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Detection Technology and Application of Borehole Radar in Complex Coal Mine Geology

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ABSTRACT

During coal mining and underground engineering, concealed structures such as fractured zones, abandoned roadways, mined-out spaces, and water-bearing disturbed zones pose significant safety risks. This study investigates a single-hole impulse borehole radar method for refined detection of such anomalies. A 20–200 MHz impulse radar probe is used for continuous acquisition during advancement along the borehole. Reflection travel time and reflection-event geometry are used to constrain the axial positions and approximate radial distances of off-hole reflectors, while Hilbert-derived instantaneous amplitude, phase, and frequency are jointly analyzed to characterize complex radar responses. Field tests were conducted at a tunnel in Yunnan Province and at a coal mine. In the tunnel test, radar attenuation zones generally corresponded to fractured intervals and lithological variations revealed by borehole television. Four of five severely fractured intervals showed corresponding weakened or disturbed radar responses, while inclined reflections at radial distances of approximately 4.0–5.6 m indicated off-hole structural features. In the coal-mine application, anomalies detected in four exploration and drainage boreholes showed clear spatial correspondence with known roadways, abandoned mining spaces, and water-bearing fractured zones. The results demonstrate that single-hole borehole radar can identify both near-borehole structural variations and off-hole geological anomalies, extending geological information from the borehole trajectory into the surrounding rock mass and providing an effective means for refined underground structural investigation.

Keywords: Borehole Radar; Coal Mine; Single Borehole; Impulse Radar

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1. Introduction

With the continuous development of coal resources, underground geological and engineering conditions in coal mines have become increasingly complex. On the one hand, mining activities are progressively extending to greater depths, where high in-situ stress and strong mining disturbance pose greater challenges to roadway stability and geological prediction. On the other hand, after decades of intensive exploitation, many mining districts are increasingly affected by legacy mining structures. Abandoned roadways, old goafs, residual openings, and previously disturbed rock masses may coexist with faults, collapse columns, and fractured zones, resulting in highly heterogeneous and spatially complicated underground conditions^[1,2]. Previous mining activities may further disturb the surrounding rock and modify local stress and structural conditions^[3,4]. These concealed structures may affect roadway stability and provide potential storage spaces or migration pathways for mine water. Therefore, refined detection of faults, abandoned workings, goafs, cavities, and fractured zones has become increasingly important for safe mining under complex geological conditions.

At present, geological investigation ahead of coal-mine roadways and underground excavations mainly relies on drilling, geophysical prospecting, and integrated exploration. Drilling can directly reveal strata and geological anomalies, but the information obtained is essentially restricted to a limited number of borehole trajectories, making continuous characterization of the geological volume difficult. In comparison, geophysical prospecting is non-destructive, efficient, and capable of providing broader spatial coverage^[2,5]. Commonly used methods include seismic prospecting, direct-current electrical methods, transient electromagnetic method (TEM) methods, and ground-penetrating radar (GPR). Seismic methods provide a relatively large investigation range and are suitable for faults and large structural discontinuities, but their resolution for small cavities and local fractures is comparatively limited under complex wavefield conditions. Electrical methods are sensitive to water-bearing and low-resistivity structures, but their volume effect makes precise boundary determination difficult. TEM methods have been widely used for water-bearing structures, mined-out areas, and other low-resistivity anomalies. Xue et al.^[6] and Yu et al.^[7] systematically summarized TEM detection of water-

bearing bodies in coal mines and verified its applicability to water-enriched mined-out areas. However, the diffusive nature of TEM fields limits the refined delineation of small-scale and closely spaced structures.

GPR detects reflections generated by contrasts in dielectric properties and, owing to its high spatial resolution, has been widely used in geological investigation, tunnel engineering, infrastructure inspection, and other near-surface applications, particularly for fractures, cavities, and structural interfaces^[8,9]. Recent developments in directional borehole radar have further improved three-dimensional target localization and imaging capability^[10]. However, high-frequency electromagnetic waves undergo relatively strong attenuation. Conventional GPR measurements from the ground, tunnel wall, or roadway surface are therefore limited in two respects for deep coal-mine exploration: surface-based radar cannot effectively investigate roadway-scale structures at large mining depths, while roadway-surface measurements cannot fully utilize geological or water-drainage boreholes that may extend tens to more than one hundred metres ahead of the excavation face. Borehole radar overcomes these limitations by placing the antennas inside the borehole, moving the observation position directly into the rock mass and reducing the propagation distance between the antenna and target.

Borehole radar can generally be implemented using single-hole reflection, cross-hole, and borehole-to-surface configurations^[11,12]. Cross-hole radar provides strong constraints on structures between boreholes but requires suitable borehole geometry, while borehole-to-surface measurements involve relatively long propagation paths. Single-hole reflection radar, in contrast, places both transmitting and receiving antennas in the same borehole and can directly utilize existing geological exploration or water-drainage boreholes. As the probe moves along a long advance borehole, the observation position extends along the entire borehole trajectory, while reflected electromagnetic waves detect geological targets within a certain radial distance. The method therefore combines the long axial reach of drilling with radial geophysical detection, extending geological information from the borehole trajectory into the surrounding rock volume.

Early studies established the capability of borehole radar to detect structures beyond the borehole wall. Serzu et al.^[13] characterized fracture zones in granitic rock using single-hole and cross-hole radar, while Giertzuch et al.^[14]

demonstrated that borehole GPR can also image fluid-related changes and transport processes within fractured rock. Polarimetric borehole-radar measurements were first used to improve fracture characterization^[15]. Directional borehole-radar techniques have been developed to further constrain target orientation and support three-dimensional imaging^[16,17]. Shen et al.^[18] combined single-hole borehole radar with optical borehole imaging to improve the azimuthal and three-dimensional characterization of rock fractures. Dorn et al.^[19] obtained high-resolution images of individual fractures using multiple-offset borehole GPR; with 100 MHz antennas, major fractures were imaged at radial distances of approximately 2–20 m. This metre-to-tens-of-metres radial investigation scale is well matched to the scale of many local structures of engineering concern around coal-mine roadways. Ni et al.^[20] further improved borehole-radar characterization of fractures through three-dimensional directional imaging, while Jiang et al.^[21] demonstrated the applicability of borehole radar to coal-seam interface detection in underground coal mines.

