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RESEARCH ARTICLE

SEISMIC RESPONSE CHARACTERISTICS OF THE COAL SEAM IN THE KASHMIR BASIN BY USING MULTI-ATTRIBUTE FUSION TECHNOLOGY

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ABSTRACT

The increasing demand for efficient and sustainable coal extraction emphasizes the critical need for accurately characterizing coal seams. This study explores the utilization of multi-attribute seismic fusion technology to analyze the seismic response of coal seams in the Kashmir Basin. Through the application of a two-dimensional forward geological model incorporating coal layers and roadways, we extracted seismic attributes such as relative wave impedance, instantaneous amplitude, and frequency, aiming to assess their effectiveness in detecting anomalies caused by roadways within the coal seam. Our findings indicate that these attributes successfully capture variations in seismic response induced by roadways. However, individual attributes may face challenges in differentiation based on roadway fill material. To address this limitation, RGB multi-attribute fusion technology was employed. Compared to single attributes, the fused attribute offers a more comprehensive representation of geological features, enabling clearer visualization of tunnel boundaries and extraction of richer geological information. This methodology enhances the accuracy of seismic data interpretation and simplifies the delineation of complex geological structures within coal seams. This research underscores the potential of multi-attribute fusion technology in advancing coal seam characterization in the Kashmir Basin and beyond. The improved understanding of complex geological structures translates to optimized resource exploration strategies and more informed decision-making in the mining industry.

KEYWORDS

Seismic attribute fusion; geological bodies; coal mining; geological exploration.

1. Introduction

In an era of rising global energy demands, the necessity for efficient and sustainable resource extraction has become increasingly urgent (Bhattacharyya et al. 2023; Pavloudakis et al. 2020). The Kashmir basin, settled among diverse landscapes, presents an unparalleled opportunity for exploration. Its intricate network of coal seams holds immense potential to fulfil the world's growing energy needs (Malkani 2020). Investigating the seismic response properties of coal seams in this area is an important endeavor that brings the accuracy of geophysics together with the complexity of the local geology. With the use of this interdisciplinary method, researchers are able to get important insights into the subsurface structures, which helps them optimize mining strategies, reduce risks, and increase overall efficiency (Chowdu et al. 2022).

In the 1980s, small-scale private mining operations commonly utilized rudimentary mining methods due to economic and technological constraints (Bhattacharyya et al. 2023; Singh and Singh 1995; Skousen and Zipper 2021). However, the absence of comprehensive mining data from this period has resulted in uncertain dimensions of potentially hazardous goaf regions (Chen et al. 2023). These unoccupied goafs pose significant safety risks to future mining and construction activities, necessitating immediate measures to delineate their boundaries and ensure the safe exploitation of forthcoming coal seams (Yuxin et al. 2023). Although considerable attention has been given to identifying traditional goaf sites, relatively little focus has been placed on detecting goaf tunnels (Sun et al. 2024). Geophysical technologies offer numerous possibilities for assessing underground conditions, every having its own benefits as well as drawbacks(Bhattacharyya et al. 2023). The electrical approach, though water-based, is hindered by its shallow detection capabilities, making it less effective in identifying deeper structures (Zohra et al. 2023). Ground-penetrating radar (GPR), renowned for its precision, faces challenges in penetrating deeper levels, limiting its applicability in certain scenarios (Joshaghani and Shokrabadi 2022).

In contrast, the three-dimensional seismic approach boasts unparalleled depth detection capabilities and enjoys widespread use in subsurface imaging (Lu et al. 2021). Pioneering initiatives led by researchers such as Cao *et al*. have advanced the application of three-dimensional seismic technology for direct tunnel identification based on time profiles and tunnel reflection wave characteristics (Cao and Liu 2023). Similarly, Cheng Jianyuan et al. advocate for seismic horizontal slicing as a viable strategy for tunnel identification, particularly in cases where the tunnel cross-section is narrow, necessitating the examination of three high seismic data (Jianyuan et al. 2023). In the crucible of the Kashmir basin, a journey to influence these cutting-edge geophysical approaches, notably three-dimensional seismic technologies, is in progress. By harnessing the transformative potential of multi-attribute fusion technology, researchers aim to unravel the seismic mysteries concealed within its coal seams (Jianyuan et al. 2019). This purpose goes beyond uncovering the Earth's subsurface secret depths. It attempts to safeguard the future of coal mining in the region by ensuring long-term viability and limiting environmental repercussions (Pavloudakis et al. 2020). Our goal in this study is to

