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Detection of Geological Structural Anomalies Using Slot Wave Tomography Technology

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Abstract: The unfavorable geological structures on the excavation surface of the mine include water bodies, collapses, fractures, etc. These hidden and extremely small geological anomalies are difficult to find in the macroscopic exploration of mines. Therefore, during the construction process of the mine roadway, it is necessary to conduct advanced detection and treatment of the mine roadway. Most mining accidents occur during the construction process of shafts and tunnels. After research, it is found that advanced testing processes are often overlooked due to time constraints. In addition, current advanced testing methods are very complex and have a high false alarm rate and negative alarm rate. Therefore, it is of great significance to find an efficient and suitable advanced detection technology for mine tunnels, to accurately and timely predict the adverse geological structures in front of the tunnels, in order to improve excavation efficiency. This article was based on this, exploring how to detect geological structural anomalies using slot wave tomography technology, and verifying the feasibility of the technology through experiments. The experimental results showed that the resolution of the slot wave tomography imaging technology for geological anomalies numbered DZ1 was about 0.5mm, which was higher than electromagnetic, radar, seismic, gravity, and magnetic methods, respectively.

1. Introduction

According to relevant data, coal mining accidents are mostly caused by geological structures, and accidents caused by road collapse account for 65% of the total accidents. To ensure safety during the mining process, various methods should be used to explore the geological structure before the road surface collapses. At present, underground engineering is being surveyed using methods such as direct current, sound wave, transient electromagnetic, and landmine detection. Among these methods, there is a significant difference between the transient electromagnetic method and the detection method of ground penetrating radar. The scope of application of various detection methods varies. It is difficult for a single detection method to provide a reasonable explanation of geological structure and water content. Due to the diversity of geophysical data and interference from the surrounding environment of measurement points, a single detection method may have multiple or multiple prediction errors.

In Chapter 3, this article introduces the principles of slot wave seismic exploration, slot wave exploration methods, tomographic imaging technology, and image reconstruction algorithms. In Chapter 4, the experimental results and analysis of geological structure anomaly exploration based on slot wave imaging technology are presented. Finally, a summary of the entire article is made.

2. Related Work

Experts have long conducted specialized research on the detection of geological structural anomalies. Airlangga G applied the local outlier factor algorithm to advanced seismic anomaly detection, which is crucial for predicting geological structural turbulence. The comparative analysis highlighted the advantages of the LOF (Local Outlier Factor) algorithm in identifying local biases and handling different data densities [1]. Michalak M P developed a machine learning framework based clustering and analysis of spatial distribution of sampling directions for geological interfaces. His method used Delaunay triangulation and K-means clustering algorithm with Euclidean distance to cluster local unit directions, thereby achieving the minimization of cosine distance within the cluster [2]. To evaluate the radon release in the two fault zones of the Dead Sea, Al-Hilal M measured the normal values of local soil radon in areas far from geological interference. He normalized the probability of radon data through statistical analysis, making the comparison work more effective and facilitating the differentiation between normal radon values and value zones related to geological structures [3]. Yin J conducted a detailed study on the abundance and spatiotemporal distribution patterns of mineral elements in different geological age rock types of the independent tellurium deposit in Dashuigou. The study concluded that the migration of deep ore-forming elements was not achieved through dispersed infiltration between overlying rock particles, but through non widely concentrated infiltration channels. This type of channel is likely to come from the intersection of faults in different directions or from the expansion structure at the intersection of linear faults and circular structures [4]. In order to meet the time requirements in an efficient way, Economou N adopted the resistivity tomography imaging method, which can guide the rapid post acquisition drilling program and is supplemented by drilling video recording, helping to directly detect karst structures. By combining underground video data, direct detection of karst structures can be achieved. After three-dimensional inversion of electrical data, an area with high rock dissolution and severe faults was obtained, and cavities ranging from 0.5 to 6 meters were detected [5]. The detection of existing geological structural anomalies usually relies on geophysical methods such as seismic exploration, electromagnetic exploration, and gravity exploration. These methods have certain uncertainties in determining the specific location and shape of anomalous bodies, and may require multiple explorations to obtain accurate results.