Recent studies have increasingly focused on engineering applications and refined geological interpretation. Liu et al.^[22] applied single-hole radar to identify fractures and karst-related anomalies around engineering boreholes, and Li et al.^[23] investigated the radar characteristics of structural planes, fissures, cavities, and fractured zones. Jiang^[24] further analyzed borehole-radar responses to hydraulic fractures in near-horizontal coal-mine boreholes, demonstrating its feasibility in underground coal-mine environments. Meanwhile, borehole-radar responses are influenced by fracture geometry, aperture, dielectric contrast, and filling conditions, particularly whether fractures are air- or water-filled^[25]. Time-lapse and reflection studies have demonstrated measurable radar responses to variations in fracture-fluid conditions^[26,27], and changes within connected fractures can also produce distinct single-hole radar responses^[28,29]. Complementary electromagnetic and elastic-wave information has additionally been investigated for improving fracture-orientation evaluation^[30]. These studies demonstrate the considerable potential of borehole radar for structural characterization, while also indicating that complex radar anomalies cannot always be interpreted reliably from a single response characteristic.

Despite these advances, existing borehole-radar studies have predominantly focused on individual fractures, rela-

tively isolated cavities, crystalline-rock environments, or specific geological targets. Systematic field evaluation under complex conditions where abandoned roadways, goafs, faults, fractured zones, and water-affected structures coexist remains limited. Moreover, radar responses are jointly controlled by target geometry and electromagnetic properties, making interpretation based solely on reflection amplitude or a single image characteristic potentially ambiguous. Existing studies also commonly rely on either borehole observations or engineering geological information for validation, whereas complementary verification of near-borehole and larger off-hole structures at different spatial scales remains insufficient.

To address these issues, this study investigates single-hole impulse borehole radar for the refined detection of complex underground geological structures. An integrated interpretation approach combining reflection-event geometry with instantaneous amplitude, instantaneous phase, and instantaneous frequency is adopted. Two complementary field investigations are conducted. At the tunnel field site, borehole radar and borehole television are performed in the same forward borehole to evaluate fractured rock masses, fissures, lithological variations, and off-hole structural anomalies. At the coal-mine field site, four existing exploration and drainage boreholes are used to investigate concealed structures, including abandoned roadways, old mining spaces, and water-bearing fractured zones. Through direct near-borehole verification and engineering-scale comparison with known geological and mining information, the capability and applicability of single-hole borehole radar for refined structural detection under complex underground conditions are evaluated.

2. Methodology

2.1. Single-Hole Radar System

The single-hole impulse borehole radar system used in this study consists of an acquisition and control computer, a borehole radar probe, and dedicated acquisition and processing software, as shown in **Figure 1**. The transmitting and receiving modules are integrated into the borehole probe and controlled synchronously by the acquisition computer. During measurement, broadband electromagnetic pulses are

transmitted into the surrounding rock mass, and reflected signals generated by geological interfaces and anomalous

bodies are received, transmitted to the acquisition computer, and subsequently processed to form borehole-radar profiles.



Figure 1. Single-hole impulse borehole radar system: (a) acquisition and control computer; (b) borehole radar probe.

To meet the requirements of long-distance borehole investigation under underground conditions, the radar probe adopts an impulse excitation scheme with an operating frequency range of 20–200 MHz. The transmitting and receiving sections both employ dipole antennas. The probe is encapsulated in a fiberglass-reinforced shell to provide electrical insulation, waterproofing, abrasion resistance, and impact resistance. The internal configuration of the radar probe is illustrated in **Figure 2**. The probe diameter is 40 mm, allowing operation in boreholes with diameters greater than 50 mm. The transmitting section is approximately 0.8 m long and weighs 1.9 kg, whereas the receiving section is approximately 1.4 m long and weighs 2.8 kg.

The transmitting section mainly consists of a transmit-

ting antenna, pulse power amplifier, fiber-optic receiving module, and power-management module. The receiving section comprises a receiving antenna, amplitude limiter, low-noise amplifier, fiber-optic transmitting module, and three-dimensional electronic compass. The amplitude limiter suppresses high-amplitude interference and protects subsequent circuits, while the low-noise amplifier enhances weak reflected signals with low additional noise. Fiber-optic transmission is adopted to reduce electromagnetic interference during long-distance signal transmission. The electronic compass records the azimuth, inclination, and roll of the probe, providing auxiliary information for monitoring the probe attitude in inclined and near-horizontal boreholes.

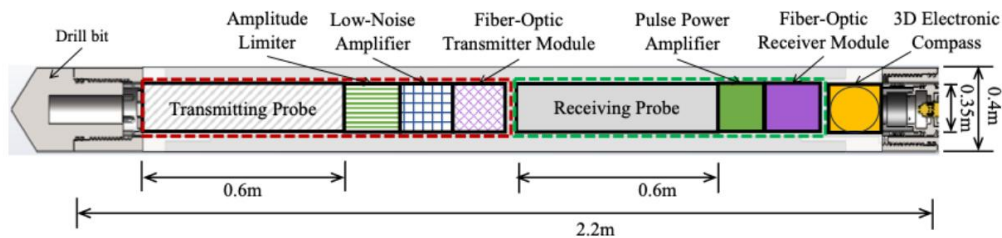


Figure 2. Structure of the single-hole borehole radar probe.

2.2. Reflection and Positioning Principle

Single-hole borehole radar detects geological structures based on the propagation, reflection, and refraction characteristics of high-frequency electromagnetic waves in underground media^[10,31]. When an electromagnetic pulse emitted by the transmitting antenna propagates through relatively ho-

mogeneous surrounding rock, its propagation characteristics remain relatively stable. When the wave encounters a fracture, cavity, lithological boundary, fault, or other interface with contrasting electromagnetic properties, part of the incident electromagnetic energy is reflected and subsequently recorded by the receiving antenna, as illustrated in **Figure 3**.

