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Practical Research on Integrated Geophysical Prospecting Technology in Identifying Fault Fracture Zones in Mountain Tunnels

Xin Jiang[1]†, Shu Chen[1]†*, Pinfeng Wang[2], Hongyu Yang[1]

[1]China Merchants Chongqing Testing Center for Highway Engineering Co., Ltd., Chongqing 400067, China
[2]Chongqing Geology and Mineral Exploration and Development Group Inspection and Test Co., Ltd., Chongqing 400700, China
†These authors contributed equally to the work.

Author to whom correspondence should be addressed.

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Abstract: Taking a certain mountain tunnel project as the research carrier, this paper integrates ground-penetrating radar (GPR), the high-density electrical resistivity method, and the seismic reflection method to build a three-in-one integrated geophysical prospecting technology system. During the study, the geophysical response patterns actually exhibited by fault fracture zones were first sorted out, and the internal mechanism of multi-method joint identification technology was explained. Subsequently, in combination with various objective constraints at the construction site, the procedures of detection layout, field acquisition, and in-office data processing were adjusted, thereby completing high-quality full-coverage detection of deep and shallow geological conditions. This compensates for the technical deficiencies of a single detection method, accurately extracts anomalous boundaries and water-bearing-related characteristics of fracture zones, and provides a referable technical basis for adverse geological forecasting and construction site safety prevention and control in mountain tunnels.
Keywords: Mountain tunnel; Integrated geophysical prospecting technology; Fault fracture zone; Data processing

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1. Introduction

Against the background of continuously expanding transportation demand, the number and scale of mountain transportation tunnel construction projects in China are continuously increasing. However, geological structures in many construction areas are complex, and underground hidden fault fracture zones are widely distributed, bringing many technical difficulties to tunnel excavation construction [1]. In view of the above engineering reality, building a multi-method integrated geophysical prospecting operation system, sorting out geophysical response characteristics and joint identification mechanisms, and adjusting various procedures in

field detection and data processing can improve the identification level of fault fracture zones and provide a referable technical approach for safe and efficient construction of mountain tunnels.

2. Response characteristics of fault fracture zones and the technical logic of multi-method joint identification

2.1. Geophysical response characteristics of fault fracture zones

There are very obvious differences in physical property parameters between fault fracture zones and intact surrounding rock, which is the core theoretical foundation for geophysical prospecting methods to identify adverse geology. First, in terms of electrical properties, intact surrounding rock is dense and internally uniformly structured, with relatively high resistivity values and a small fluctuation range. In contrast, the interior of fault fracture zones is filled with mud and sand, water may accumulate in fissures, and the medium has a large pore proportion; therefore, they usually exhibit prominent low-resistivity anomalies. If the stratum is water-bearing, the electrical difference will be further amplified. Second, in terms of the response performance of electromagnetic waves, intact surrounding rock attenuates GPR electromagnetic waves to a relatively large extent, but the loss is limited, and events can remain continuous. In contrast, the internal interfaces of fracture zones are disordered, and the medium composition is uneven; when electromagnetic waves reach this position, scattering and strong reflection occur, leading to phenomena such as amplitude jumps, chaotic signals, and event dislocation in observed waveforms. Third, in terms of seismic waves, the wave impedance of intact surrounding rock remains uniform, the seismic wave propagation velocity is relatively stable, and the acquired waveform morphology is regular. However, the wave impedance at fracture zone positions changes abruptly, causing a sharp drop in seismic wave propagation velocity, energy attenuation, and waveform distortion [2].

2.2. Technical logic of multi-method joint identification of fault fracture zones

A single geophysical prospecting method has unavoidable technical shortcomings. Using the three technologies in combination for identification can compensate for the weaknesses of a single technology, achieve technical complementarity, offset observation errors, and improve the reliability of identification results. Among them, GPR has the technical advantages of high resolution and fast field detection speed, and is suitable for fine shallow-layer exploration on tunnel faces. It can quickly detect small-scale fissures and shallow-developed fracture zones, but its detection depth is limited, and its resistance to electromagnetic interference is insufficient. The high-density electrical resistivity method is based on the principle of electrical imaging and has the advantages of large detection coverage and considerable operating depth. It is highly sensitive to water-rich fracture zones and can effectively judge the degree of rock looseness and actual stratum water content [3]. However, its resolution for shallow-layer results is not ideal. The seismic reflection method has good profile continuity during deep detection and a strong ability to distinguish structural morphology. It can help the detection team quickly locate the occurrence of large fault fracture zones and their outward extension scale, and is suitable for deep geological exploration. The combination of the three methods means that GPR is responsible for fine shallow-layer exploration, the high-density electrical resistivity method is responsible for mid-layer electrical analysis, and the seismic reflection method is responsible for deep structural tracking. The integration of technologies enables full coverage of the detection space. At the same time, cross-comparison of multi-source observation anomalies can screen out

