CASE STUDY

Multi-source seismic geological ahead-prospecting for TBM tunneling in fractured strata: improved strategies and case studies in a water conveyance project, China

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Abstract

The Tunnel Boring Machine has inherent limitations in adapting to adverse geological conditions. When operating in complex strata, encounters with challenging geological formations such as faults and fractured zones can result in tunnel collapses or TBM blockages. This article outlines the successful implementation of a multi-source seismic prospecting strategy designed to achieve advanced prediction of unfavorable geological bodies in a water conveyance project in Northwest China. Due to long-distance broken strata along the construction path, to ensure safety, a single shield TDM replaced the initial open type TBM for the starting section of TBM3-2. With the change in the tunnel environment prompted by the TBM modification, the conventional active source seismic prospecting method previously employed in the open type TBM section became unsuitable. Consequently, we adopted TBM drilling source seismic prospecting technology, refining the arrangement of geophones to capture high-quality seismic signals. Employing this strategy allowed for continuous seismic ahead prospecting across the entire tunnel, providing crucial data to guide safe TBM operation and tunnel support. The multi-source seismic exploration strategy has notably enhanced the TBM's capability to manage complex geological scenarios, such as long-distance fractured zones. This approach has been instrumental in bolstering risk warnings and minimizing TBM blockages, effectively addressing and resolving engineering challenges.

Keywords Multi-source seismic geological ahead-prospecting · TBM tunneling · TBM selection · Fractured strata · TBM blockage

Introduction

The Tunnel Boring Machine (TBM) is the most advanced high-end equipment used in tunnel and underground engineering construction. Compared to the traditional drilling and blasting method, TBM offers significant advantages, such as enhanced safety and environmental protection, faster excavation speed, and reduced labor intensity. Consequently, TBMs are widely employed in tunnel construction for water conservancy, hydropower, and transportation projects (Gong et al. 2016; Tang et al. 2018). However, TBMs face significant challenges when dealing with adverse geological conditions (Dammyr et al. 2017; Rasouli and Narimani, 2018). Particularly in fault fracture zones and water-rich weak surrounding rock sections, excavation can easily lead to rock mass instability, triggering cavity collapses. These collapses can cause the TBM cutterhead or shield to become stuck, severely impacting construction progress and safety (Zhao, 2014; Ayhan et al. 2019). For instance, during the construction of the Pinglin Tunnel, a rock mass collapse obstructed the cutterhead when the TBM encountered a main fault (Tseng et al. 2001; Barton 2012). Similarly, the construction of the Shanggongshan Tunnel faced multiple TBM blockages, primarily due to challenging

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geological conditions such as folds and faults (Shang et al. 2005). In Iran, the Ghomroud Tunnel construction was significantly impeded by severe geological challenges, including face extrusion and collapse, leading to frequent TBM shutdowns and blockages (Farrokh and Rostami 2009). In Turkey's Gerede Tunnel, the Havullu and Camlidere sections experienced TBM blockages caused by high-pressure water and material intrusion, resulting in considerable delays (Alp and Apaydin 2019). Consequently, adoption of ahead prospecting methods for positioning adverse geological units and enforcement of precautions is effective as it prevents Geological disasters during tunnel construction (Zhang et al. 2023).

Many ahead prospecting methods based on geophysics have been developed, which effectively image the distribution of physical parameters in geological bodies ahead of the tunnel face, enabling precise localization of adverse geological bodies (Kaus and Boening 2008; Li et al. 2022a; Liu et al. 2018, 2023; Su et al. 2020). Given that various types of geological disasters are characterized by distinct physical properties, the applicable geophysical methods vary accordingly. Among all the possible hazards associated with tunnel construction, faults and fractured zones are the predominant disaster sources, leading to instability and collapse of the surrounding rock, which subsequently results in TBM blockages. Among these prospecting methods, tunnel seismic prediction technology is especially effective for identifying the location and distribution of faults and fracture zones ahead of the tunnel face, owing to its heightened sensitivity to geological interfaces and its high resolution. (Nyugen and Nestorovic 2016; Song et al. 2019).