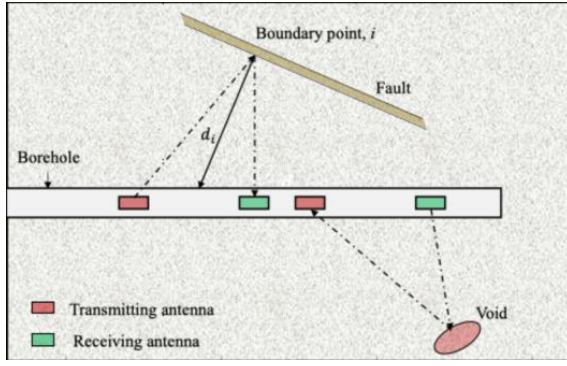


Figure 3. Schematic diagram of borehole radar detection for geological anomalies.

Within a locally homogeneous medium, the propagation velocity (V) of electromagnetic waves can be approximated as constant. Therefore, based on the time difference ΔT between the borehole wall reflection and the reflection from an anomalous body recorded by borehole radar, the distance d_i between the borehole wall and a boundary point i of an anomalous structure, measured along the normal direction to the boundary, can be calculated using Equation (1):

$$d_i = V \times \Delta T / 2 \quad (1)$$

Here, V represents the propagation velocity of electromagnetic waves in the subsurface medium, which can be expressed as:

$$V = C / \sqrt{\mu_\gamma \epsilon_\gamma} \quad (2)$$

where C is the propagation velocity of electromagnetic waves in air, approximately 3×10^8 m/s; $\mu_\gamma, \epsilon_\gamma$ are the relative magnetic permeability and relative dielectric permittivity of the medium, respectively.

When electromagnetic waves propagate across the interface between two different media, the incident angle θ_1 and the transmission angle θ_2 , corresponding to wave velocities V_1 and V_2 , respectively, satisfy Snell's law^[31], as given in Equation (3):

$$\frac{V_1}{V_2} = \frac{\sin \theta_1}{\sin \theta_2} \quad (3)$$

For reflected waves, the reflection angle is equal to the incident angle. Consequently, inclined faults and structural interfaces can produce coherent inclined reflection events in borehole-radar profiles. The continuity and geometrical variation of these events along the borehole provide useful constraints on the spatial distribution and occurrence of off-hole structures.

In addition to travel time and reflection geometry, the reflected-wave amplitude is closely related to the electro-

magnetic contrast across the interface. Under the interface relationship adopted here, the reflection coefficient can be expressed as:

$$R = \frac{\sqrt{\epsilon_{r1}} - \sqrt{\epsilon_{r2}}}{\sqrt{\epsilon_{r1}} + \sqrt{\epsilon_{r2}}} \quad (4)$$

where (R) is the reflection coefficient and (ϵ_{r1}) and (ϵ_{r2}) are the relative dielectric permittivities of the media on the two sides of the interface. A greater electromagnetic contrast generally results in a stronger reflected response. Therefore, fractures, cavities, faults, lithological interfaces, disturbed zones, and water-affected structures may exhibit different reflection characteristics depending on their geometry, filling materials, and electromagnetic properties.

In a single-hole radar profile, the probe position along the borehole provides the axial position of a potential reflector, whereas the reflection travel time can be used to estimate its radial distance according to Equation (1). The geometry, continuity, and inclination of reflection events therefore provide the primary spatial constraints on off-hole structures.

2.3. Multi-Attribute Interpretation

Complex underground geological structures may generate superimposed radar reflections associated with fractures, faults, lithological interfaces, cavities, and disturbed rock masses. Their responses are affected not only by reflector geometry but also by dielectric contrast, electrical conductivity, filling conditions, water content, and propagation attenuation. Interpretation based on a single reflection characteristic may therefore lead to ambiguity. In this study, the geometrical characteristics of reflection events are integrated with instantaneous amplitude, instantaneous phase, and instantaneous frequency to provide complementary constraints on geological anomalies.

The real signal received by the radar antenna can be expressed as:

$$x(t) = A(t) \times \cos(\omega_0 t + \varphi(t)) \quad (5)$$

where t is the time variable, $A(t)$ is the instantaneous amplitude, ω_0 is the central angular frequency, and $\omega_0 t + \varphi(t)$ represents the instantaneous phase. This expression provides a physical description of the variations in signal amplitude, phase, and frequency caused by changes in subsurface electromagnetic properties. To quantitatively extract these instantaneous attributes from the measured radar trace, the analytic

signal is constructed using the Hilbert transform^[32,33]:

$$z(t) = x(t) + j\hat{x}(t) = A(t)e^{j\Phi(t)} \quad (6)$$

where $z(t)$ is the Hilbert transform of $x(t)$, $A(t)$ is the instantaneous amplitude, and $\Phi(t)$ is the total instantaneous phase. In terms of Equation (5), $\Phi(t) = \omega_0 t + \varphi(t)$.

The instantaneous amplitude can therefore be obtained as:

$$A(t) = |z(t)| = \sqrt{x^2(t) + \hat{x}^2(t)} \quad (7)$$

which represents the local energy envelope of the radar signal. Interfaces with pronounced electromagnetic contrasts or strong structural discontinuities commonly produce significant variations in instantaneous amplitude. This attribute is therefore mainly used to identify anomalous intervals and characterize variations in reflected energy.

The instantaneous phase is obtained from the argument of the analytic signal:

$$\Phi(t) = \arg[z(t)] = \text{atan2}[\hat{x}(t), x(t)] \quad (8)$$

and is relatively insensitive to variations in signal amplitude. It highlights the continuity, termination, and geometrical characteristics of reflection events and thus provides additional constraints on structural boundaries. Phase reversal may occur when the sign of the electromagnetic reflection coefficient changes across an interface; however, the specific phase response depends on the electromagnetic contrast and boundary conditions.

The instantaneous frequency is calculated from the temporal derivative of the instantaneous phase:

$$f_i(t) = \frac{1}{2\pi} \frac{d\Phi(t)}{dt} = \frac{1}{2\pi} \left[\omega_0 + \frac{d\varphi(t)}{dt} \right] \quad (9)$$

and characterizes local variations in the frequency content of the radar signal. Changes in lithology, fracture development, water content, and electromagnetic attenuation can modify the local frequency characteristics of the reflected wavefield. Instantaneous frequency therefore provides supplementary information for identifying variations in subsurface material properties.