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investigate the properties of coal seams' seismic response in the Kashmir basin in order to overcome these difficulties. The Kashmir Basin, located in the region's northernmost portions, is home to a diverse range of geological formations such as coal seams, sedimentary layers, and structural anomalies (Malkani 2020). This geological marvel, which covers around 5,200 square kilometers, is located in an intermontane valley produced by the Great Himalayan Range's branching west of the Ravi River (Singh and Singh 1995). Its oval-shaped basin is bounded by the Pir Panjal Range in the southwest and the Zanskar Range to the northeast as shown in figure 1 (Jianyuan et al. 2019). Our principal goal is to assess how well multi-attribute fusion technology can improve coalfield interpretati on techniques.

Figure 1: Study Area

2. Methodology

The study aimed to examine the seismic response traits of coal seams in the Kashmir basin through advanced seismic techniques, notably multi-attribute fusion technology. For this purpose, a two-dimensional seismic forward geological model was meticulously crafted using genuine depth and thickness data of coal seams in the study area. Specifically, the model featured three coal layers denoted as coal 3, coal 9, and coal 15, each characterized by distinct depths and thicknesses. Furthermore, the model integrated roadways filled with air and water at specified depths, mirroring authentic conditions closely. Seismic forward modeling, employing the acoustic wave equation, was then utilized to simulate wave propagation through the model. This approach unveiled the effects of roadways on reflection waves and seismic wave amplitudes.Subsequently, pivotal seismic attributes, such as relative wave impedance, instantaneous amplitude, and average amplitude, were extracted from the modeling outcomes to scrutinize potential variations resulting from the presence of roadways within the coal seams.

3. Results and Discussions

3.1 Geological Model Design

In order to study the seismic response characteristics of goaf tunnels, a two-dimensional seismic forward geological model was designed with reference to the actual depth and thickness of each coal seam in the study area(Singh and Singh 1995). To facilitate an intuitive understanding of the model, the coal seams and roadways have been enlarged to a certain extent. The actual parameters of the model are shown in Table 1 and figure 2. The model is 1000 *m* long and 1000 *m* deep, with a total of 3 coal layers designed, from shallower to deeper: coal 3, coal 9, and coal 15. Among them, 3 coals have a depth of 500 *m* and a thickness of 4 *m*; 9 coals The depth is 550 *m* and the thickness is 5 *m*; the coal depth is 600 *m* and the thickness is 5 *m*. 3 The coal mine is designed to have two lanes with a width of 5 m and a height of 4 m. The distance between the two lanes is 90 *m.* Lane 1 is filled with air and is located at 455 m in the horizontal direction; Lane 2 is filled with groundwater and is located at 545 m in the horizontal direction.

Table 1: Properties of Strata in the Geological Model

Stratum (medium)	Shock wave speed/($m{\cdot}s^{-1}$)	density/($kg{\cdot}m^{-3}$)	Thickness/*m*
Formation 1	2500	1900	496
3 coal	2100	1400	4
Lane 1 (air)	300	1.29	4
Lane 2(Water)	1500	1000	4
Formation 2	2900	2400	45
9 coal	2200	1500	5
Formation 3	3100	2500	45
15 coal	2300	1600	400