In tunnel seismic exploration, methodologies are categorized according to the seismic source utilized, distinguishing between active and passive source seismic detection technologies. Active source seismic detection employs explosives or hammers positioned on tunnel sidewalls to generate seismic waves, subsequently recorded by detector arrays installed along both tunnel walls. Currently, prominent technologies in this sector encompass Tunnel Seismic Prediction (TSP) (Alimoradi et al. 2008; Tzou et al. 2020), True Reflection Tomography (TRT) (Liu et al. 2020; Du et al. 2022), Horizontal Sonic Profiles (HSP) (Song et al. 2006; Zhao et al. 2021), and Seismic Ahead Prospecting (SAP) (Liu et al. 2017). These foundational technologies have facilitated the development of advanced exploratory methods, such as the Tri-loop Electrical Tunnel Seismic Prediction introduced by Lu et al. (2020). This novel method enhances traditional TSP systems by increasing the detector count to six and symmetrically placing 24 shot points along the tunnel walls. The imaging effectiveness of this augmented configuration has been corroborated through both forward modeling and practical engineering implementations. On the other hand,

passive source seismic detection relies on the vibrations from Tunnel Boring Machines (TBM) or rock drilling rigs during excavation as the seismic source, with geophones also placed along the tunnel sidewalls to record the seismic waves (Petronio and Poletto 2002; Harmankaya et al. 2018). This approach does not encroach upon construction time; however, due to the complex nature of the seismic signals received, typically characterized by a lower effective signal spectrum, its detection accuracy is generally inferior to that of active source methods. Wang et al. (2021) explored a Real-Time Seismic Geological Ahead Detection System during excavation, harnessing vibrations from excavation machinery as the seismic source. This system transmits seismic data in real-time via a fiber optic network for processing and imaging, effectively mapping the fault distribution ahead of tunnels in the Yushupo Coal Mine in Shanxi. Furthermore, an enhanced version of the tunnel-seismic-while-drilling (TSWD) method, developed by Li et al. (2022b), has been successfully implemented for advanced prospecting in TBM tunnels within the Songhua River Water Supply Project. This refined approach accurately identifies the locations and distributions of fracture zones and fault boundaries, with the results showing high concordance with the actual excavation outcomes.

In the TBM3 section of a water conveyance project in Northwest China, the geological conditions are exceptionally challenging. The surrounding rock, primarily composed of carbonaceous shale and siltstone, exhibits poor structural integrity, with approximately 85% of the tunnel sections passing through broken or extremely fragmented zones. Frequent serious issues, including machine blockages, were encountered during the excavation with the open type TBM. Given that the initial 1.5 km of the ensuing section consist entirely of highly fragmented carbonaceous siltstone, a strategic decision was made to upgrade the TBM with critical technological enhancements and to implement a single shield mode to ensure the safety and continuity of construction. During the excavation phase utilizing the open type TBM, active source seismic prediction technology (SAP method) was employed for geological ahead prospecting. However, in the phase involving the single shield TBM, the complete encapsulation of the surrounding rock by the segment support system precluded the traditional placement of seismic sources and geophones. This limitation significantly hampered the implementation of the active source seismic prediction technology. Consequently, we adopted the passive source seismic technology (TSWD method) as an alternative to the SAP method, effectively addressing the challenges related to seismic source excitation. Despite this adaptation, optimizing the placement of geophones beneath the segment-supported tunnel sidewalls to capture high-quality, effective seismic signals remains an urgent and

significant technical challenge that requires further investigation and innovative solution development.

This paper proposes a multi-source seismic detection strategy designed for geological ahead-prospecting within complex tunnel environments, applicable across various TBM types. Both active and passive seismic techniques necessitate adequate spatial allocation within the tunnel to deploy the observation systems. Given that passive seismic technology leverages the vibrations produced by TBM excavation as its source, and active seismic technology depends on explosives or hammers to stimulate seismic sources on tunnel sidewalls, the former offers greater adaptability to diverse tunneling conditions. In a specific case of a TBM tunnel excavation in Northwest China, the project confronts an long-distance zone of fragmented rock. To ensure the safety of the TBM operation and maintain construction progress, the SAP method was implemented for geological ahead prospecting in sections excavated using open type TBM configuration. However, with the transition of the TBM to single shield mode to better handle extremely fractured strata, traditional active source seismic techniques became impracticable. Consequently, we adopted passive source seismic detection methods. A detailed study was conducted on the optimal installation of geophones under this configuration to capture high-quality seismic signals, ultimately leading to precise detection outcomes. The multi-source seismic detection strategy introduced herein provides scientifically robust and practically viable guidance for TBMs to navigate safely and efficiently through long-distance zones of broken rock strata. This approach not only enhances the predictability of geological conditions ahead of the excavation face but also adapts flexibly to the varying demands of different tunnel environments.