Based on the reflection characteristics and instantaneous attributes, a three-stage interpretation procedure is adopted in this study. First, coherent reflection events are identified from the conventional borehole-radar profile, and their travel-time geometry is used to constrain the approximate axial position and radial distance of potential off-hole

structures. For inclined reflection events, their continuity and geometrical variation along the borehole provide additional information on structural occurrence. Second, instantaneous amplitude and instantaneous frequency are jointly analyzed to identify intervals exhibiting pronounced variations in reflected energy and local frequency content. Third, instantaneous-phase continuity and phase variations are used to further refine the interpreted locations and boundaries of anomalous structures.

The instantaneous amplitude, phase, and frequency are derived using established Hilbert-transform-based signal analysis. In this study, these attributes are integrated with reflection-event geometry to form a unified interpretation workflow for complex off-hole geological structures. Reflection-event geometry provides spatial constraints, whereas the instantaneous attributes characterize local variations in reflection energy, phase continuity, and frequency content, thereby reducing the ambiguity associated with interpretation based on a single radar-response characteristic.

2.4. Measurement Procedure

The field measurement procedure mainly includes system initialization, probe installation and positioning, continuous radar acquisition during probe advancement, marker recording during rod connection, and post-acquisition position–attitude calibration and data interpretation. Before measurement, the borehole depth, diameter, and available trajectory information are checked, and the radar acquisition parameters are set according to the borehole conditions and expected geological targets. The radar probe is then connected to the drill-rod or push-rod assembly and positioned at the borehole collar. The initial probe position is defined as the reference point for the along-hole distance, and the radar acquisition system and attitude-sensing module are initialized before measurement.

Radar data are acquired continuously during probe advancement. As the drill rod or push rod advances the probe into the borehole, the transmitting antenna continuously emits broadband electromagnetic pulses, and the receiving antenna records reflected electromagnetic signals from the surrounding rock mass. The probe therefore performs continuous dynamic scanning while moving along the borehole, rather than point-by-point acquisition after stopping.

The acquisition system uses the probe attitude/motion sensor to identify the probe motion state. Radar acquisition is enabled when the probe is advancing and is automatically suspended when the probe stops. During field operation, the probe is advanced at an approximately stable rate to maintain relatively uniform spatial sampling along the borehole. Position and attitude information, including azimuth, inclination, and roll, are recorded synchronously and associated with the radar traces, providing the basis for subsequent spatial positioning of the continuous radar profile.

For long-distance borehole measurements, drill rods or push rods need to be connected successively as the probe advances. When rod connection is required, probe advancement is stopped and radar acquisition is automatically suspended after the stationary state is identified. A marker is then recorded after the probe reaches a stable state, together with the corresponding insertion depth and stable attitude parameters. These stationary marker points serve as position–attitude control points along the borehole. After the next rod is connected, probe advancement resumes; once the motion state is detected, continuous radar acquisition is automatically restarted. The procedure of continuous advancement and acquisition–stationary marking during rod connection–resumption of continuous acquisition is repeated until the designed detection depth is reached.

After field acquisition, the stationary marker points are used to calibrate the spatial information of the continuously acquired radar data. The known rod lengths and cumulative insertion depths are matched with the corresponding marker positions to establish the relationship between radar traces and along-hole distance. The stable azimuth, inclination, and roll measurements at the marker points provide reference constraints for checking and correcting the continuously recorded attitude information and reconstructing the borehole trajectory. In this way, the radar traces acquired during probe advancement can be accurately registered to their corresponding positions along the borehole.

Following position–attitude calibration, the radar data are subjected to quality control and signal processing to enhance effective reflection events and suppress background interference. Coherent reflection events are first identified from the conventional radar profile, after which instantaneous amplitude, instantaneous phase, and instantaneous

frequency are extracted. The calibrated borehole position and attitude information are then integrated with reflection–event geometry and the instantaneous attributes to identify anomalous intervals, estimate off-hole distances, and constrain structural boundaries. Finally, the interpreted anomalies are compared with available borehole observations or engineering geological information for geological identification and validation.

3. Field Results and Validation

3.1. Field Test in a Tunnel

3.1.1. Site and Geological Conditions

To evaluate the effectiveness of the proposed borehole–radar method for identifying structural anomalies within rock masses, a field investigation was conducted in a forward horizontal borehole drilled at the excavation face of a tunnel in Yunnan province, China. Borehole television logging was subsequently performed in the same borehole to provide independent near-borehole verification of the radar results.

The total length of the investigated tunnel section is 10.350 km, with a maximum overburden depth of 1,432 m. The longitudinal gradient of the tunnel is 2.183%. The structural clearance of the main tunnel is 11.0 m in width and 5.0 m in height. A parallel pilot tunnel is constructed on the southern side of the main tunnel, located approximately 40 m from the main tunnel axis. In cross-section, the designed elevation of the pilot tunnel is 0.7–1.0 m lower than that of the main tunnel. The pilot tunnel extends from chainage PK12+963.298 to PK23+280, with a total length of 10.316 km and a maximum burial depth of approximately 1,445 m. The pilot tunnel has a single upward gradient of +2.194%, with a structural clearance width of 5.6 m and a height of 4.5 m.

During construction, multiple sudden inrush events involving mud and water occurred, which severely affected construction safety and progress. At the time of the experiment, the excavation face of the main tunnel was located at chainage K80+118, approximately 41 m away from the mud–water inrush location at chainage K15+130 of the parallel pilot tunnel, as shown in **Figure 4**.