3. Methods

3.1 Principles of Slot Wave Seismic Exploration

(1) Formation of slot waves

Slot waves have dispersion characteristics, and their velocity is related to frequency [6]. Slot wave seismic exploration is a technique that uses the kinematic and dynamic characteristics related to the presence and intensity of slot waves to distinguish geological anomalies in the detection area [7]. When the fracture height is close to or greater than the coal thickness, the waveguide is completely or almost completely blocked, and a reflected groove wave is generated. Under smaller fault spacing, the waveguides of some coal seams can be obstructed, and only a portion of energy can be reflected, resulting in weaker reflection groove waves. When the fault drop is small or there is no fault, there is no reflected trough waves. In seismic exploration, abnormal interfaces can be extracted by analyzing the surface wave travel time of a seismic map. It is also possible to use common center point gathers for stacking to obtain geological anomaly interfaces based on this. The formation principle of trough waves is shown in Figure 1 [8].

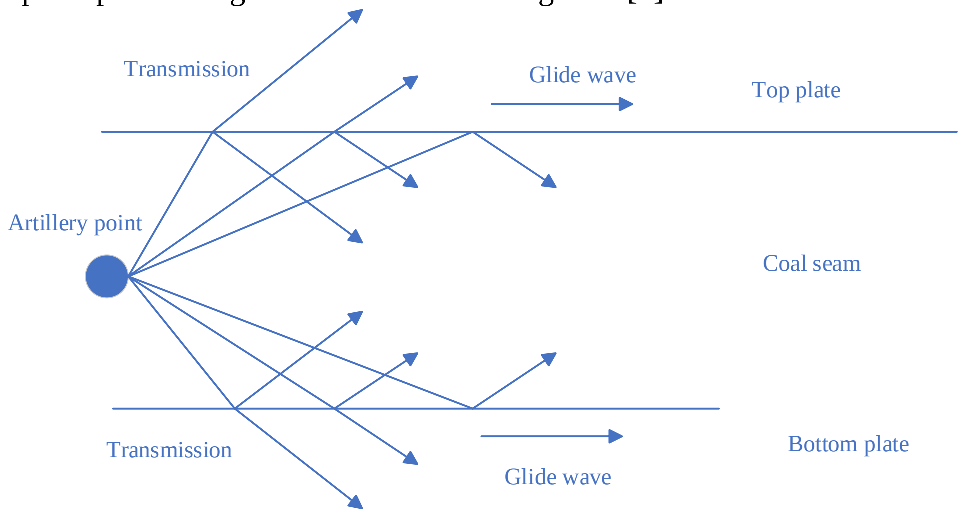

Figure 1: Schematic diagram of the formation principle of slot waves

(2) Principle of slot wave reflection method

The equivalent waveform of the slot wave reflection method is the reflected slot wave. When the slot wave propagates in the coal seam, it encounters the structural plane inside the coal body, which is in contact with the interface of seismic wave impedance (velocity and density difference), forming a reflected slot wave signal, which can accurately locate the structural plane [9]. From Figure 2, it can be seen that the excitation and reception points are set in the same tunnel. The biggest advantage of the slot wave reflection wave method is that it can detect the small structures on both sides of a coal roadway, so it has high practical application value. The slot wave transmission method and the slot wave reflection method are two complementary methods that can be combined under different exploration conditions and objectives to achieve the best results [10-11].