Background of the study region

The TBM3 section of a tunnel in a certain section of a water transfer project in Northwest China extends over a total distance of 20,142 m, subdivided into TBM3-1 and TBM3-2 sections, measuring 10,624 m and 9,518 m respectively. The surrounding rock quality within this segment is poor, characterized by extensive zones of weak rock. This study focuses on the sections between KS58 + 153 and KS73 + 300. Here, the terrain primarily consists of erosional hilly landforms with slight undulations, typical of areas with scattered hills and minor gullies. Lithologically, the interval from KS58 + 153 to KS67 + 077 is dominated by Devonian tuffaceous sandstone, whereas the segment from KS67 + 077 to KS73 + 300 features Carboniferous calcareous siltstone interlayered with carbonaceous siltstone (Deng 2018). The rock mass in the study area exhibits low

strength and undergoes significant softening upon water contact, posing serious challenges during excavation. The tunnel is buried at depths ranging from 184 to 270 m, where TBM operations encounter complex and variable rock conditions. Additionally, the area is intersected by 12 large and medium-sized faults, with widths varying from 9 to 37 m and fault strikes forming angles between 42° and 78° relative to the tunnel axis (Fig. 1a). The discovery of several small fractured zones, approximately 1 m wide, during excavation significantly hampers efficiency and highlights notable safety concerns in the construction process.

