A Tunnel Seismic Advance Prediction System Based on Wireless Acquisition

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Abstract

Conventional tunnel seismic advance prediction systems are often hindered by cumbersome cabling, limited deployment flexibility, inadequate synchronization accuracy in multi-node acquisition, and spatially ambiguous imaging under small-aperture conditions. To overcome these limitations, a wireless-synchronized tunnel seismic advance prediction system integrating three-dimensional Fresnel volume migration imaging is proposed. The system comprises a master unit, a slave unit, and a trigger module, and implements distributed synchronized acquisition via a wireless ad hoc network. A high-precision timing module provides time stamps and PPS pulses to dynamically discipline the sampling clocks in real time, thereby effectively mitigating record-time drift induced by clock-source discrepancies. For imaging, a three-Dimensional Fresnel volume migration approach is introduced, in which polarization analysis of three-component data is used to estimate the incidence direction of reflected waves, and migration energy is confined to the intersection of the equal-travel-time surface and the first Fresnel volume, thus reducing spatial smearing and enhancing anomaly localization. Field validation in a tunnel in western China demonstrates that the proposed system enables stable wireless synchronized acquisition and robust identification of a fractured zone ahead of the tunnel face, with predictions in good agreement with subsequent excavation results. These findings indicate that the proposed method offers high synchronization precision, flexible deployment, efficient data transmission, and improved three-Dimensional imaging resolution, providing a reliable tool for tunnel advance prediction in complex geological settings.

Keywords: *tunnel seismic advance prediction; wireless acquisition; Three-Dimensional imaging; Fresnel volume migration*

1. Introduction

With the rapid development of railway, highway, and underground engineering in China toward deeper burial, longer tunnel lengths, and more complex geological conditions, adverse geological problems such as fault fractured zones, water-bearing bodies, karst, weak interlayers, and failure induced by high in-situ stress increasingly threaten tunnel construction safety. Fine-scale geological prediction ahead of the tunnel face has therefore become an important technical means for optimizing construction organization, determining support parameters reasonably, and reducing disaster risk [1,2]. Among the available advance prediction methods, seismic reflection surveys have become one of the most widely used approaches in tunnel engineering because of their long detection range, broad applicability, and strong anomaly identification capability[3-5].

At present, most tunnel seismic advance prediction systems use a centralized wired acquisition architecture, requiring sensor cables, trigger lines, and data transmission lines to be laid. In the confined space near the tunnel face, where mechanical operations are frequent and dust and moisture are severe, such systems suffer from cumbersome cabling, difficult construction organization, and inconvenient equipment handling[6,7]. In recent years, the development of wireless seismic instruments has mainly followed the path of miniaturization, low power consumption, and high integration[8]. Traditional bulky moving-coil sensors are gradually being replaced by smaller, broadband micro-electro-mechanical systems sensors. On the acquisition side, new-generation nodes generally integrate ultra-low-power microcontrollers and high-precision 32-bit analog-to-digital converters, significantly improving dynamic range[9,10]. In addition, with the introduction of high-density solid-state storage, advanced wireless communication modules such as LoRa, Wi-Fi, and 4G/5G, and high-energy-density battery packs or photovoltaic self-powered systems, modern wireless seismic nodes can now operate independently for months in extremely harsh field environments without cable constraints[11,12]. Although wireless acquisition improves deployment efficiency, if time synchronization relies only on generic wireless network protocols, millisecond-level synchronization will be affected by backoff mechanisms, delay jitter, and asymmetric bidirectional links, making it difficult to meet the high-precision synchronization requirements of seismic reflection imaging. This may lead to record-time drift among multiple nodes and thereby affect travel-time analysis and imaging accuracy.