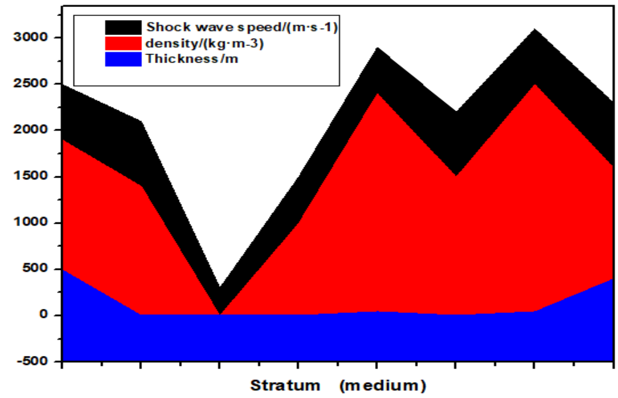

Figure 2: Properties of Strata in the Geological Model

3.2 Forward Modeling Results

This part focuses on the results obtained from the acoustic wave equation forward simulation method (Akbudak et al. 2020). It presents the forward seismic profile, illustrating reflection waves of coal seams and variations in seismic wave amplitudes at roadway locations (Abdelrasoul et al. 2022). Additionally, seismic amplitude attributes extracted along each coal seam are analyzed to provide insights into amplitude anomalies and geological features (Jianyuan et al. 2019).

Figure 3a displays the forward seismic profile, highlighting the reflection wave of the No. 3 coal seam at two roadway locations. The reflection wave of the coal seam below the roadway shows a local amplitude weakening phenomenon, while the reflection wave of the No. 3 coal seam at the two roadway locations exhibits an obvious local amplitude enhancement phenomenon. The change in amplitude is more pronounced in tunnel 1, which is filled with air, compared to tunnel 2, which is filled with water. To further illustrate the amplitude anomalies, seismic amplitude attributes were extracted along each coal seam, as shown in Figure 3b. These attributes provide a more intuitive and clear view of amplitude anomalies in coals 3, 9, and 15. The analysis of these attributes can help identify geological features and amplitude anomalies in coal tunnels.

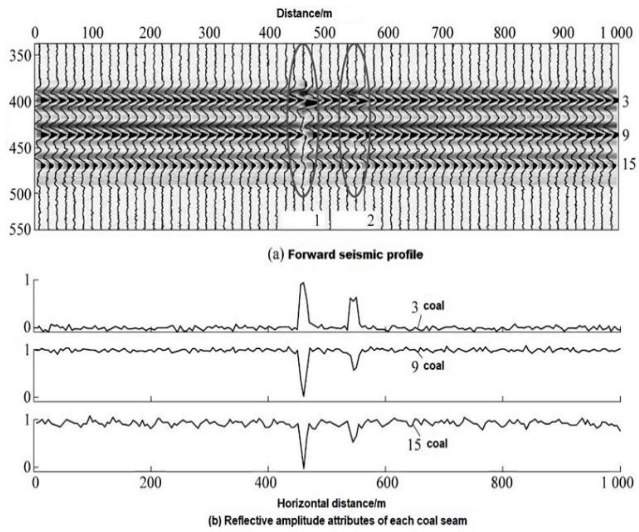

Figure 3: Forward Seismic Profile and Reflective Amplitude Attributes of Coal Seams in a two-Dimensional Geological Model.

3.3 Seismic Attributes Extraction and Analysis

Seismic attributes play a crucial role in characterizing geological features, especially in coal seam analysis (Xi and Yin, 2022). These attributes, including relative wave impedance, instantaneous amplitude, and average amplitude, offer valuable insights into the composition and structure of coal seams (Xi and Yin, 2022). By analyzing seismic data, we can derive measurements related to seismic wave characteristics, aiding in identifying underground phenomena such as river channels, faults, lithological changes, and reservoirs.

In conventional goaf areas, the gradual collapse of the surrounding rock under the pressure of overlying formations leads to the formation of a loosely packed geological body (Yang et al., 2022). This results in a profile characterized by discontinuous and disorderly events with weak reflected energy, as there's no distinct wave impedance interface formed. Conversely, in tunnels or tunnel goafs, the small cross-section prevents immediate roof collapse, often leading to the accumulation of groundwater or air within. When observed vertically, the tunnel can be perceived as a unique geological cavity within the coal seam, sharing the same roof. Here, the presence of a noticeable wave impedance interface allows for the production of visible reflected waves.