In the study area, two principal excavation methods were employed: Tunnel Boring Machine (TBM) technology and conventional drilling and blasting. The TBM method was applied to two distinct sections: TBM3-1, extending from KS58 + 153 to KS67 + 750, and TBM3-2, from KS69 + 635 to KS73 + 300. The intermediary segment, ranging from KS67 + 750 to KS69 + 635, was subjected to drilling and blasting method. In the TBM3-1 section, the integrity of the surrounding rock was poor, with numerous fault fracture zones present, resulting in inadequate rock strength near the TBM shoe. This deficiency hindered the necessary reaction force required for the advancement of the open-type TBM. To counter these challenges, construction teams were frequently tasked with clearing fragmented rock around the support shoe and implementing advanced support measures to bolster the surrounding rock's stability. This labor-intensive process significantly reduced the excavation's efficiency. Moreover, during the construction of the open-type TBM in the TBM3-1 section, broken zones were frequently encountered. The fragile state of the surrounding rock at the face often led to collapses during excavation, causing substantial amounts of debris to obstruct the cutterhead and subsequently jam the machine. Notably, two significant TBM blockage incidents, occurring at face mileages KS63 + 814 and KS64 + 410 respectively, required extensive resources to address and caused considerable project delays. Subsequent geological assessments identified that the initial 1.5 km of the TBM3-2 section predominantly consisted of highly fragmented carbonaceous siltstone, presenting substantial challenges for conventional open-type TBM operations. In response, the construction team enhanced the TBM system by incorporating a single shield mode, which was initiated upon entering the TBM3-2 section (Fig. 1b). This section, utilizing single shield TBM tunneling with segment support, markedly improved the surrounding rock's stability. As excavation approached KS71 + 624 and the quality of the surrounding rock ameliorated, it became feasible to revert to the open-type TBM mode. Following this transition, shotcrete support technology was employed in the subsequent excavation segments to achieve more efficient progress.
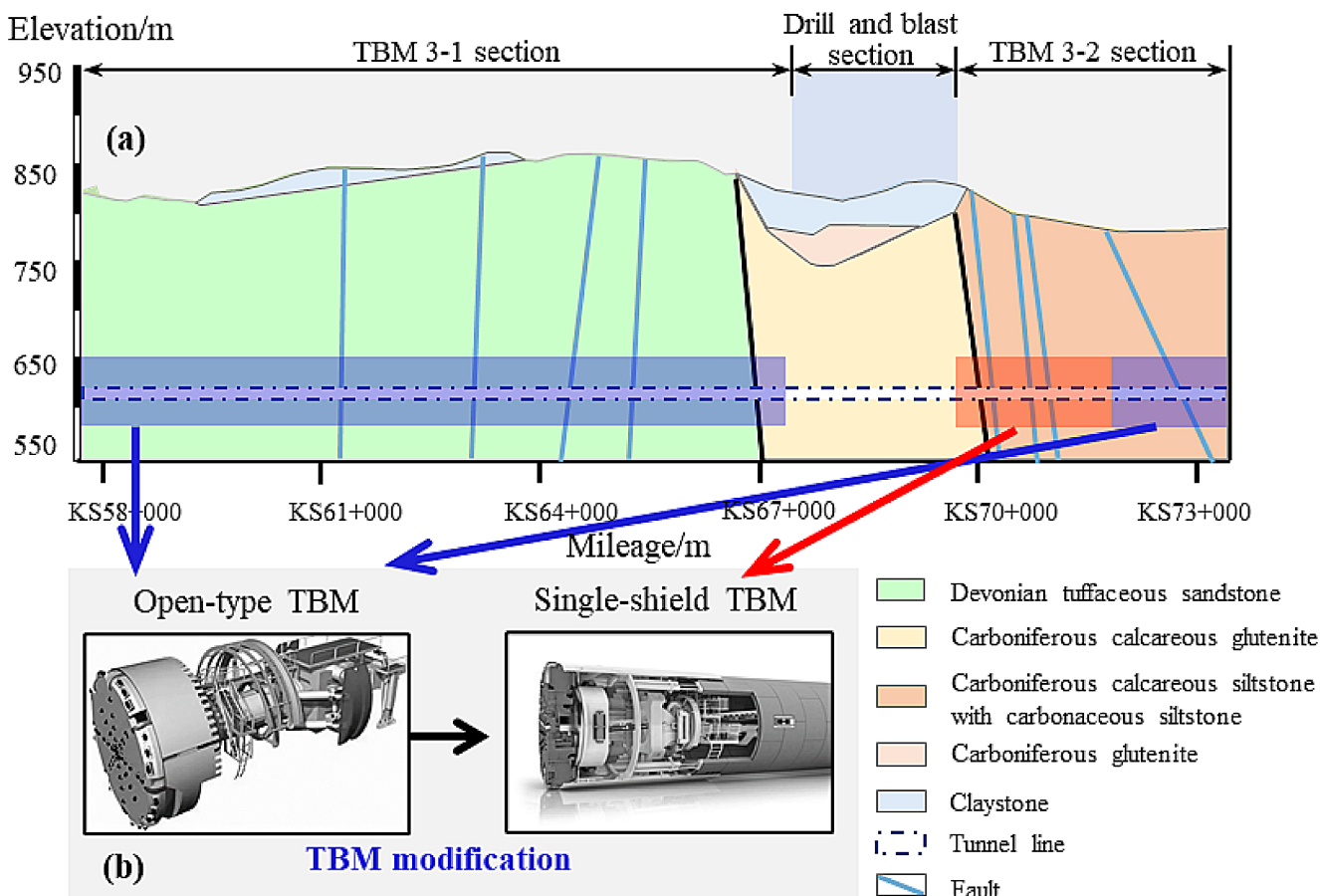
Fig. 1 Geological longitudinal section and construction schematic diagram of the KS IV section of a water transmission project in northwest China. (**a**) Geological profile, (**b**) TBM modification

As highlighted previously, the faults and fractured zones have been identified as a major risk factor for the safe construction of TBM tunnels in the study area. In response, we consistently conduct advanced seismic geological exploration concurrent with tunnel excavation, delivering crucial seismic imaging results and geological interpretations to the construction teams. These insights serve as valuable references for informed decision-making during the construction process. However, modifications to the TBM setup have led to significant environmental changes that pose challenges to the seamless execution of seismic forecasting activities. To address these challenges, we have developed a multi-source seismic detection strategy. The specifics of this approach will be elaborated in the subsequent section.