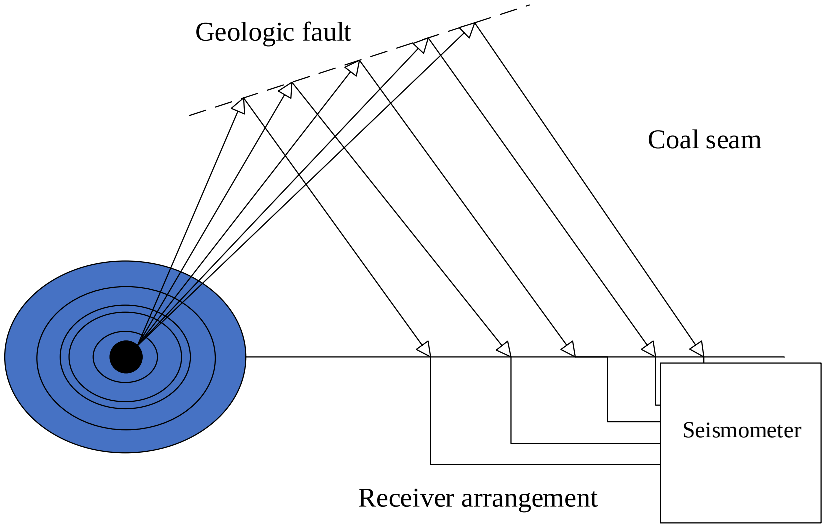

Figure 2: Schematic diagram of slot wave reflection method exploration

3.2 Slot Wave Exploration Methods

According to the positional relationship between excitation and reception, slot wave detection can be divided into two methods: transmission detection and reflection detection [12-13]. As the most basic groove wave detection method, the transmission method has mature data processing technology, simple interpretation of results, wide detection range, and high accuracy. It has been widely used for geological structure detection in coal mining faces. When using the transmission method for detection, the inspector sets up seismic sources and detectors in the two tunnels on both sides of the mining face, and determines the continuity of the coal and rock mass in the area based on the presence and intensity of the transmitted waves. When using the reflection method for detection, the seismic source points and detectors are simultaneously arranged on the side of a tunnel. The arrangement of the observation system is similar to the detection principle and two-dimensional seismic exploration on the ground. The reflection method can detect when only one roadway is formed in the working face, and can detect separately outside the two sides of the roadway, with a wider range of applications [14-15].

3.3 Tomographic Imaging Technology

Tomography technology is a research method similar to medical imaging technology, which analyzes the projection data on the surface of the measured object to obtain its internal physical characteristics. In seismic travel time tomography technology, seismic energy from the medium is received from the surface or underground. On this basis, this article proposes a tomographic imaging technology model based on seismic wave propagation, which uses seismic wave travel time data to reconstruct the velocity structure of seismic waves. Although travel time tomography can achieve high theoretical accuracy, it is difficult to pick up the travel time of non equidistant waves along the same phase axis, and the difficulty increases as the construction becomes more complex [16-17].

Tomography inversion technology (image reconstruction technology) is mainly based on certain mathematical algorithms and reflects the advanced geological structure of coal mines through certain images. The algorithms of tomographic imaging technology are mainly divided into three categories: ① amplitude inversion imaging: using the average amplitude of a certain wave train or the maximum amplitude of a specified wave; ② travel time inversion imaging: using direct wave travel time data; ③ wave field inversion imaging: using information from the background wave field and seismic wave field contained within a given time window. At present, the travel time inversion imaging algorithm has been widely used, and it belongs to the algorithm for solving integral formulas. This article uses travel time inversion imaging to perform tomographic imaging techniques [18-19].

3.4 Image Reconstruction Algorithm

SART (Simultaneous Algebraic Reconstruction Technique) is an improved method of ART (Algebraic Reconstruction Technique). By improving the error correction calculation of ART, it can effectively improve the uncertainty and slow convergence speed brought by algebraic reconstruction methods. Therefore, it has been continuously improved and developed.

The iterative formula for SART is as follows:

$$x_j^{(k+1)} = x_j^{(k)} + \frac{\sum_{j=1} r_{ij}}{\sum_{i=1}^{I} r_{ij}} \tag{1}$$

In the formula, the projection coefficient corresponding to projection $\sum_{j=2}^{N} r_{ij} x_j$ is r_{ij}, and the projection error is:

$$e_i = y_i - \sum_{i=1}^{N} r_{ij} x_j \tag{2}$$

Under the given projection direction, all scanning beams that have a cross relationship with the j-th pixel point (represented by i) are added [20-21]. Only after correcting all pixels $x_j^{(k)}$ can the estimation of the measurement point be corrected. In other words, after calibration, the estimation of the measurement field can be corrected. In other words, the calibration benchmark is within a certain pixel range, based on a certain scanning angle, which can effectively reduce the uncertainty introduced in ART.