To quantify reflection, the reflection coefficient (R) comes into play. It's defined as the ratio of the amplitude of the reflected wave to the amplitude of the incident wave and can be calculated using Equation (1) (Xi and Yin, 2022)

$$R = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (1)$$

Where, R is the reflection coefficient and ρ_1 and v_1 represent the density and velocity of the upper medium of the reflection interface, respectively. On the other hand, ρ_2 and v_2 represent the density and velocity of the medium below the reflection interface, respectively. The product of density and velocity is the wave impedance Z. A negative reflection coefficient indicates a polarity opposite to that of the incident wave. By calculating the main parameters according to equation (1) and the medium parameters in Table 1, it becomes evident that with a constant incident wave amplitude, a higher reflection coefficient at the interface results in a greater amplitude of the reflected wave as shown in table 2.

Table 2: Calculated Reflection Coefficient Of Interfaces

Interface	Reflection Coefficient (R)
Formation 1 - 3 Coal	-0.2358
3 Coal - Lane 1 (Air)	-1 (almost total reflection)
Lane 1 (Air) - Lane 2 (Water)	0.9997 (almost total reflection)
Lane 2 (Water) - Formation 2	-0.1486
Formation 2 - 9 Coal	-0.1627
9 Coal - Formation 3	-0.2571
Formation 3 - 15 Coal	-0.2356

For both air and water, which have significantly lower densities and velocities compared to the coal seam, the reflection coefficient at their interface with surrounding rock is greater than that of a normal coal seam. Therefore, the amplitude of the reflected wave produced at this interface surpasses that of a typical reflected wave. This amplification in amplitude becomes apparent in the section where both the amplitude of the event axis and energy experience an increase. Furthermore, since the reflection coefficient at the air-tunnel interface exceeds that of the groundwater-tunnel interface, the amplitude of the reflected wave in tunnel 1 is greater than that in tunnel 2.

Additionally, Figure 4 presents the seismic attributes derived from the forward modeling outcomes across the specified coal seam. These attributes include critical parameters like relative wave impedance, instantaneous amplitude, and instantaneous frequency. Notably, the relative wave impedance attribute proves instrumental in delineating shifts in formation wave impedance induced by tunnels, while the amplitude attribute emerges as a reliable indicator of underground irregularities associated with tunnels (Bhattacharyya et al., 2023). However, the frequency attribute exhibits limitations in discerning between different fillings within tunnels, as tunnels filled with various media showcase similar abnormal characteristics. Hence, in the context of multi-attribute fusion, precedence should be accorded to attributes such as relative wave impedance and amplitude. Here the analysis reveals a notable subsurface anomaly approximately 600 meters away horizontally, marked by spikes in relative instantaneous amplitude, frequency, and instantaneous frequency. The simultaneous spikes across these three seismic attributes suggest the presence of a geological feature, such as a coal seam or a fault line, with potentially significant implications for coal mining operations.