Methodology

Multi-source seismic geological ahead-prospecting strategy

In the sections excavated using the open-type TBM, the surrounding rock exhibited high quality with a robust natural self-stabilizing capacity, supporting the TBM excavation effectively. During construction, techniques such as shotcrete and steel arch support were routinely applied to fortify the surrounding rock and ensure rock mass stability. Importantly, these support methods did not interfere with the installation of the tunnel seismic wave observation system. Seismic geophones and shot points were conveniently installed directly on the tunnel walls (Fig. 2a), facilitating both active source seismic prospecting and TBM drilling source seismic prospecting successfully.

Upon transitioning to a single shield TBM, traditional shotcrete and anchor supports were replaced by robust segmented support. This enhancement not only bolstered the stability of the surrounding rock but also provided the necessary reaction force for the TBM support shoes, significantly
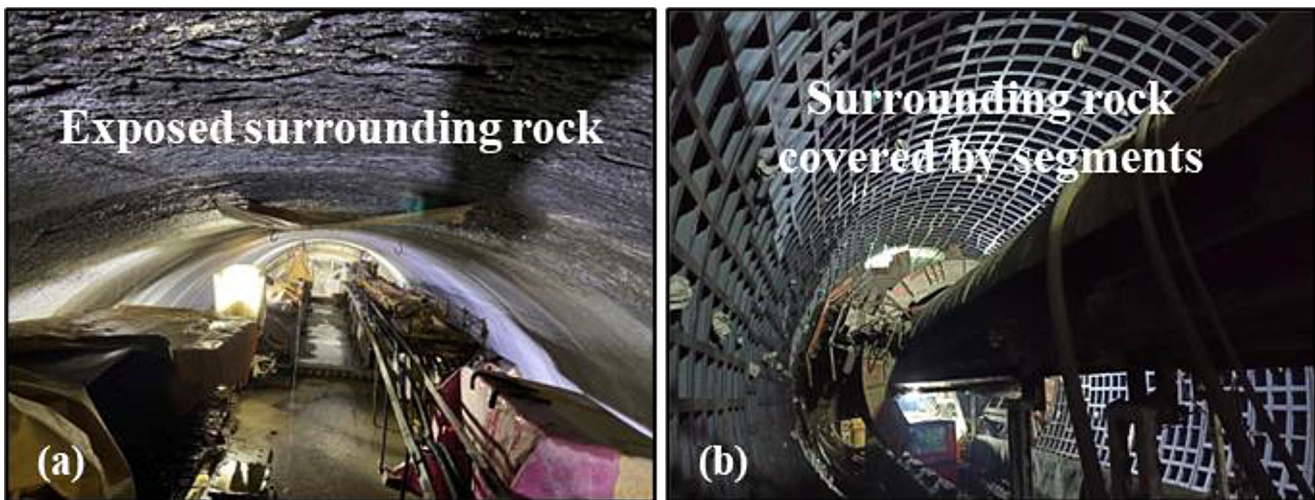
Fig. 2 (**a**) the environment in open-type TBM tunnels, and (**b**) concrete segments for support in single-shield TBM tunnels

mitigating the risk of blockages. However, this modification introduced substantial challenges for seismic advance prospecting. The segments, while stabilizing the structure, impede direct access to the rock mass (Fig. 2b), complicating the installation of geophones and making the placement of shot points impractical. Consequently, active source seismic methods became unfeasible under these modified conditions. Under such constraints, TBM drilling source seismic prospecting emerged as the only viable method for several reasons: (i) It utilizes the noise generated by the TBM cutterhead breaking rock as the seismic source. This approach addresses the challenge of deploying explosive or hammer seismic sources within a single-shield TBM tunnel; (ii) Despite the segment support obscuring the rock, the grouting holes preserved in the segments allow geophones to make direct contact with the underlying rock, making it possible to receive effective seismic wave signals.