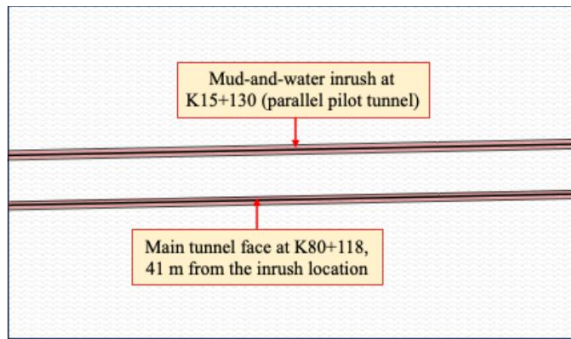
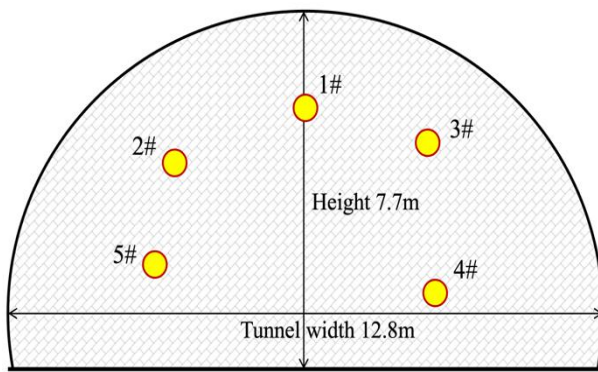


Figure 4. Plan view of detection area.



(a)



(b)

Figure 5. Diagram of borehole radar field test: (a) detection borehole layout; (b) field detection photo.

Borehole radar data acquisition was carried out on the same day the borehole was completed, with a detection depth of 45 m corresponding to chainage K80+118 to K80+163. Borehole television logging was performed on the following day. During this interval, the excavation face advanced by 4 m; therefore, the effective detection depth of the borehole television survey was 41 m, corresponding to chainage K80+122 to K80+163. Both borehole radar and borehole television measurements were conducted in the field by manually advancing the probes into the borehole at a constant speed using drill rods.

3.1.3. Test Results

The borehole radar detection results are shown in Figure 6. Distinct variations in electromagnetic response can be observed at different positions along the borehole. Within the borehole depth intervals of 11–17 m and 21–25 m, pronounced attenuation of the radar signals occurs. These intervals are characterized by locally weakened electromagnetic responses and reduced continuity of the radar image. Such signal attenuation indicates significant variations in the electromagnetic properties of the surrounding rock mass and

3.1.2. Test Scheme

Five forward horizontal boreholes were drilled at the test site. All boreholes were drilled perpendicular to the excavation face, with a borehole diameter of 60 mm. The layout of the forward horizontal boreholes at the working face is shown in Figure 5. The borehole radar advance detection test was conducted in borehole No. 2, which has a total depth of 45 m and extends from chainage K80+118 to K80+163.

suggests the presence of structurally disturbed zones close to the borehole.

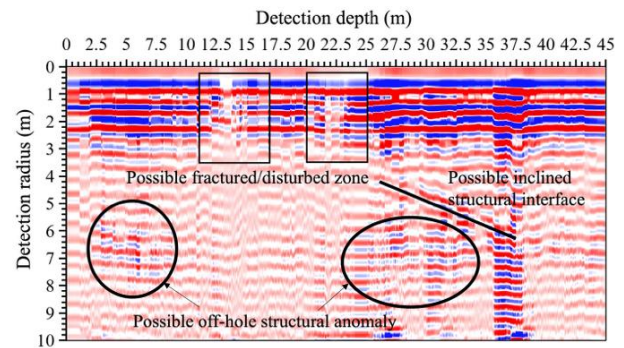


Figure 6. Borehole radar detection results.

In addition to the near-borehole attenuation zones, inclined reflection events are observed within the borehole depth interval of approximately 25–35.5 m. These reflection events occur at a radial distance of approximately 4.0–5.6 m from the borehole. Their spatial morphology differs from the responses generated by anomalies directly intersecting the borehole and is consistent with reflections from planar geological interfaces located outside the borehole trajectory.

Therefore, the borehole radar profile reveals two princi-

pal types of anomalous response: localized signal attenuation along the borehole and coherent inclined reflection events at a certain radial distance from the borehole. The former mainly reflects changes in the properties of the rock mass close to the borehole, whereas the latter indicates the presence of geological interfaces or structural anomalies that are not directly intersected by drilling.

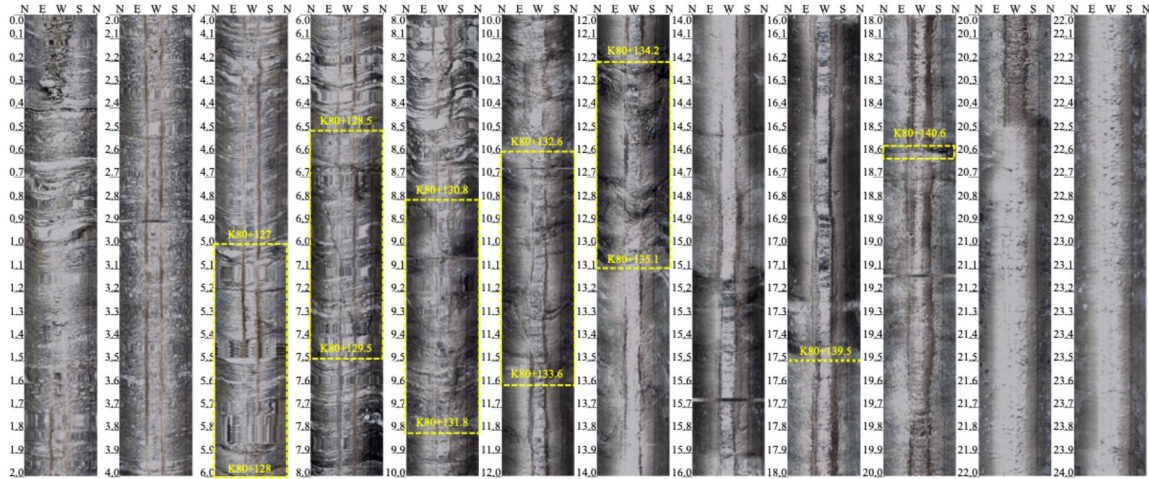


Figure 7. Borehole television logging results.