In addition, the reason why SART has better computational speed and imaging accuracy than ART is that the former includes all projection data in each iteration process. The introduction of the attenuation coefficient of transmitted slot wave energy is as follows:

During the transmission groove wave construction, a detector is installed in one side of the coal mining face roadway, while explosives are excited in the other side of the roadway. Each pair of shot points and detection points forms a ray. Assuming that on a ray, the amplitude of the slot wave excitation is A_s, and when it passes through the working surface and is received by the detector, the amplitude is A_r. If the ray length is x, then there is:

$$A_r = A_s e^{-\beta x} \tag{3}$$

In the formula, β is the total energy attenuation coefficient of the slot wave on this ray. If the entire working face is gridded and divided into N grids, the path length formed when the ray passes through the nth grid is x_n. When this ray does not pass through the nth grid, then $x_n = 0$. If the attenuation coefficient of the slot wave in the nth grid is β_n, then Formula (3) can be written as:

$$\sum_{n=1}^{N} \beta_n x_n = lnA_s - lnA_r \tag{4}$$

The attenuation coefficient corresponding to each grid is related to the lithology of the medium in that grid and is an unknown quantity required. x_n can be calculated from the observation system, and A_s and A_r can be obtained from the collected data. By inferring β_n from these known quantities, the attenuation effect of the medium in each grid of the working face on the channel wave can be obtained, thereby determining the position and shape of geological anomalies.

4. Results and Discussion

The exploration data in this article comes from a certain mining face, where the main minable coal seam is the Number 6 coal seam at the top. The coal seam has a thickness of 20-27.1 meters and a diameter of 23.02 meters, belonging to a thick coal seam; the height of the coal seam floor is about 812-861m; the pressure of the coal seam floor is 0.12-0.51MPa; the thickness of the coal source is 16.11-27.11m; the diameter is 22.13m, and the dip angle of the coal seam is 0-7 °, 3 °, and

5 °. The coal seam structure is complex, with 0-13 layers of covering layers. The upper wall is composed of siltstone, sandy siltstone, and mudstone, and the lower wall is composed of mudstone. The stability of the coal seam is stable. The upper wall is generally composed of sandstone, sandy siltstone, and mudstone, while the lower wall is composed of siltstone. The stability of the coal seam is relatively stable. The actual samples in the abnormal area are shown in Table 1.

Table 1: Actual samples of abnormal areas

Number	Direction and influence range	Geological explanation
DZ1	Located in the inner part of the working face, 86-134m from the inlet roadway, 311-481m from the cutting eye, in a T-shape, extending about 151m in the working face, with an angle of about 20 ° with the direction of the working face.	Faults greater than 1/4 of the coal thickness
DZ2	Located in the inlet tunnel, 0-94 m from the inlet tunnel, 173-211 m from the cutting eye, S-shaped, running from the inlet tunnel to the return tunnel, and the angle of about 55 ° with the direction of the working face.	Faults greater than 1/6 of the coal thickness
DZ3	Located in the return-airway, 5-89 m from the return-airway, 6-73 m from the cutting eye, in the shape of a strip, extending about 76 m in the working face, with an angle of about 78 ° with the direction of the working face.	Faults greater than 1/5 of the coal thickness

(1) Construction process: The construction of tunnel wave detectors should be carried out in the following order: transportation, exploration, drilling, installation of detectors and instruments, crushing and sealing.

(2) Construction report: According to the construction drawings, the drilling coordinates are determined and adjusted and recorded in special circumstances. The dosage is 0.3 kilograms per cannon.