false anomalies caused by environmental interference, alleviate the non-uniqueness inherent in geophysical prospecting results, and ultimately, based on the working path of "shallow-layer screening, mid-layer verification, and deep-layer delimitation," gradually complete qualitative and quantitative identification of fault fracture zones [4].

3. Integrated geophysical prospecting technical scheme and implementation for fault fracture zones in mountain tunnels

This paper adjusts the technical scheme in combination with objective constraints at the construction site, integrates detection layout, field acquisition, and in-office processing, and builds a practicable engineering application technical framework.

3.1. Geology of the work area and operational constraints

The study area selected in this paper is a typical mountain tunnel construction section. Under the influence of tectonic movement, the surrounding rock is mainly composed of weathered rock and cataclastic rock. Joints and fissures are extensively developed, hidden fault fracture zones are visible in many places, and groundwater accumulates in some fissures. The overall geological conditions are highly complex. There are several hard constraints when carrying out geophysical prospecting operations inside the tunnel chamber [5]. First, at the spatial level, the internal cross-section size of the tunnel is fixed, and the available working area around the tunnel face is very narrow, restricting the placement of large detection equipment and the laying of long-distance survey lines. Second, at the environmental level, a large amount of construction machinery and metal components are placed inside the tunnel, lighting equipment operates continuously, and there is strong electromagnetic disturbance and vibration interference, making the signals acquired by geophysical prospecting highly prone to distortion. Third, at the physical condition level, detection work is constrained by construction progress. The tunnel excavation process must advance continuously, and geophysical prospecting operations can only be interspersed during construction intervals, leaving very limited effective time for detection. Finally, the rock surface at the tunnel face is uneven, and a large amount of loose debris accumulates on the surface, making it difficult for detection equipment to fit tightly against the rock wall, and the stability of electrode grounding for the high-density electrical resistivity method is greatly reduced. The superposition of multiple constraints means that using only a single detection method will lead to large data errors, and integrated geophysical prospecting technology is needed to cope with the many technical constraints brought by site conditions [6].

3.2. Integrated geophysical prospecting combination scheme, instruments and equipment, and survey line layout

In combination with the various constraints of the case area and the practical requirements for fracture zone identification, a trinity combination scheme of "GPR fine detection + high-density electrical resistivity method electrical detection + seismic reflection method structural detection" is used to balance detection accuracy, operating depth, and on-site operability. During instrument and equipment selection, lightweight design and strong anti-interference ability were used as screening criteria to adapt to the restricted working conditions inside the tunnel chamber. Among them, a portable GPR model equipped with a shielded antenna was selected to effectively resist electromagnetic interference and ensure that shallow detection resolution

meets technical requirements. The high-density electrical resistivity method used a distributed small electrical acquisition system to effectively overcome the constraints caused by uneven rock surfaces. For seismic detection instruments, highly sensitive geophones were used to ensure effective acquisition quality of weak deep seismic signals.

During survey line layout, three principles were strictly followed: full-area coverage, guaranteed accuracy, and convenience for on-site implementation. GPR survey lines were arranged on the tunnel face along both horizontal and vertical directions to support shallow-range scanning. High-density electrical resistivity survey lines were arranged longitudinally along the tunnel arch and both side walls, with appropriately densified electrode spacing to ensure higher-density electrical data. Seismic reflection survey lines were arranged along the tunnel axis, and the detection offset was adjusted according to actual conditions to complete continuous detection of deep structures.

3.3. Key points of field data acquisition operations

The quality of detection data acquired in the field directly affects the actual effectiveness of subsequent interpretation work. Therefore, the entire process should be standardized in the field operation stage, and key technical details should be controlled [7]. Before formal detection, designated personnel should comprehensively clean loose debris and loose stones accumulated around the survey lines, level the working surface, and remove nearby operating construction equipment to reduce electromagnetic and vibration interference. At the same time, equipment should be strictly calibrated, signal status debugged, and the actual effect of electrode grounding tested to confirm that the entire set of equipment can operate stably.