On the other hand, tunnel seismic geometry are constrained by cross-sectional geometry and construction conditions and are usually deployed in a limited-aperture configuration along the tunnel axis. As a result, conventional migration imaging often exhibits obvious arc-shaped artifacts, insufficient spatial positioning capability, and difficulty in accurately characterizing the three-dimensional distribution of anomalies ahead of the tunnel face. In recent years, with improvements in full-space geometry and computational capability, tunnel seismic advance prediction has undergone a profound transformation from traditional one-

dimensional distance estimation and two-dimensional interface construction to true three-dimensional high-precision imaging[13,14]. To overcome the wavefield complexity and serious spatial aliasing caused by the narrow tunnel geometry, researchers have begun to introduce advanced imaging algorithms such as three-dimensional elastic reverse time migration and full-waveform inversion into tunnel applications[15]. By exploiting the kinematic and dynamic characteristics of multi-wave and multi-component data, such methods enable accurate localization of the spatial distribution, dip, and strike of adverse geological bodies such as faults and karst ahead of the tunnel face[16]. In addition, to further improve imaging efficiency and suppress arc-shaped artifacts caused by the limited observation aperture, intelligent three-dimensional inversion strategies based on deep learning and waveform feature extraction have become a new research focus[17]. These methods not only significantly improve the resolution of three-dimensional migrated sections in complex media but also provide a more intuitive and reliable three-dimensional geological model for tunnel construction. However, these methods all rely on accurate velocity models and involve relatively complex data processing, making them difficult to apply on a large scale in engineering practice. Fresnel volume migration introduces Fresnel-zone constraints into conventional Kirchhoff migration by limiting the migration aperture. By incorporating incidence-direction constraints, this method confines migration energy to a local spatial region closer to the true reflection point, making it more suitable for three-dimensional imaging under limited tunnel-aperture conditions and more practical for engineering applications.

Based on these considerations, this paper proposes a tunnel seismic advance prediction system based on wireless synchronized acquisition and three-dimensional Fresnel volume migration. In terms of hardware, the system adopts a wireless distributed synchronized acquisition architecture consisting of a master unit, a slave unit, and a trigger module. In terms of imaging, a three-dimensional Fresnel volume migration imaging method constrained by polarization analysis is introduced, forming a tunnel seismic advance prediction solution integrating wireless operation, synchronization, and three-dimensional imaging.

2. Overall System Architecture

The proposed tunnel seismic advance prediction system is shown in Fig. 1. It mainly consists of a mast unit, a slave unit,a trigger module, a wireless signal synchronizer, 2 3-component geophones, and a processing terminal. The master unit is responsible for system networking, unified time synchronization, acquisition parameter distribution, trigger-event monitoring and broadcasting, data aggregation, and communication with the host computer, while also connecting to one three-component geophone for seismic wave acquisition. The slave unit is connected to another three-component geophone for seismic signal acquisition. The trigger module and wireless signal synchronizer are deployed near the shot hole to record the precise time of the explosion and wirelessly transmit it back. The 3-component geophone are installed in the receiver holes to acquire 3-component seismic signals. The processing terminal is used for system configuration, data preprocessing, velocity modeling, three-dimensional imaging, and interpretation of the results.

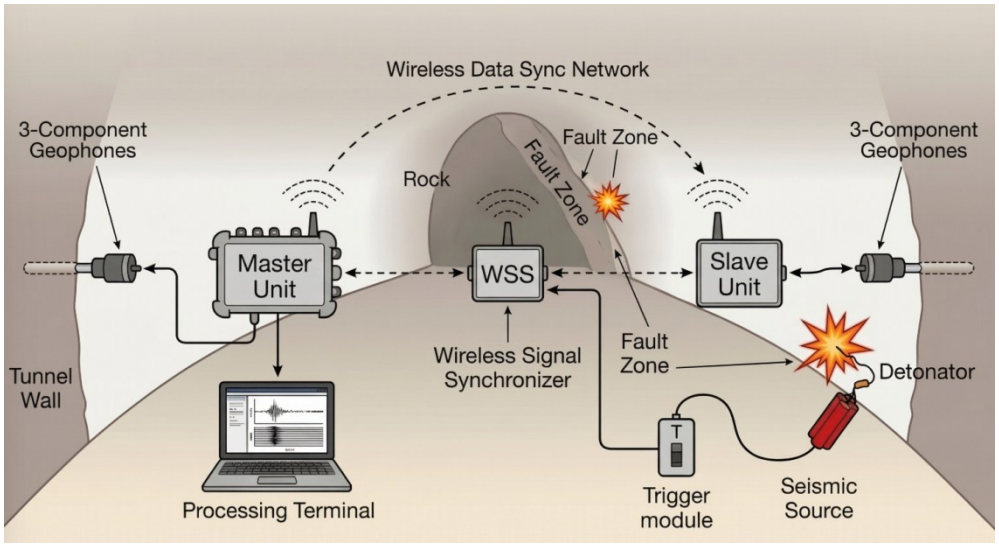

Fig. 1. Tunnel seismic advance prediction system.