(3) Before stratigraphic measurement, a simple method is used to determine whether the formation is heterogeneous radially based on the array curve. The apparent velocity obtained from array correlation should be taken as the average wave propagation velocity through the array, and the time for the wave to propagate to the first receiver should be calculated based on this velocity, which is defined as the reference travel time TT_{ref}, that is:

$$TT_{ref} = \int_{s}^{r_1} \frac{dz}{v(z)} + TT_f \tag{5}$$

The evaluation indicators for the experiment include:

(1) Resolution: The resolution of slot wave tomography technology determines its ability to distinguish underground structural anomalies, and high resolution can more clearly display the shape and position of underground anomalies.

(2) Quantitative accuracy: The quantitative accuracy indicators of slot wave tomography imaging technology can evaluate its accuracy in interpreting and identifying underground anomalous body attributes (such as velocity, density, etc.), which is crucial for the interpretation and identification of geological structural anomalies.

(3) Cost effectiveness: The cost-effectiveness of this technology in detecting geological structural anomalies is evaluated, including imaging costs, data acquisition costs, and data processing costs.

(4) Actual application effect: Through actual geological exploration cases, the application effect

of slot wave tomography imaging technology in detecting geological structural anomalies is evaluated, including its feasibility and practicality in geological exploration.

Control group: electromagnetic method, radar technology, seismic exploration, gravity exploration, and magnetic method.

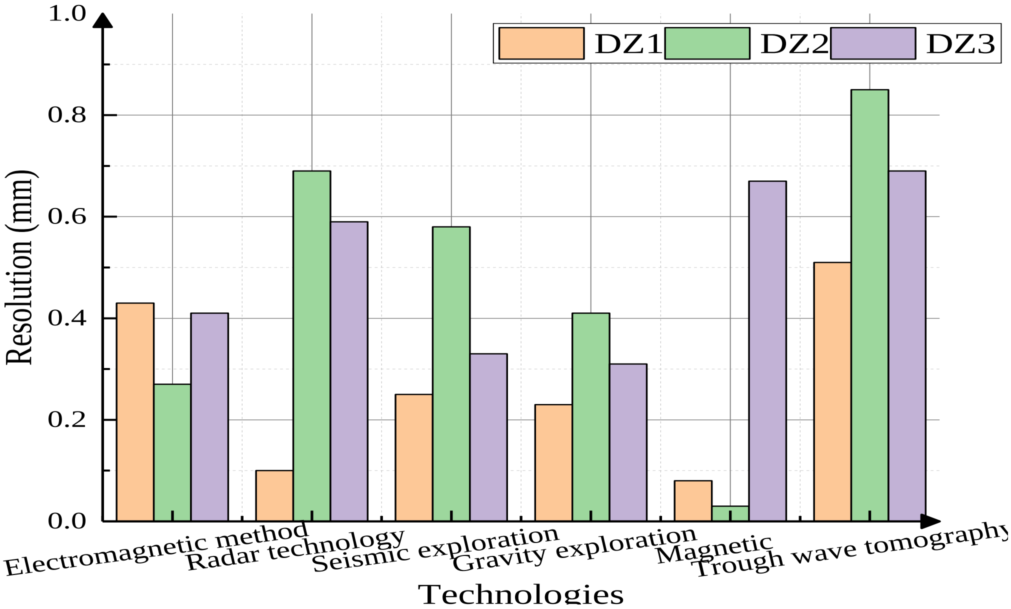

Figure 3: Resolution of different technologies

From Figure 3, it can be seen that different techniques have different resolutions in analyzing the images formed by slot wave data. For the three geological anomaly data samples in this experiment, the resolution of slot wave tomography imaging technology is significantly higher than other technologies. The resolution of the formation image of geological anomalies in DZ1 is about 0.5mm, which is about 0.1mm, 0.4mm, 0.25mm, 0.3mm, and 0.42mm higher than electromagnetic, radar, seismic, gravity, and magnetic methods, respectively. From the perspective of the resolution of the formation image of geological anomalies, the slot wave tomography imaging technology in this article is more conducive to exploring geological anomaly situations.