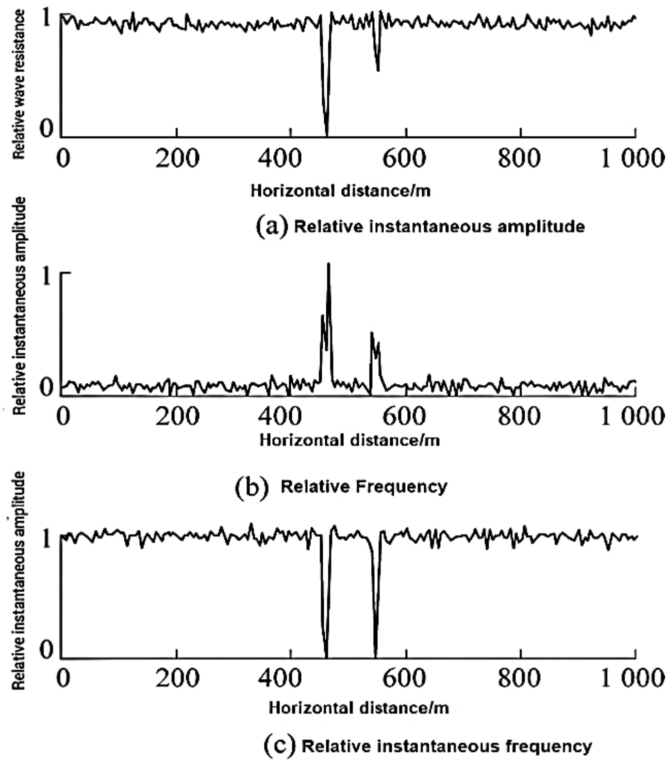

Figure 4: Seismic Attribute Analysis of Relative Instantaneous Amplitude and Frequency

The derivation of seismic attributes from seismic data involves employing nonlinear mathematics (Malehmir et al., 2020). These attributes represent transformed measurements of seismic wave characteristics encompassing geometric, kinematic, dynamic, and statistical aspects. As changes in underground media correspondingly alter seismic attributes, utilizing seismic attributes to study underground abnormal geological bodies is feasible. Seismic attributes offer descriptive capabilities for various underground geological phenomena, including river channels, faults or fractures, lithological changes, and reservoir fluctuations (Xi and Yin, 2022). Consequently, they find widespread application in structural interpretation, stratigraphic interpretation, lithological interpretation and simulation, and reservoir characterization.

3.4 Overview of the study area

The study area is located in the northern part of the Kashmir Basin, where the coal-bearing strata are stable and gentle. From shallow to deep, there are mainly 3, 9, and **15 coal**s in the area. Among them, the depth of coal 3 is 366 ~ 660 m, and the average thickness is 2.58 m; the depth of coal 9 is 418 ~ 688 m, and the average thickness is 4.10 m; 15 The coal depth is 484 ~ 766 m, and the average thickness is 4.32 m. Before the three-dimensional seismic data collection, some main tunnels had been developed along the coal seam to provide the basis for the research.

3.5 RGB attribute fusion

To facilitate attribute fusion, normalization of various attributes was necessary to standardize their values from 0 to 255. Equation (2) was employed for this purpose(Xi and Yin, 2022)

$$z = \left(\frac{x - x_{min}}{x_{max} - x_{min}}\right) \times 225$$

Where:

Z is the standardized attribute value

X is the original attribute value.

X_{min} is the minimum value of the attribute.

X_{max} is the maximum value of the attribute.