As shown in **Figure 7**, borehole television observations indicate that the rock mass is generally fractured and characterized by well-developed fissures within the depth interval of 5.0–13.1 m (chainage K80+127–135.1), as well as near a depth of 18.6 m (chainage K80+140.6). Distinct lithological changes are also observed at depths of 15.1 m and 17.5 m (chainages K80+137.1 and K80+139.5, respectively). In particular, severe local fracture development is observed within the chainage intervals K80+127–128, K80+128.5–129.5, K80+130.8–131.8, K80+132.6–133.6, and K80+134.2–135.1.

The borehole television results show good overall correspondence with the borehole-radar responses shown in **Figure 6**. Significant attenuation and disturbance of the radar signals occur mainly within chainage intervals K80+129–135 and K80+139–143, corresponding broadly to zones of fracture development and lithological variation revealed by borehole television. A more detailed comparison shows that four of the five intervals with severe local fracture development, namely K80+128.5–129.5, K80+130.8–131.8, K80+132.6–133.6, and K80+134.2–135.1, show clear spatial correspondence with zones of weakened or disturbed

3.1.4. Borehole Television Verification

The borehole television logging results are presented in **Figure 7**. Beyond a detection depth of 20.5 m (chainage K80+142.5), a large amount of drilling mud was present in the borehole, extensively covering the borehole wall and resulting in extremely low visibility; therefore, this interval is not considered in the present analysis.

radar responses. In contrast, the severely fractured interval at K80+127–128 was not clearly resolved by the present borehole-radar survey.

Overall, the comparison indicates that borehole radar identified most of the major fractured intervals and lithological variations within the effective overlapping survey interval, although the fractured zone at K80+127–128 was not clearly resolved. In addition, the inclined reflections observed away from the borehole trajectory demonstrate that borehole radar can provide structural information beyond the borehole wall, thereby extending direct borehole observations into the surrounding rock mass.

3.2. Field Application at a Coal Mine

3.2.1. Site Conditions and Borehole Layout

To further evaluate the applicability of single-hole borehole radar for detecting concealed mining-related structures and water-bearing fractured zones, field measurements were conducted in the –200 m West Haulageway and the –130 m New East Haulageway of a coal mine in China. Existing exploration and drainage boreholes were directly utilized

for the radar measurements. A total of four boreholes were investigated, including one borehole drilled from the -200 m West Haulageway and three boreholes drilled from the -130 m New East Haulageway. As shown in **Figure 8**, Borehole No. 1 was drilled from the -200 m West Haulageway and is

located close to an old goaf and abandoned roadways associated with the former No. 22 mining district and the -180 m West Haulageway. The borehole has an azimuth of 287° , an inclination of 23° , and a total length of 58.4 m, with a bottom elevation of -175.5 m.

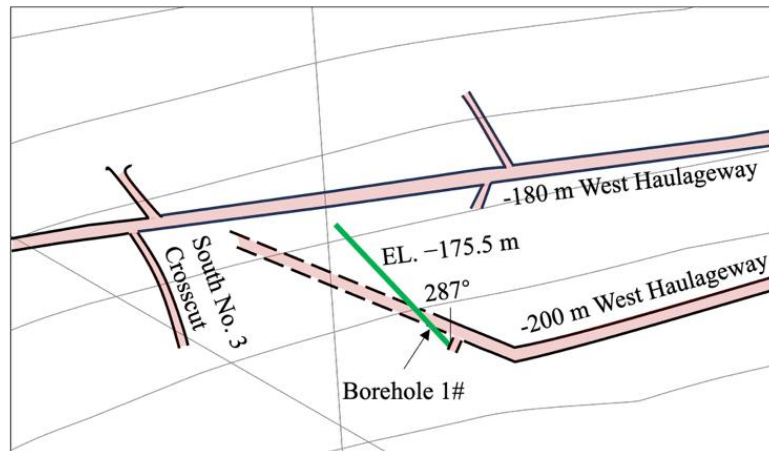
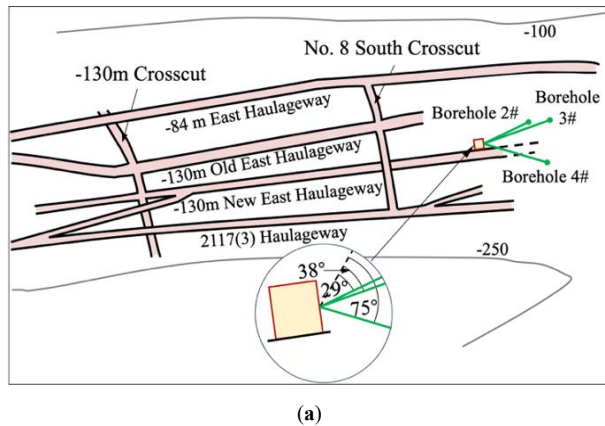


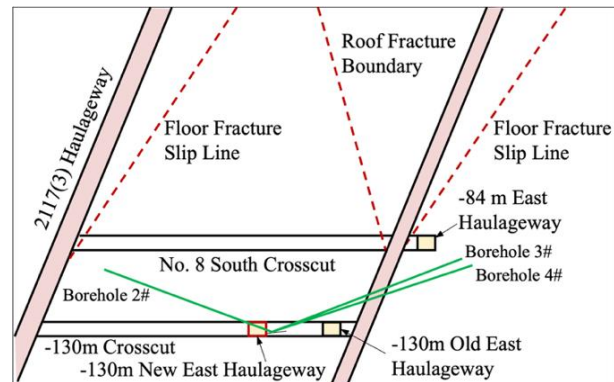
Figure 8. Layout of radar detection borehole 1#.

The layouts of borehole radar survey boreholes Nos. 2–4, together with the adjacent void structures, are shown in **Figure 9**. Boreholes Nos. 2–4 were drilled from the drilling site in the -130 m New East Haulageway. Borehole No. 2 was drilled with an azimuth of 29° and an inclination angle of 23° , reaching a total length of 83 m, with the borehole bottom

at an elevation of -96 m. Borehole No. 3 was drilled with an azimuth of 38° and an inclination angle of 23° , reaching a length of 88 m, with the borehole bottom at an elevation of -94 m. Borehole No. 4 was drilled with an azimuth of 75° and an inclination angle of 16° , reaching a length of 81 m, with the borehole bottom at an elevation of -97 m.