3. Hardware Design

The hardware design schematic is shown in Fig. 2 and mainly consists of a master unit and a slave unit. The master unit is composed of a control-processing module, a signal-processing module, a trigger unit, a wireless synchronization module and a wireless data transmission module. The control-processing module is responsible for synchronized acquisition control, slave-node management, trigger-event distribution, and data aggregation. The signal-processing module is used for filtering, gain amplification, and analog-to-digital conversion of the received geophone signals. The trigger unit is directly connected to the explosive source, outputs a trigger signal at the moment of excitation, and wirelessly transmits the trigger event and trigger time to the control-processing module. The wireless synchronization module is used to network the master unit with the slave unit and trigger module and to complete time synchronization, while also providing the control module with unified time and PPS synchronization pulses. The wireless data transmission module is used to transmit seismic data to the data-processing terminal. The slave unit has a structure basically similar to that of the master unit. It mainly includes a control-processing module, a signal-processing module, a wireless synchronization module and a wireless data transmission module. The control-processing module receives commands from the master unit and performs synchronized sampling and buffer management. The wireless synchronization module establishes a subordinate synchronization relationship with the master unit and provides the local control-processing module with time stamps and PPS synchronization pulses. The signal-processing module is used for local three-component geophone signal conditioning, gain control, and A/D conversion. The wireless data transmission module is responsible

for returning acquired data to the master unit. The distributed deployment of the slave units can effectively avoid noise coupling and signal attenuation caused by long-distance analog cables and facilitates system channel expansion.

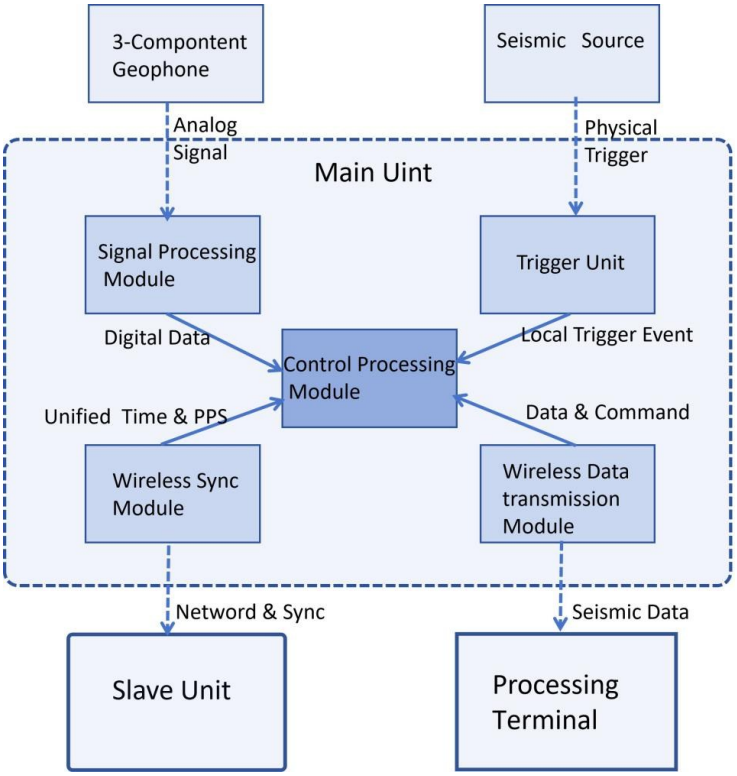

Fig. 2. Hardware design schematic

The key to a wireless acquisition system lies in multi-node time consistency. In this study, a high-precision wireless synchronization module is used as the unified time-reference core, with the master unit operating in master mode and the slave unit and trigger module operating in slave mode. After power-on, all nodes complete networking and time synchronization, and sampling is initiated at the rising edge of PPS at the agreed time. During acquisition, each node uses periodic PPS signals to dynamically discipline its local clock and prevent cumulative record-time drift caused by oscillator errors. Compared with millisecond-level synchronization under generic wireless network protocols, this scheme better meets the requirements for identifying the small travel-time differences of seismic reflection signals, thereby providing a reliable time base for multi-node joint imaging.