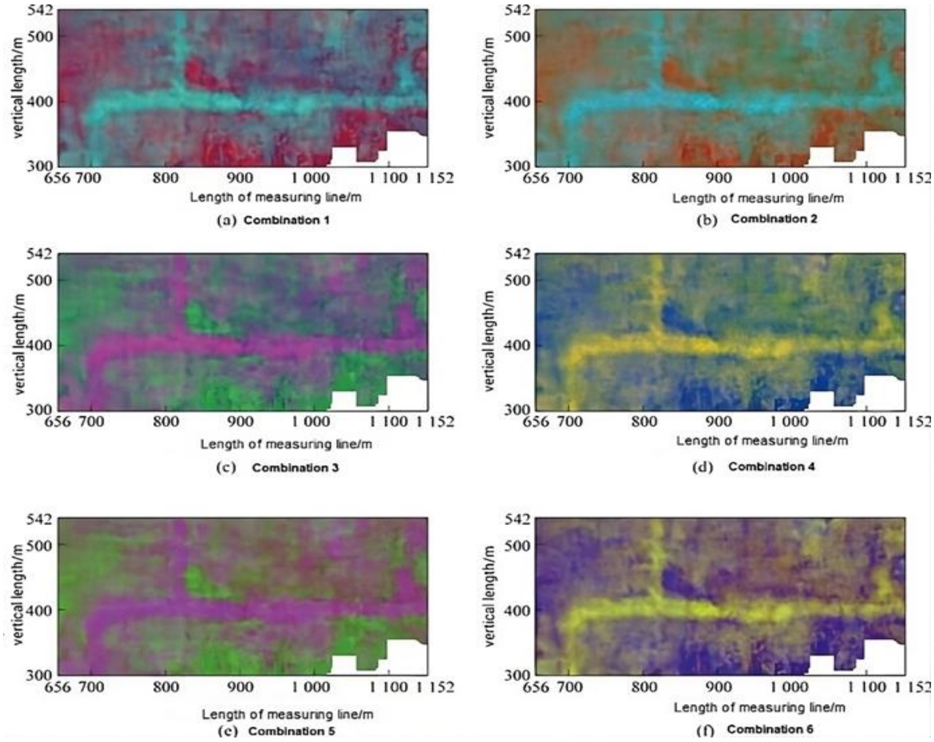

Figure 5: Visualization of Seismic Attribute Fusion: RGB Sequence Fusion Permutations

After normalization, RGB attributes are fused. It is easy to know from the knowledge of permutation and combination that there are six different permutations of the three attributes. Figure 5 shows the attribute fusion results of these six different permutations. Figure 5 shows that the effects of attribute fusion in different orders are similar. Consequently, the decision was made to designate the relative wave impedance attribute as the red component (R), the instantaneous amplitude attribute as the green component (G), and the average amplitude attribute as the blue component (B). The final fusion attribute is obtained by combining these three attributes in the RGB color space. The accuracy of the inversion depends on the known log and the established low-frequency model. The accuracy of the inversion process hinges upon two critical factors: the known log and the established low-frequency model. A comprehensive time-depth relationship between well logging and seismic data is meticulously established by a single individual. Additionally, the low-frequency model is meticulously crafted through seismic interpretation of stratification, fault analysis, and seismic data synthesis. Throughout the inversion process, the spatial variation function is computed, leveraging well logs to guide model interpolation.

Figure 6a presents the relative wave impedance attribute, while Figure 6b illustrates the instantaneous amplitude attribute, Figure 6c shows the average amplitude attribute, and Figure 6d represents the fused attribute In Figure 6, the original attributes exhibit strip-shaped lanes, but the overall lanes appear blurred with intermittent boundaries that cannot be continuously traced. For instance, the relative wave impedance attribute in Figure 6a struggles to identify the roadway boundary in the eastern part of the area, while Figures 6b and 6c show intermittent boundaries in the southern and eastern regions, hindering continuous tracing of the roadway. However, after multi-attribute fusion, the laneway appears more continuous in the fused attribute (Figure 6d), with clearer boundaries, facilitating the depiction of laneway boundaries and extension ranges. Figure 7 presents the results of laneway identification using fusion attributes alongside the results of laneway identification.

Comparison of the actual position of the track: Figure 7a shows the recognition result, and Figure 7b shows the actual position. Figure 7 shows that the fusion attributes' results correspond very accurately to the actual tunnel distribution range and boundary location. Because between the lanes, the distance between them is small (the distance between east-west tunnels is 25 m and the distance between north-south tunnels is 40 m), which is reflected in the seismic attributes and will be superimposed into wider strip anomalies. Different types of coal structures affect the development of CBM through pore structure differences. According to Xu et al. (2019), both fractured-fragmented and primary-fragmented coals are good for gas adsorption percolation. However, primary-fragmented coals have more developed adsorption pores, while fractured-fragmented coals are under a lot of tectonic stress.