The complex tunnel environment resulting from the use of multiple TBM systems presents significant challenges to the implementation of effective seismic ahead prospecting techniques. Traditional single-source seismic exploration methodologies are often inadequate for addressing the sophisticated detection requirements in such settings. Accordingly, this paper introduces a multi-source seismic ahead prospecting strategy, depicted in Fig. 3. The principal components of this strategy are outlined as follows:

(i) Multi-source Seismic Ahead Prospecting: For tunnel segments excavated using open-type TBM, Seismic Ahead Prospecting method is employed (Li et al. 2018). These involve generating seismic waves by striking a hammer source, with a detection array strategically positioned on the exposed surrounding rock of the tunnel sidewalls. Conversely, for sections excavated using single shield TBM, TBM drilling source

seismic prospecting method (TSWD) are utilized (Xu et al. 2021). The detection arrays in these segments are arranged in accordance with the distribution of grouting holes within the tunnel, with an approximate interval of three segments between detectors, equivalent to 4.5 to 5.4 m.

(ii) Geological Interpretation: Both SAP and TSWD are capable of imaging the geological structures up to 100 m ahead of the tunnel face. By integrating the observed conditions of the surrounding rock near the tunnel face with geological sketches, it is possible to accurately identify the location and distribution of adverse geological formations. This strategic approach enhances the precision and reliability of geological assessments, facilitating safer and more efficient tunnel construction.