Different detection methods require differentiated acquisition operation requirements. During GPR operation, the antenna is required to move at a uniform speed while closely adhering to the rock wall, without suspension or shaking. A total of 10 data groups were collected, and data with a better signal-to-noise ratio were subsequently selected from the 10 groups. During high-density electrical resistivity operation, electrodes were firmly pressed into the rock surface. For points with poor grounding, contact conditions were improved by watering or backfilling fine soil, and missed or incorrect acquisitions were not allowed. During seismic reflection operation, geophones were required to be firmly fixed, and the distance between source excitation points was controlled to ensure that acquired waveforms remained continuous and regular. During operation, changes in observed data waveforms and signal-to-noise ratio should be constantly monitored. If signal distortion or excessively high noise levels occur, operation should be immediately suspended and acquisition resumed only after troubleshooting [8].

4. In-office data processing and anomaly information extraction

4.1. Preprocessing of geophysical data and parameter setting

During preprocessing of geophysical data, multi-source data denoising and purification were first carried out. For GPR data, band-pass filtering and background denoising algorithms were used to remove clutter caused by electromagnetic disturbance and equipment shaking inside the tunnel, retaining electromagnetic reflection signals with analytical value. For high-density electrical resistivity data, distorted records caused by poor grounding and equipment fluctuations were screened out, and random noise was suppressed using smoothing filtering. For seismic observation data, techniques such as amplitude equalization and noise suppression were used to filter out invalid waveforms generated by construction vibration, and then core

parameters were configured according to the actual geological conditions of the work area. During parameter setting, the physical properties of the surrounding rock medium and detection depth determine the selection of radar sampling frequency and gain coefficient [9]. Electrode spacing is used to determine the number of electrical inversion iterations and the convergence threshold. Measured surrounding rock wave velocity results can serve as the basis for setting seismic sampling intervals and filtering frequency bands, ensuring that parameter settings fit site conditions. At the same time, multi-source data need to be normalized, with coordinate datum, scale, and accuracy standards fully unified, thereby eliminating data deviations caused by equipment differences and different operating conditions and creating a standardized dataset for multi-source data comparison and joint interpretation.

4.2. Data inversion and profile generation

After data preprocessing, standardized data were obtained, and professional algorithms were used for inversion imaging to present the surrounding rock geological structure in a visual form. The core of geophysical inversion is to continuously adjust subsurface model parameters so that the calculated theoretical response is as close as possible to field-measured data. Therefore, the residual calculation formula should adopt the more intuitive mean squared error form, as shown in Equation 1:

$$E = \frac{1}{N}\sum_{i=1}^{N}\left(d_i^{obs} - d_i^{cal}(m)\right)^2 \tag{1}$$

In Equation 1, the inversion residual is E; the number of sampling points of valid data is N; the field-measured geophysical signal at the i-th survey point is di, that is, the data collected by the instrument at the tunnel site. $fi(m)$ represents the theoretical calculated signal based on the subsurface physical property model, and m represents the set of unknown subsurface physical property parameters, including resistivity, electromagnetic wave dielectric constant, and seismic wave velocity. During calculation, the smaller the inversion residual, the higher the consistency between the calculated model and the actual on-site geological conditions.

For GPR data, the finite-difference time-domain method was used for inversion calculation, correcting signal time differences and amplitudes, followed by migration imaging to reconstruct the shallow electromagnetic reflection profile of the tunnel face. Based on this profile, the distribution morphology of shallow fissures, loose rock masses, and local water-rich anomalies can be clearly displayed, thereby depicting the boundary range of small fracture zones. For high-density electrical resistivity data, the least squares method was used for iterative inversion. An underground electrical structure model was constructed based on measured resistivity data, and model parameters were then corrected through multiple iterations to reduce the inversion residual, ultimately producing a longitudinal electrical imaging profile. According to differences in resistivity values, intact surrounding rock and fracture zones can be identified, and the degree of rock looseness and actual water content can be judged. Seismic reflection data were processed using wave equation migration and velocity tomography techniques to correct wave velocity propagation time differences and terrain-induced deviations, producing deep surrounding rock wave velocity profiles and structural profiles. The occurrence, outward extension scale, and structural boundaries of fracture zones are reflected in the profiles. Finally, the spatial datums of the three types of profiles were unified to produce standardized imaging results that can be mutually referenced.

4.3. Extraction and comparison of anomaly characteristics from multi-source geophysical profiles

Cross-comparison of anomalies from multi-source profiles can alleviate the non-uniqueness problem of geophysical prospecting results and is a key step in improving identification quality. During implementation, single-source profile anomaly extraction should first be completed, followed by mutual verification of multi-source results, gradually completing geological body identification.