The signal conditioning module includes three parts: low-pass filtering, programmable gain amplification, and high-precision A/D conversion, as shown in Fig. 3. Low-pass filtering is used to suppress high-frequency interference and prevent aliasing; the programmable gain amplifier is used to accommodate the large dynamic range differences between direct waves and weak reflected waves under different excitation conditions; and the A/D converter adopts a high-resolution analog-to-digital converter to improve the quantization accuracy of weak reflection events. This signal chain is well suited to the characteristics of tunnel seismic signals, which are high-frequency, weak-reflection, and embedded in a complex noise background.

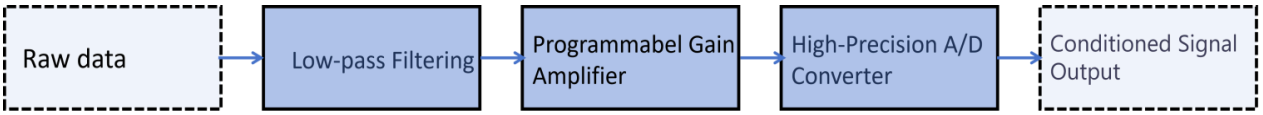

Fig. 3. Signal conditioning chain

4. Three-Dimensional Imaging Method

4.1 Principle of Three-Dimensional Fresnel Volume Migration

Tunnel advance prediction geometry are usually limited-aperture, small-space observation configurations distributed along the tunnel axis. Under such conditions, conventional Kirchhoff migration tends to spread a single true reflection point into an arc band or shell, resulting in spatial smearing and positioning errors, which are unfavorable for fine interpretation of anomalous bodies. Therefore, an improved method capable of using wavefield direction information to constrain the migration space is required.

In this paper, three-dimensional Fresnel volume migration is adopted as the core imaging method. The basic idea is to build on three-dimensional Kirchhoff pre-stack depth migration and, by combining the incidence direction of reflected waves at the receiver, confine the migration energy to the intersection between the equal-travel-time surface and the first Fresnel volume, rather than allowing the energy to spread over the entire equal-travel-time surface. This improves imaging focusing capability. The imaging formula is given in Eq. (1).

$$V(m) = \frac{-1}{2\pi} \iint_A F_c \omega(m,x) \dot{u}(x, t_S + t_R) \bullet e_r dx \tag{1}$$

In the equation, V(m) is the imaging result, t_S is the travel time from the source point to the imaging point, t_R is the travel time

from the imaging point to the receiver, $u(x,t_S+t_R)$is the received seismic wavefield, and vector x describes the positions of the sources and receivers on aperture A, that is, the region occupied by the source and receiver arrays. The weighting function $\omega(m,x)$ is used to correct the amplitude effect during wavefield back propagation. For an incident P-wave in a homogeneous velocity model, e_r is a unit vector whose direction is defined by the straight ray between the image point and the receiver position. The main difference between Fresnel volume migration and conventional migration imaging is the introduction of the Fresnel volume factor F_c, which sets the contribution of points outside the first and second Fresnel volumes that are not on the specular reflection path to zero, making the imaging result closer to the actual reflection point.

4.2 Polarization Analysis and Incidence-Direction Estimation

Three-Dimensional Fresnel Volume Migration requires estimation of the propagation direction of reflected waves when they arrive at the receiver. In this study, polarization analysis is performed using three-component seismic data. For a three-component seismic data within a selected time window, a covariance matrix is constructed. Eigenvalue decomposition is then performed on the matrix, and the eigenvector corresponding to the largest eigenvalue is taken as the dominant vibration-direction estimate. For P-wave-dominated reflection events, this direction can approximately represent the wave propagation direction. By combining travel-time and slowness analysis results, a three-dimensional incidence-direction constraint at the receiver can be established.