(a)



(b)

Figure 9. Layout of radar detection boreholes 2#–4#: (a) Borehole plan view; (b) Borehole profile view.

According to the borehole design drawings and mining engineering plans, the main known structures surrounding Borehole No. 2 include the 2117(3) Return Airway (elevation -70 m), the 2117(3) Haulageway (elevation -80 m), and the No. 8 South Crosscut of Seam 1 (elevation -80 m). The structures surrounding Boreholes Nos. 3 and 4 include the

former -130 m East Haulageway (elevation approximately -120 m), the -84 m East Central Roadway (elevation -76 m), the No. 8 South Crosscut of Seam 1 (elevation -80 m), and the goaf of Seam 5. These known underground structures provide independent engineering information for comparison with the borehole-radar anomalies.

3.2.2. Borehole Radar Results

The borehole-radar results for Borehole Nos. 1–4 are shown in **Figure 10**. Distinct anomalous responses are ob-

served at different positions along the four boreholes, mainly characterized by signal attenuation, reduced reflection continuity, and locally disturbed radar patterns.

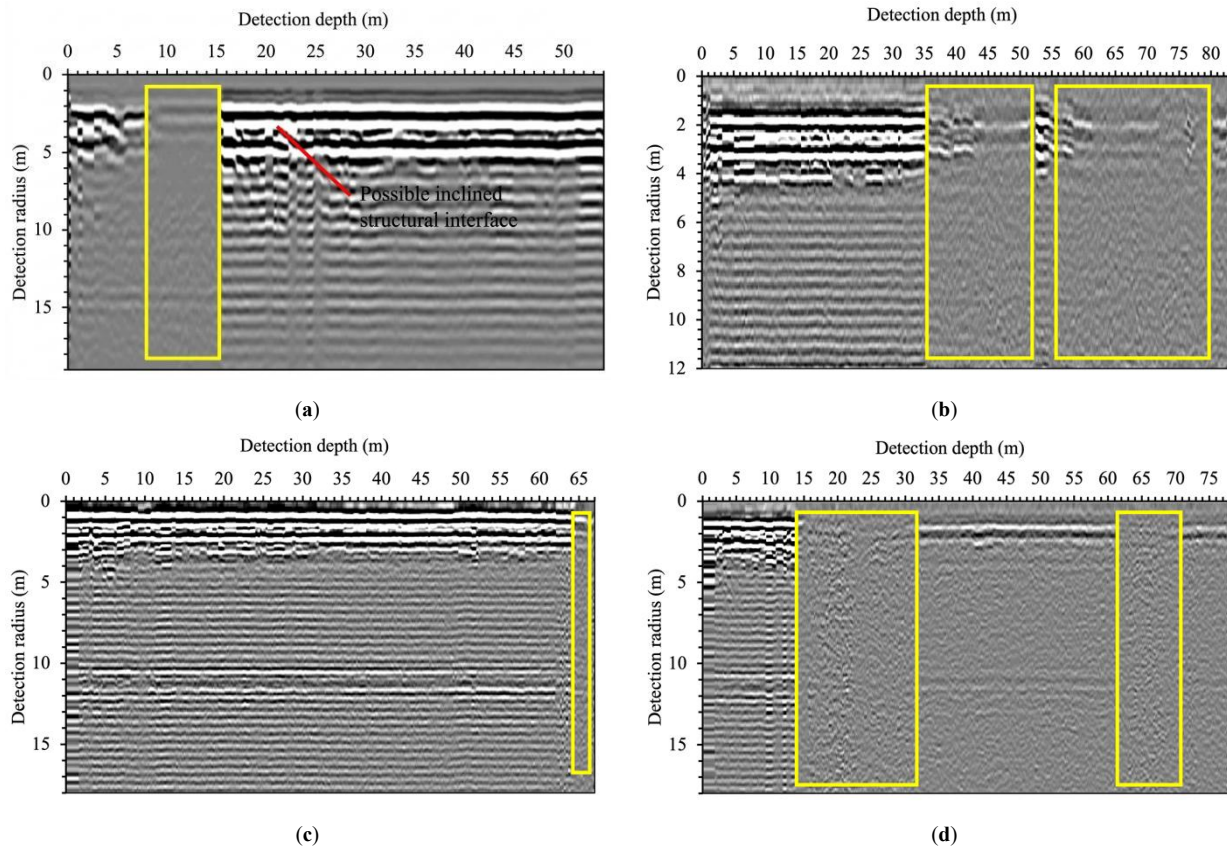


Figure 10. Borehole radar detection results of the coal mine field site: (a) Borehole 1#, (b) Borehole 2#, (c) Borehole 3#, and (d) Borehole 4#.

From **Figure 10a**, in Borehole No. 1, pronounced attenuation of the radar signal occurs at depths of 8.0–15.5 m. A second distinct anomalous response is observed at depths of 21–28 m, where the radar characteristics differ markedly from those of the adjacent intervals. Borehole No. 2 in **Figure 10b** exhibits two relatively broad anomalous zones. The first occurs at depths of 35–52 m, and the second extends from approximately 55 to 80 m. Both intervals show pronounced changes in signal amplitude and reflection continuity, with the latter anomaly extending over a relatively large interval along the borehole. The radar profile of Borehole No. 3 in **Figure 10c** is relatively stable over most of the investigated interval, except for a localized anomalous response at depths of approximately 64.5–66.5 m. Two distinct anomalous zones are identified in Borehole No. 4 in **Figure 10d**. The first extends from approximately 14 to 32 m, whereas the second occurs at depths of approximately

61.5–71 m. Both zones exhibit marked variations in radar response relative to the adjacent borehole sections.

Overall, the four boreholes contain radar anomalies with substantially different spatial extents, ranging from localized responses of only a few metres to broad disturbed zones extending over several tens of metres. This variation suggests that the radar response is related not only to the presence of an anomalous structure but also to its spatial scale and the electromagnetic properties of the surrounding rock mass.