Seismic ahead prospecting method

The active source seismic prospecting method

The 3D observation configuration for active source seismic ahead prospecting in TBM tunnels is depicted in Fig. 4 (Liu et al. 2017). The arrangement involves shot points and geophone arrays positioned on the exposed surrounding rock located immediately behind the TBM cutterhead and shield. A total of 12 geophones are installed, with six on each side wall, and a spacing of 4 m between adjacent geophones. The closest geophones (G6 and G12) are situated approximately 10 m from the tunnel face. Ten shot points are strategically placed on the side wall 43 m from the tunnel face, utilizing a hammer source. During the measurement phase, data from each source point is collected thrice and superimposed to enhance the signal quality. To minimize the impact of construction noise on data quality, data acquisition is conducted
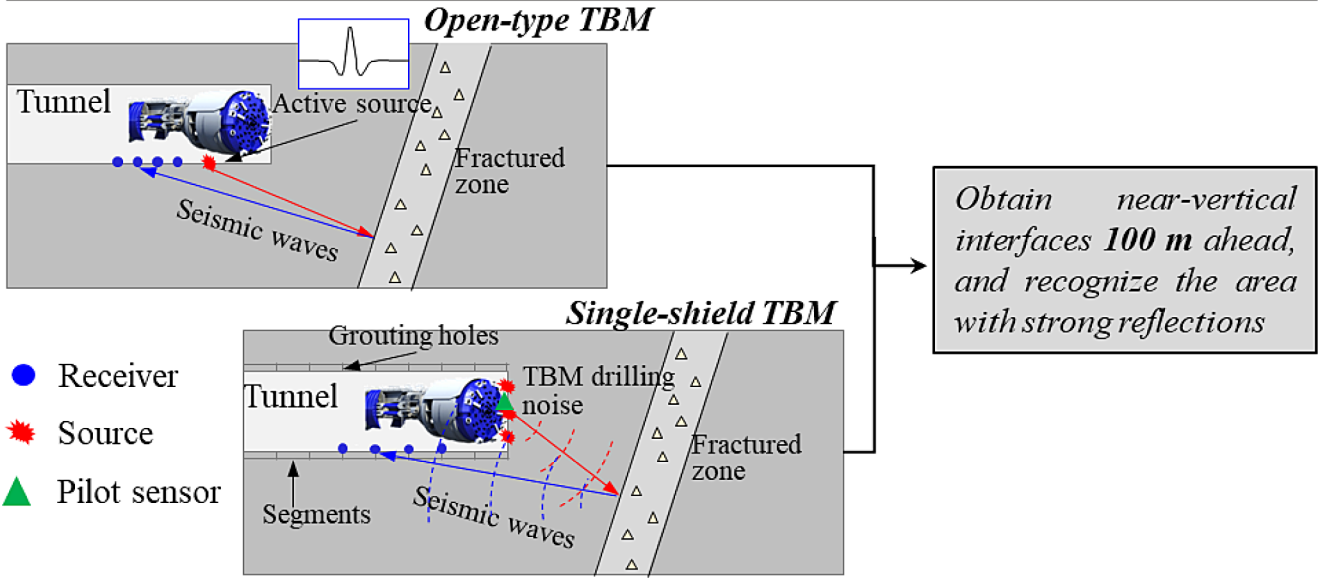
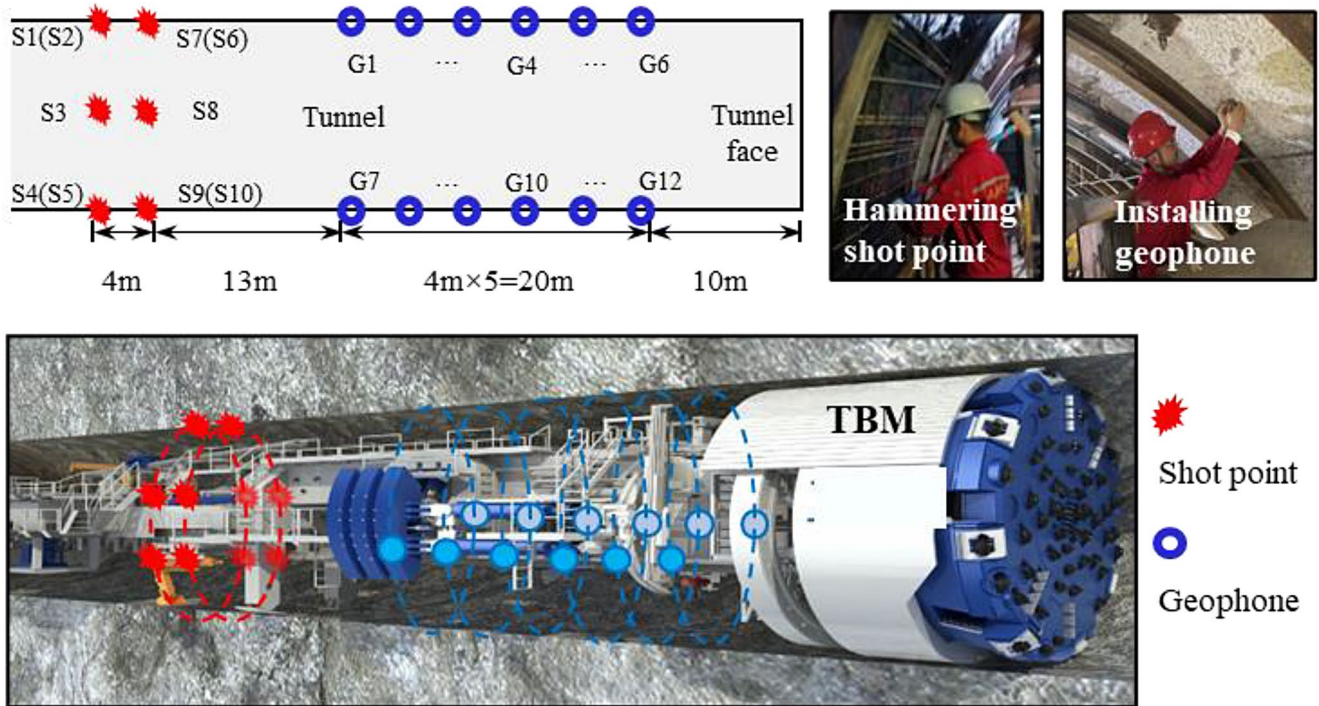**Fig. 3** The multi-source seismic ahead prospecting strategy

Fig. 4 Schematic diagram of the layout of active source seismic prospecting observation mode for TBM tunnels

during periods when the TBM is not operating. The data processing sequence encompasses preprocessing, bandpass filtering, diffusion compensation, first arrival picking, direct wave velocity, wave field separation, velocity analysis, migration imaging, and geological interpretation.