First, during single-profile analysis, areas in GPR profiles with event dislocation, amplitude jumps, and chaotic signals mostly correspond to shallow rock mass fragmentation or water-bearing fissures. High-density electrical resistivity profiles focus on identifying banded and blocky low-resistivity anomalies. The lower the measured resistivity value, the higher the degree of rock fragmentation and the more obvious the stratum water content. In seismic profiles, sections with a rapid decrease in wave velocity and destroyed waveform continuity can be regarded as response markers of deep structural fragmentation. Second, multi-source anomaly cross-comparison was carried out. In the field, the idea of "prioritizing coincident anomalies and cautiously identifying single-point anomalies" can be followed. If obvious anomalies appear at the same spatial position in all three types of profiles, the area can be judged as a fault fracture zone. At this point, the spatial range of the fracture zone should be delineated and the water-bearing state analyzed in combination with the characteristics of multiple profiles. Finally, various types of anomaly information were integrated to grade the development degree of fracture zones, eliminate false anomaly records, correct anomaly boundaries, and depict clear three-dimensional occurrence characteristics of fracture zones, obtaining final interpretation results and providing geological reference materials for support design and disaster risk prevention and control in the later construction stage of the tunnel [10].

5. Conclusion

In summary, aiming at practical engineering problems such as multiple solutions and limited identification accuracy in the detection of fault fracture zones in mountain tunnels, this paper builds a trinity integrated geophysical prospecting technical system of "GPR + high-density electrical resistivity method + seismic reflection method." Combined with a superimposed analysis of multiple objective constraints such as the internal space, environment, and construction progress of mountain tunnel chambers, it improves the entire process of survey line layout, field acquisition, in-office data processing, and anomaly interpretation. The integrated geophysical prospecting method proposed in this paper can complete coverage exploration of deep and shallow adverse geology in tunnels, effectively compensate for the technical limitations of a single geophysical prospecting method, improve the identification accuracy of fault fracture zones, and clearly reflect the spatial distribution, rock looseness state, and water-bearing conditions of fracture zones.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Ye W, Zhou JH, Chen N, et al., 2026, Application of Geophysical Prospecting Technology in the Whole Process of

Tunnel Construction. China Railway, 2026(3): 101–109.

[2] Lyu HL, 2026, Application of Integrated Geophysical Prospecting Methods in Urban Rail Transit Engineering Investigation: A Case Study of Yuanshan Station–Apollo South Station on Shenzhen Metro Line 16. Resources Information and Engineering, 41(2): 45–49.

[3] Chen N, Zhao YH, Wang H, et al., 2024, Research on the Application of Integrated Geophysical Methods in the Investigation of Long and Deeply Buried Tunnels. Progress in Geophysics, 39(6): 2420–2431.

[4] Chen C, 2026, Application and Verification of Integrated Geophysical Prospecting Methods in the Investigation of Daxiangshan Tunnel on Fuzhou Coastal Express Line. City Weekly, 2026(12): 157–159.

[5] Gong H, 2026, Research on Optimized Application of Integrated Geophysical Prospecting Technology for Advanced Geological Prediction in Tunnels. Transport Manager World, 2026(17): 102–104.

[6] Ma T, 2025, Research on the Application of Integrated Geophysical Prospecting Technology in Tunnel Collapse Emergency Rescue. Chinese Journal of Engineering Geophysics, 22(2): 191–198.

[7] He CL, 2025, Application of Integrated Geophysical Prospecting in Tunnel Investigation in Hilly and Mountainous Areas. Site Investigation Science and Technology, 2025(4): 69–75.

[8] Sun TL, 2025, Practice and Effect Evaluation of Integrated Geophysical Prospecting Technology in Tunnel Hydrogeological Investigation. Engineering Technology Research, 10(7): 210–212.

[9] Lin XQ, Deng TL, Xiao DW, et al., 2026, Research on Optimization and Integrated Application of Geophysical Prospecting Technology for Advanced Geological Prediction in Long Railway Tunnels. Architecture Technology, 57(12): 1462–1467.

[10] Liu JC, Zhou YB, Xing XY, 2024, Application research of Integrated Geophysical Prospecting Methods in the Investigation of Adverse Geological Bodies in Tunnels in High-Cold and High-Altitude Areas: A Case Study of Maqin Tunnel. Technology Innovation and Application, 14(11): 147–150 + 155.

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