>
<td>Yes/6%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>Yes/High resistivity</td>
<td>Coal seam thicken in the position of +427.5m</td>
<td>Coal seam thicken (1.9m increase 4.2m)</td>
<td>Yes/7%</td>
<td></td>
</tr>
</tbody>
</table>

5. Conclusion and Outlook

In this paper it has great effect on the coal-rock interfaces by the forward modeling and inversion calculation which based on the wave equation in full space. The transient electric magnetic response characteristic is conspicuous when adopting 2.5D finite difference method to calculate the thickness variation of coal seam. According to the conclusion of the numerical simulation, we summarize that, in full space, in the process of advanced detecting the change of coal seam thickness, the coal-rock interfaces can be determined from the reflected wave energy anomaly by MSP, and the thick or thin coal seam area can be differentiated from the apparent resistivity by MTEM. From the verification results they are analyzed that, the qualitative evaluation of the thickness variation are forecasted accurately within the scope of 100m ahead of the driving face, and Maximum error rate of mutation interface position is 2%.

Due to the concrete conditions of the laneway, theoretical study of the reflected wave and transient electromagnetic method is far behind practical application. In terms of MSP theory, it need to increase offset at times of data acquisition and separate P-wave and S-wave in accordance with polarization characteristics at times of data processing, moreover consider using common image pointing gathers migration velocity modeling. It must strengthen high resolution inversion of full space in respect of MTEM theory. In order to satisfy the actual demands, we use sufficiently the advantages of all kinds of geophysical methods, utilize fuzzy neural network and wavelet analysis to fuse the multi-information.
Acknowledgements

Financial support for this work, provided by the Natural Science Foundation of Jiangsu Province (BK2009095), the National Natural Science Foundation of China (No. 51004102), the National Science & Technology Support Project of 11th five-year Plan of China (2007Bak24B03) and the State Basic Research and Development Program of China (No. 2007CB209400), is gratefully appreciated.

References