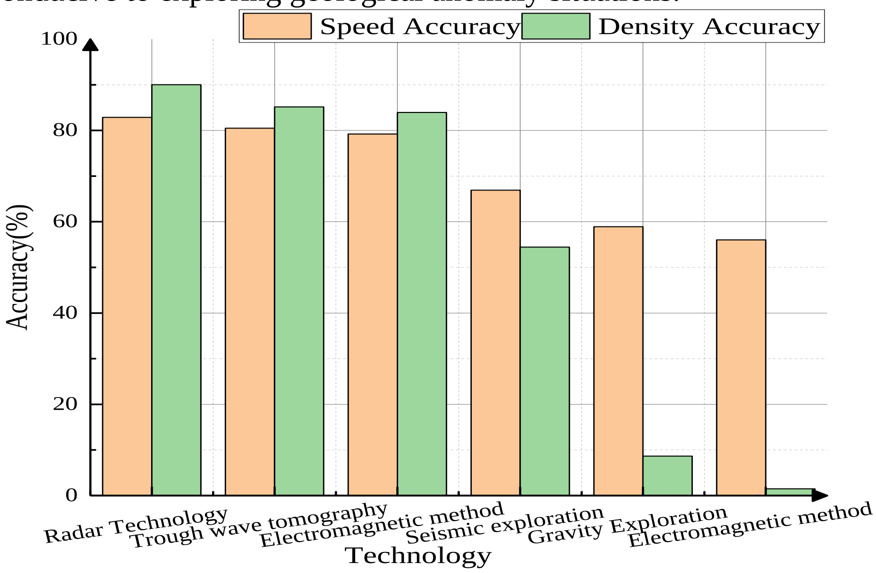

Figure 4: Speed accuracy and density accuracy of different technologies

Seismic exploration is a commonly used geological anomaly exploration technique with fast speed and high accuracy, which can effectively detect underground structures and geological anomalies. Electromagnetic exploration can be used to detect underground mineral resources and groundwater, with fast speed and high accuracy. From Figure 4, it can be seen that the order of velocity accuracy is: radar technology>slot wave tomography technology>electromagnetic method>seismic exploration>gravity exploration>magnetic method. Density accuracy ranking: radar technology>slot wave tomography technology>electromagnetic method>seismic exploration>gravity exploration>magnetic method. The accuracy of this method in terms of speed and density is slightly inferior to radar technology, but it is superior to other technologies.

Due to the fact that the cost of real experiments must be based on different geological anomalies, the resulting costs may vary, but the amount of technical cost in the same situation is the same. The costs of different technologies are summarized. Among them, "+++" indicates a higher cost; "++" indicates average cost; "+" indicates lower cost.

Table 2: Costs of different technologies

Sample	Imaging cost	Data collection costs	Data processing costs
Electromagnetic method	+++	+	+++
Radar technology	+	+	++
Seismic exploration	+++	+++	+++
Gravity survey	+	+	+
Magnetic	+	+	++
Trough wave tomography	+++	+++	+++

From Table 2, it can be seen that the cost of slot wave tomography imaging technology and seismic exploration technology is relatively high. The imaging and data processing costs of electromagnetic methods are relatively high, but the cost of data acquisition is relatively low. Therefore, in exploration, different geological anomaly structure exploration techniques can be selected according to different situations, or two or more techniques can be used.

5. Conclusions

Geological structural anomalies are an important research object in geological exploration, usually referring to the heterogeneity and heterogeneity of underground rock bodies, which may include ore bodies, faults, folds, etc. The accurate detection and identification of these abnormal bodies is of great significance for resource exploration, geological hazard prediction, and so on. Slot wave tomography imaging technology is an advanced geophysical exploration technique that can effectively detect the heterogeneity and anomalous bodies of underground media. Therefore, it has important application value in the detection and research of geological structural anomalies. This article first summarized various aspects of slot wave tomography imaging technology, and then conducted research and analysis through examples to verify the feasibility of various geological anomaly exploration techniques.

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