4.3. Three-Dimensional Velocity Model Construction

Three-dimensional migration imaging relies on a reliable velocity model. In this study, the following modeling strategy is adopted. First, a two-dimensional first-arrival travel-time tomographic inversion is performed based on first-break picking results to obtain a P-wave velocity model along the tunnel axis. Then, combined with the tunnel geometry, the two-dimensional velocity results are extended into three-dimensional space to establish a three-dimensional velocity field of the surrounding rock. The tunnel cavity is assigned the air propagation velocity. For cases with a clearly known asymmetric anomaly zone, the three-dimensional model can be locally modified according to geological information.

4.4. Data Processing Workflow

The workflow of the proposed data-processing scheme is presented in Fig. 4. Raw seismic data and acquisition geometry are first imported into the system. Quality control is subsequently conducted to remove defective channels and ensure data reliability. To compensate for amplitude loss associated with geometric spreading and intrinsic attenuation, automatic gain control (AGC) is applied. The data are then processed using band-pass filtering to retain the useful frequency components and suppress out-of-band noise. Trigger time-zero correction is further performed to correct timing deviations introduced during data acquisition. After preprocessing, F-K filtering is used to isolate the effective wavefield in the tunnel advancing direction. The first-arrival times are then determined through first-break picking, providing the basis for velocity tomography modeling and the construction of the background velocity model. On this basis, three-component polarization analysis and incidence-direction estimation are carried out to separate wavefield components and identify their propagation characteristics. Finally, three-Dimensional Fresnel Volume Migration imaging is performed to obtain the tunnel-face imaging results.

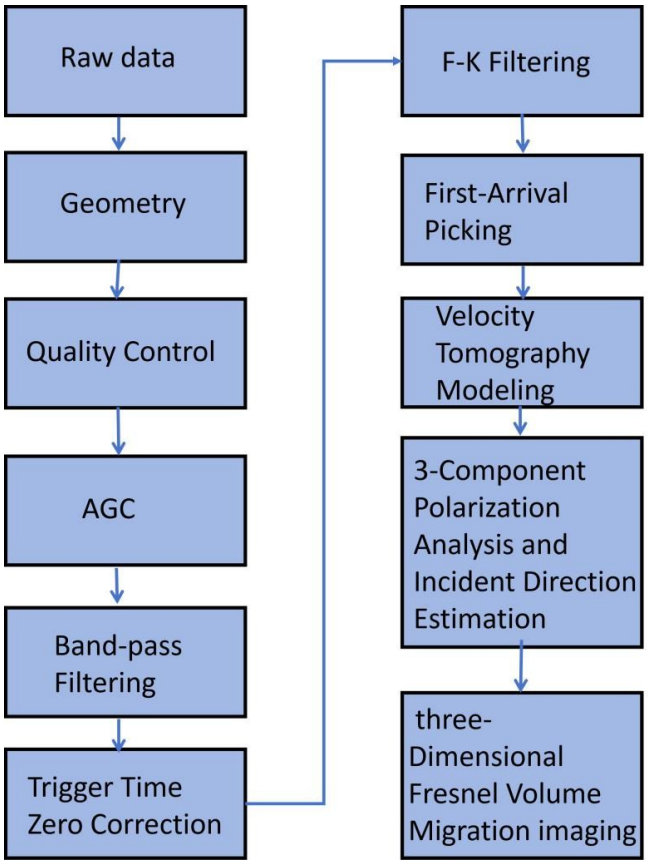

Fig. 4. Data processing flowchart

5. Engineering Application

5.1. Data Acquisition

To verify the field applicability of the proposed system, a field test was conducted in the Daqing Tunnel of the Xichang–Ningnan Expressway project in western China, as illustrated in Fig. 5. The tunnel site is located in the middle section of the north–south structural system in Sichuan and Yunnan. The area is mainly affected by a series of nearly north–south-trending folds and compressive faults, including the Zemuhe Fault and related low-order compressional-tensional or tensional-shear faults. The surrounding rock of the tunnel is mainly composed of argillaceous siltstone and fine sandstone. Locally, dense joint and fracture zones and tectonically fractured zones are developed, resulting in complex construction geology. According to the preliminary geological mapping and advance drilling data, lithological transition zones and fractured anomaly zones may exist ahead of the tunnel face, and these may be water-bearing. This provides typical conditions for applying tunnel seismic advance prediction.

