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Concealed fault analysis based on the CT projection matrix

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ABSTRACT

This paper proposes the concept of projection curves based on the theory of CT image reconstruction to probe the internal structure of the working panel prior to formal mining of the working panel. As well as reducing costs, this method provides safe and efficient excavation of the working panel. According to the results of the numerical model and the actual working panel, the new method has been proven to be accurate in detecting the location of the fault that extends into the face. Concealed faults of the internal working panel, as well as the start and end points of the fault, can be detected by this method. Engineering practice has proven that the method is highly reliable, has a highly decisive impact on faults for coal mining, and can be used to guide the safe mining of the working panel.

1. Introduction

In the process of coal mining, untapped abnormal geological bodies are often encountered, resulting in the application of complicated mining technologies, increasing mining costs, reduced recoverable coal reserves, and even frequent catastrophic accidents. In addition, the safety of the underground mining workers is at risk, causing huge economic losses. Therefore, probing smaller geological structures prior to mining is of critical importance to the coal-mining plan as well as reserves estimation, hazard assessment, and groundwater management. At present, the detection methods commonly used in coal mines are electromagnetic CT (tunnel perspective) and seismic wave CT (channel wave CT). Due to the larger size of the working panel, traditional CT observation systems are all designed with a cross-ray covering way by which waves are transmitted in a roadway and received in another roadway, upon which the transmitting and receiving waves are swapped. This approach is prone to cause incomplete projection data resulting in an ill-conditioned projection matrix and serious rank defects.

Many experts have made a large number of explorations directed at the current problems of incomplete projection in CT detection. For example, Peter put forward an overview of the application of geophysics in coal mining; Lavu proposed the radio-wave imaging in a coal seam waveguide using a pre-selected enforced resonant mode; Dong raised several issues over cross-hole resistivity tomography; Cao put forward the application limitations in a pit through technology under complex geological conditions; Zhang considered the iterated Tikhonov Regularization for ill-posed problems; Wang proposed electrical conductivity imaging using dual frequency EM data based on Tikhonov regularization; Liu considered a predictor–corrector iterated Tikhonov regularization for linear ill-posed inverse problems; Ali proposed a balanced combination of Tikhonov and total variation regularizations for reconstruction of piecewise-smooth signals. Sidky raised the problem of making accurate image reconstruction from few-views and limited-angle data in divergent-beam CT; Liu carried out an experimental study in a pit using the high-precision CT tomography measurement method; Guo proposed a small mechanized mining face of the geological structure with radio wave tunnel perspective technology; Yue considered the research and application of cross-hole electromagnetic tomography; and Liu conducted a frequency-domain electromagnetic study of coal and rock medium attenuation characteristics [1–13]. Meanwhile, some other experts put forward new methods. For example, Cao suggested the model-based evaluation method for the imaging inversion algorithms and SASART algorithm; Liu proposed the ART algorithm weight factor of the industrial CT; Li suggested a practical industrial dimensional CT reconstruction algorithm; Huang raised the application of cross-hole radar tomography in studying the characteristics of strata in depth; Sun proposed the influence of transverse dimensions on electromagnetic wave propagation in rectangular tunnels; Chen proposed a CT algorithm with a direct re-targeting feature [14–19]. Chen et al. [20] suggested the fracture mechanical model and criteria of insidious fault water inrush in coal mines.

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These theories have mitigated the influence of serious rank defects on the inversion results to some extent, but still cannot accurately determine the boundary of the abnormal area, the start and end points of the fault, as well as the abnormal structure of the mining face.

This article proposes the concept of projection curve based on grid discretization. Through the observation of curve shape and curvature changes, the location of structures can be accurately identified, thus solving the problem of how to find concealed structures. This provides a major guiding significance for the safe mining of the working panel.

2. CT theoretical analysis

In order to study the distribution of the abnormal areas in the actual working panel, the mining face is usually discretized, dividing the whole area into pixels of L ($L = m \times n$) as shown in Fig. 1.

The total contribution of all grids penetrated by ray i is:

$$F(x, y) = \sum \alpha_{ij} x_j \tag{1}$$

where a_{ij} is the intercept of the straight line L_i in the grid j.

$F(x, y)$ is the projection value of the ray i obtained from the linear array after it passes through the object.