3.2.3. Comparison with Known Geological and Mining Information

Comparison with the borehole design drawings and mining engineering plans indicates that the major radar anomalies are spatially associated with three principal types of underground targets: existing or abandoned road-

ways, abandoned mining spaces, and water-bearing mining-induced fracture zones. The responses in Borehole No. 1 are associated with a nearby roadway and abandoned mining structures at the −200 m and −180 m levels. The anomalies in Borehole No. 2 are spatially related to the No. 8 South Cross-cut of Seam 1 and the 2117(3) Haulageway, together with adjacent water-bearing floor fracture zones. The localized anomaly in Borehole No. 3 occurs within an area affected by water-bearing roof and floor fractures developed after the mining of Seam 5, whereas the responses in Borehole No. 4 are associated with the former East Haulageway, the −84 m East Central Roadway, and the surrounding water-bearing mining-induced fracture zones.

The comparison further shows that different geological targets produce radar anomalies of different spatial scales. Relatively localized fractured zones tend to generate confined anomalous responses, whereas underground roadways accompanied by disturbed or water-bearing fractured rock may produce broader and more continuous anomalous zones. Therefore, the extent of a radar anomaly should not be interpreted directly as the geometric width of an underground opening; rather, it represents the combined electromagnetic response of the target, its filling conditions, and the surrounding disturbed rock mass.

Overall, the spatial correspondence between the radar anomalies and the known mining structures provides engineering-scale evidence that single-hole borehole radar can identify concealed roadways, abandoned mining spaces, and mining-induced fractured zones around existing exploration and drainage boreholes. The results further demonstrate that borehole radar extends geological information beyond the drilling trajectory and provides useful constraints on structures that are not directly intersected by the borehole.

4. Discussion

The two field investigations demonstrate that single-hole borehole radar can provide structural information beyond the borehole trajectory, while the response characteristics vary with the scale, geometry, and electromagnetic properties of the geological targets. At the tunnel field site, the pronounced attenuation zones at borehole depths of 11–17 m and 21–25 m generally corresponded to fractured intervals and lithological variations

identified by borehole television. Four of the five severely fractured intervals—K80+128.5–129.5, K80+130.8–131.8, K80+132.6–133.6, and K80+134.2–135.1—showed corresponding weakened or disturbed radar responses, whereas the interval at K80+127–128 was not clearly resolved. This indicates that not every borehole-intersecting fracture necessarily produces a distinguishable radar anomaly, consistent with previous studies showing that fracture detectability depends on aperture, orientation, filling conditions, and electromagnetic contrast^[14,18]. Inclined coherent reflections at borehole depths of approximately 25–35.5 m and radial distances of about 4.0–5.6 m further demonstrate the capability of single-hole radar to detect structures away from the borehole trajectory. At the coal-mine field site, the major radar anomalies identified in the four boreholes showed spatial correspondence with known underground roadways, abandoned mining spaces, and water-bearing fractured zones. Compared with the relatively localized responses associated with fractures in the tunnel test, these engineering-scale structures generally produced broader and more continuous anomalous zones. The two field investigations therefore provide complementary evidence at different spatial scales: borehole television provides direct near-borehole verification, whereas known geological and mining information provides engineering-scale constraints on larger off-hole anomalies. Combined with the multi-attribute interpretation of reflection-event geometry, instantaneous amplitude, phase, and frequency, these complementary observations reduce the uncertainty associated with interpretation based on a single radar-response characteristic.

Several limitations should nevertheless be considered when applying the method. First, the effective investigation range of borehole radar is strongly controlled by formation conductivity, dielectric permittivity, water content, and antenna frequency. Conductive or highly water-saturated formations can cause rapid electromagnetic attenuation, reducing both the detectable radial distance and the continuity of reflected events. Second, the radial position of an interpreted reflector depends on the electromagnetic-wave velocity adopted in the travel-time conversion; spatial variations in dielectric properties therefore introduce positioning uncertainty. Third, the dipole antennas used in the present system provide effective single-hole reflection measurements but do not uniquely constrain reflector azimuth. Consequently, the

method can estimate the axial position and radial distance of an off-hole anomaly, whereas its full three-dimensional position may remain ambiguous without directional measurements, additional boreholes, or independent geological constraints. Borehole diameter, drilling fluid, wall roughness, antenna coupling, probe motion, and underground electromagnetic interference may also affect data quality. Therefore, single-hole borehole radar should be regarded as a high-resolution extension of borehole investigation rather than a complete replacement for drilling, borehole television, or other geophysical methods. Its principal advantage lies in directly utilizing existing long boreholes to extend geological information from the borehole trajectory into the surrounding rock mass, while the proposed multi-attribute interpretation and complementary validation strategy improve the reliability of structural identification. Future work should focus on quantitative calibration of electromagnetic-wave velocity and dielectric properties, directional or multi-hole radar acquisition for improved three-dimensional localization, and integration with complementary geophysical and borehole observations to further reduce interpretation ambiguity in complex coal-mine environments.

5. Conclusions

The main conclusions of this study are as follows:

- (1) A single-hole impulse borehole radar method was developed for continuous acquisition during probe advancement. By integrating reflection-event geometry with Hilbert-derived instantaneous amplitude, phase, and frequency, the method provides complementary constraints for identifying the location and boundaries of complex off-hole geological anomalies.
- (2) At the tunnel field site, radar attenuation zones generally corresponded to fractured intervals and lithological variations revealed by borehole television. Four of five severely fractured intervals showed corresponding radar anomalies, while the interval at K80+127–128 was not clearly resolved. Inclined reflections at radial distances of approximately 4.0–5.6 m further demonstrate the capability of borehole radar to detect structures away from the borehole trajectory.
- (3) At the coal-mine field site, radar anomalies in four boreholes showed clear spatial correspondence with known

roadways, abandoned mining spaces, and water-bearing fractured zones. The results indicate that single-hole borehole radar can extend geological information from the borehole trajectory into the surrounding rock mass and provides an effective approach for refined investigation of concealed underground structures.

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Informed Consent Statement

Not applicable.

Data Availability Statement

Some or all data, formulations, or codes generated or used during the study are available from the corresponding author upon request. The data contain sensitive information about the mining operations and related parties that could potentially compromise the security and competitive position of the mining company involved. Access to such data is subject to strict regulations and agreements that prevent us from sharing the raw data outside of the research context.

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Conflicts of Interest

The author declares no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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