Fig. 5. A field test in the Daqing Tunnel

In the field application, receiver holes were first drilled behind the tunnel face, and three-component geophones, the master unit, and the slave unit were installed. The trigger module was installed near the shot hole. After power-on, the system automatically completed initialization, wireless networking, and unified time synchronization. Subsequently, acquisition parameters such as sampling frequency, record length, gain, and trigger mode were set on the master unit or host computer. After excitation began, the trigger module recorded the excitation time and uploaded the trigger event to the master unit. The master unit distributed the trigger information to slave unit, and all nodes acquired data synchronously under a unified time base and returned the data. After all observations were completed, the host computer processed the data and performed three-dimensional imaging, ultimately producing the spatial distribution of adverse geological bodies ahead of the tunnel face.

Field tests showed that the system has a short networking time and a stable data link, and each acquisition node can complete synchronous sampling under a unified time base. Compared with traditional wired systems, wireless deployment significantly reduced cable laying near the tunnel face, facilitating mechanical operations and personnel passage, and the field deployment efficiency was greatly improved.

5.2. Results and Analysis

Using the workflow described in Section 4, the data were processed and a two-dimensional first-arrival travel-time velocity model was established based on first-break picking results, as shown in Fig. 6. The results show that the overall surrounding-rock velocity of the tunnel is relatively high, but a large low-velocity perturbation zone appears in the mileage range 1975–1995 m, which is inferred to be related to lithological variation or local tectonic fracturing.

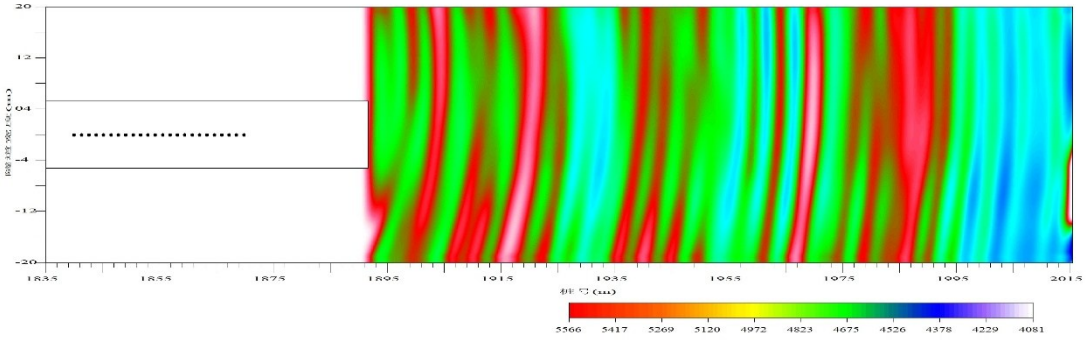

Fig. 6. Two-dimensional first-arrival travel-time velocity model

Three-Dimensional Fresnel Volume Migration is shown in Fig. 7. It can be seen that after the incidence-direction information obtained from polarization analysis is used to constrain the migration energy, the anomalous reflection interface becomes more concentrated and continuous, and the arc-shaped smearing phenomenon is significantly reduced. Compared with the shell-like anomaly around the tunnel obtained by conventional migration, the spatial position of the anomaly obtained by Fresnel Volume Migration imaging is more stable, and its geometric shape is more consistent with the actual geological structure. A distinct reflection impedance anomaly appears at mileage 1980–1990 m. Combined with the geological conditions, this section is inferred to be a lithological transition zone or a densely jointed and fractured zone, and it may contain fractured water.