Eq. (1) is abbreviated as the matrix form:

$$B = AX \tag{2}$$

In the above equation, B is the measured data. The matrix A can be obtained according to the ray after the detected two-dimensional area is discretized with the grids. In the actual working panel, only an approximate solution can be obtained from Eq. (2) as the number of projection data is generally much less than that of the unknown pixels.

In the actual solving process, a solution model can be set up as follows:

$$\begin{cases} \min \ f(x) \\ s.t \|B - AX\| \leqslant \varepsilon \end{cases} \tag{3}$$

where X is the pixel of the image that is to be reconstructed, $f(y)$ is the optimized objective function, and ε is the parameter used to measure noise.

There are many criteria for image evaluation. The one commonly used is the objective function of the Tikhonov regularization, namely

$$\min \|Ax - b\|_2^2 + \lambda^2 \|Lx\|_2^2 \tag{4}$$

where $\|\cdot\|_2^2$ is the square of a two-norm vector, λ is the regularization parameter, and L is the regular operator, that are related to the specific form of the matrix system.

The objective function used in this article is that of the Tikhonov regularization. Considering the actual situation of the working panel, each result should be added with a limit. After the pixels meeting the conditions are calculated, the elements in each column should be superimposed to draw a projection curve. Then the derivation of the projection curve is to be conducted to draw a graph with varied curves. The control equation is as follows:

$$\begin{cases} F(x) = \arg\min \|Ax - b\|_2^2 + \lambda^2 \|Lx\|_2^2 \\ s.t \quad x \geqslant 0 \\ \quad y_i = \sum_{j=1}^{m} x_{ij} \end{cases} \tag{5}$$

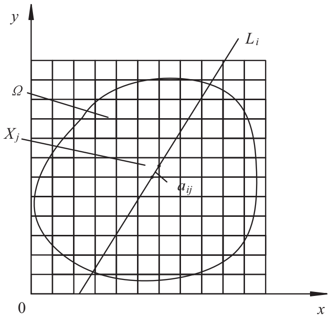

Fig. 1. Grid discretization of the area that is to be reconstructed.

Due to the special structure of the working panel, complete structures cannot be obtained in the reconstruction, but the calculated values are relatively close to the true values in the vertical direction. Therefore, the pixels in each column are superimposed through the projection curve to weaken its own deficiency in transformation. In addition, the current images through CT reconstruction have poor effectiveness and quality in inversion and vague boundary as the pixels between boundaries are closer to each other. Based on the projection curves, the boundary effect can be increased so the clear boundary of the abnormal area can be found.

A smooth curve can be drawn when the discretized result values of each column are superimposed, so the zone with curve change can be intuitively discovered, i.e. the start and end points of the fault, as well as the vanishing points. The problem that the fault in the mining face is difficult to be located can be properly solved through this method. Through further derivation of the curves, the intensity of the mining face varying with the change of its geological conditions can be obtained, which is more conducive for the analysis of the recoverable coal range.

3. Numerical simulation

The structure of the working panel is relatively narrow. Generally, the length of most working panels in China is between 1000 m and 3000 m, and the width along the dip direction of the mining face is approximately 200 m. The detection of the internal structure of the working panel with electromagnetic CT is based on the principle that, due to different properties of various coals and rocks, there are also differences for the absorption of electromagnetic waves, which are transmitted in underground rock stratum. Therefore, the attenuation of electromagnetic energy involves the geological information in the direction of the electromagnetic radiation, so it is possible to reconstruct the geological abnormal areas within the ray coverage with the received electromagnetic energy.

Fig. 2 is a numerical model with length of 1000 m and width of 200 m by reference to the actual working panel. It is assumed that the mining face includes an exposed fault and also a concealed fault in its interior. The layout of the standard observation system (Fig. 3) for the electromagnetic CT of the working panel is used for the ray coverage by which waves are transmitted at one side while received at the opposite side in the approximate pattern of a fan. In this observation system, the ray is not completely projected, resulting in a highly sparse, ill-conditioned coefficient matrix with serious rank defects. Fig. 4 is the reconstructed image with the SIRT algorithm. The location of faults are difficult to figure out through the simple analysis of the reconstructed images. Therefore, a new technique is required.

The special nature of the coal-mining environment determines the incomplete coverage of rays in the layout of the CT observation system. Due to sparse rays, problems such as an abnormal boundary, low resolution and distorted results can occur in the process of image reconstruction. As can be seen from the reconstructed image 4, the image of the CT inversion cannot completely restore the