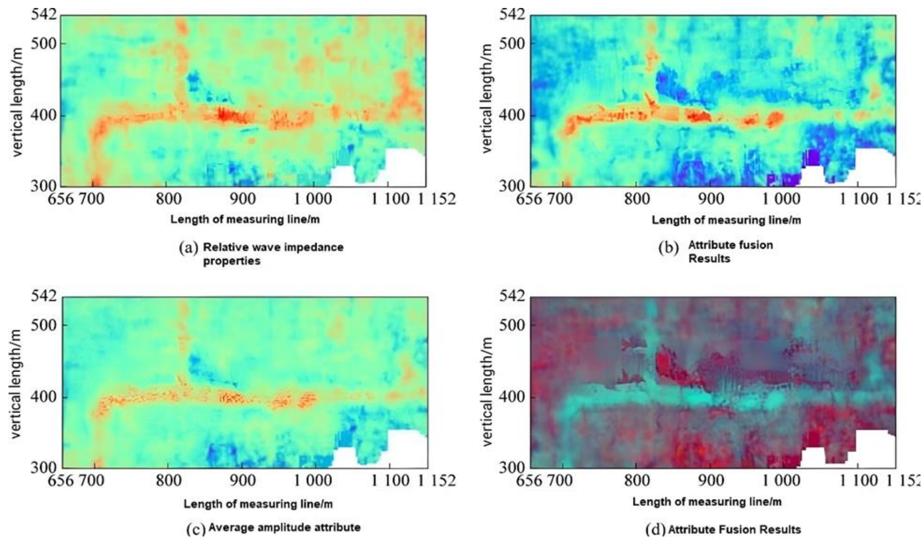

Figure 6. Seismic Multi-Attribute Fusion Results: (a) Relative Wave Impedance, (b) Instantaneous Amplitude, (c) Average Amplitude, and (d) Fused Attribute

Figure 7 shows the results of laneway identification using fusion attributes and the results of laneway identification. Comparison of the actual position of the track: Figure 7a shows the recognition result, and Figure 7b shows the actual position. Figure 7a shows that the fusion attributes results correspond very accurately to the actual tunnel distribution range and boundary location. Because between the lanes, when superimposed, the abnormal bands are weak, making it relatively difficult to accurately identify their locations. The final results demonstrate that the multi-attribute fusion technology can accurately identify the tunnel's plane position and boundary range.

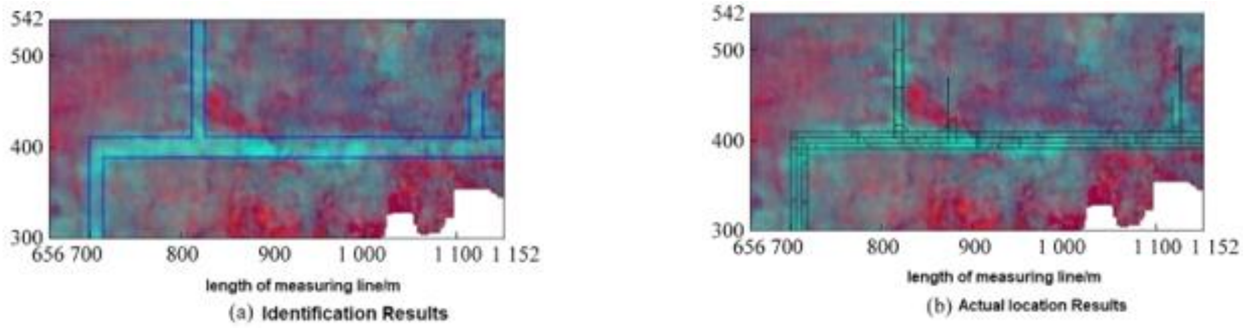

Figure 7: Laneway Identification Results Using Fusion Attributes: Comparison with Actual Tunnel Distribution and Boundary Locations

4. Conclusions

This study investigates the application of multi-attribute seismic fusion technology for analyzing coal seam response in the Kashmir Basin. Through analysis of a two-dimensional geological model, we found that seismic attributes such as relative wave impedance, instantaneous amplitude, and frequency effectively identify anomalies caused by roadways within the coal seam. Moreover, our research highlights the benefits of utilizing RGB multi-attribute fusion. In comparison to individual attributes, the fused attribute provides a more comprehensive perspective on geological features, facilitating easier visualization of tunnel boundaries and extraction of richer geological information. This methodology enhances interpretation accuracy and streamlines the delineation of complex geological structures. The successful application of multi-attribute fusion technology in this study suggests its potential for broader utilization in seismic data analysis. This approach holds promise for various geoscience applications, including enhanced coal seam characterization, optimized resource exploration strategies, and ultimately, more informed decision-making in the mining industry.

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