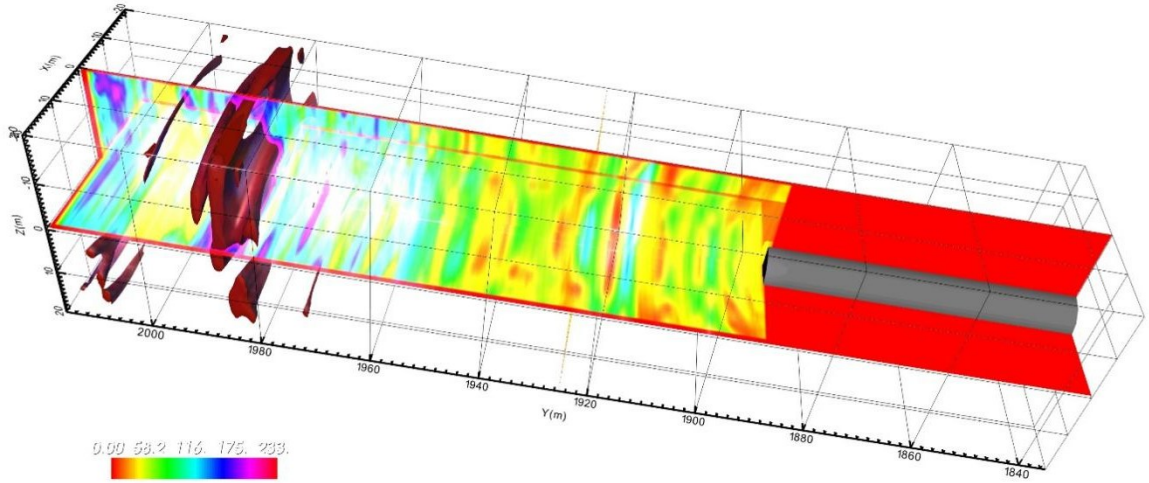

Fig. 7. Three-dimensional fresnel volume migration

Subsequent excavation revealed that at mileage 1980 m, the surrounding rock gradually transitioned from relatively intact siltstone to a zone with developed joints and fractures. Continued excavation to about 1990 m exposed a tectonic fractured zone, where the rock mass was broken, the block size decreased, and seepage water was observed, as shown in Fig. 7. The revealed results are basically consistent with the predicted location and anomaly scale obtained by the three-dimensional Fresnel Volume Migration method.

Fig. 8. Photograph of the tunnel face at chainage 1990 m

This engineering case demonstrates that the proposed system can stably perform multi-node wireless synchronized acquisition under complex construction conditions, with advantages of rapid deployment, low construction interference, and stable data return. Compared with conventional two-dimensional or direction-unconstrained migration methods, Three-Dimensional Fresnel Volume Migration performs better in anomaly localization, boundary focusing, and spatial distribution characterization, and can more realistically reflect the three-dimensional geometry of fault fractured zones and lithological transition zones ahead of the tunnel face, showing good potential for engineering application.

6. Conclusions

Aiming at the problems of cabling, synchronization, and imaging in conventional tunnel seismic advance prediction systems, this paper proposes a tunnel seismic advance prediction system based on wireless synchronized acquisition and three-dimensional Fresnel volume migration, and verifies it through an engineering case study. The main conclusions are as follows:

A wireless distributed acquisition architecture consisting of a master unit, multiple slave units, and a trigger module was

constructed, realizing wireless networking and multi-node synchronous sampling for tunnel seismic advance prediction.

Through a high-precision wireless time-synchronization module and a PPS pulse dynamic disciplining mechanism, clock drift among devices can be effectively suppressed, meeting the time-consistency requirements of seismic reflection imaging.

The use of a low-noise signal conditioning chain helps improve the fidelity of high-frequency weak reflection signal acquisition and provides basic data for polarization analysis.

To address the serious spatial smearing of conventional migration under limited-aperture tunnel observation conditions, a three-dimensional Fresnel volume migration method was introduced. By estimating the incidence direction of reflected waves through polarization analysis and constraining the migration energy distribution, the focusing capability and three-dimensional localization accuracy of anomalous bodies can be significantly improved.

Engineering application results show that the proposed system can effectively identify fractured zones and lithological transition zones ahead of the tunnel face, and the prediction results are basically consistent with subsequent excavation results, demonstrating good engineering application value and promotion prospects.

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