TBM drilling source seismic prospecting method

Figure 5 illustrates the 3D observational mode for TBM drilling source seismic prospecting method. This configuration involves an array of six geophones, positioned using the grouting holes at the rear, spaced approximately 5 m apart. The precise placement is tailored based on the specific locations of the grouting holes on-site, with the nearest geophone (G6) positioned about 15 m from the tunnel face (Chen et al. 2023). Details regarding the installation of the geophones will be provided in the subsequent section. The TBM cutterhead will generate continuous seismic wave signals during rock breaking operations. A precursor geophone, installed just behind the cutterhead, captures an approximation of the vibration signals generated during this process. Meanwhile, the geophone array records seismic signals induced by these vibrations as they propagate through the strata. The seismic sources generated by TBM rock breaking are characterized by high randomness, disorder, and uncontrollability. Consequently, during data processing, the equivalent pulse signal is initially extracted through cross-correlation between the signal received by the precursor geophone and that collected by the geophones. Subsequently, this is supplemented by techniques such as normalization of single-channel seismic records and segmented superposition of long-term continuous seismic records. These methods effectively suppress interference noise, facilitating the "normalization" of seismic records from TBM rock breaking (Li et al. 2022a). Following this, the data processing techniques previously described for active source seismic exploration are applied to the reconstructed TBM drilling source seismic records. The control host and pilot sensor are pre-installed on the TBM equipment. The detection process involves properly arranging the geophone array and conducting data acquisition through the control host while the TBM is excavating. Each data collection session typically lasts between 15 and 20 min, ensuring comprehensive coverage and data integrity.

Fig. 5 Schematic diagram of the layout of TBM drilling source seismic prospecting observation mode for TBM tunnels
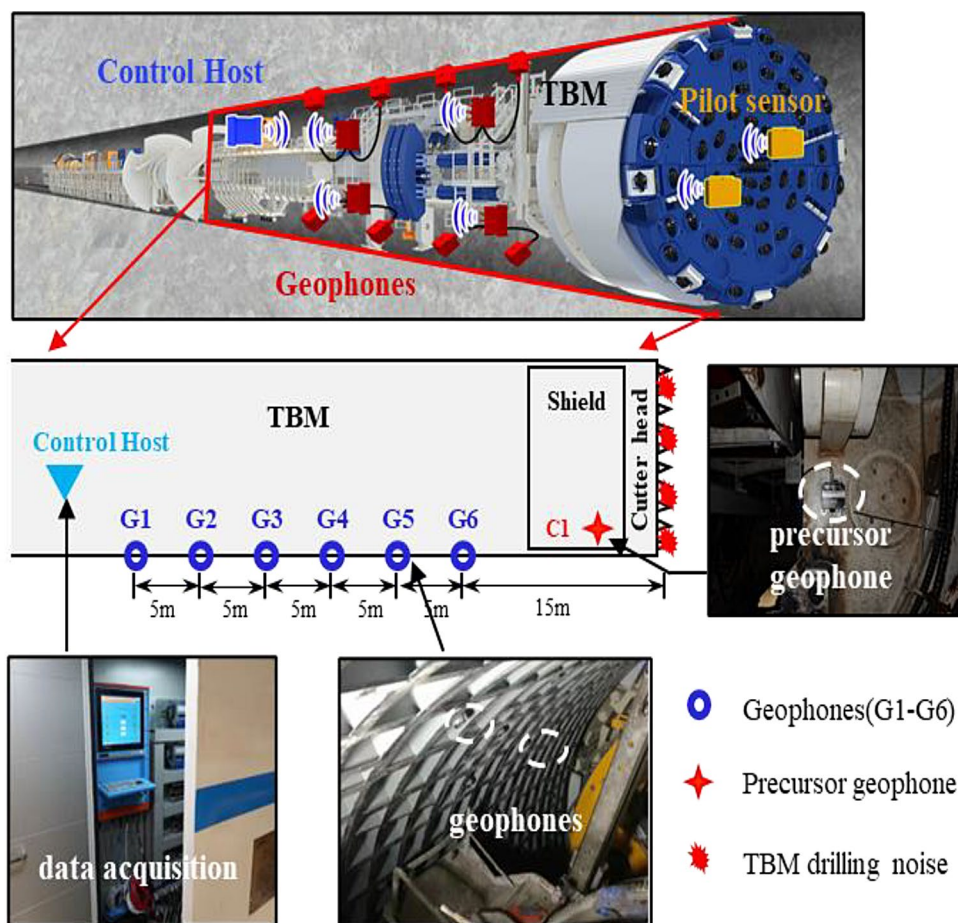
Improved installation of geophones in single-shield TBM segments

Seismic waves generated by the TBM cutterhead during rock breaking propagate omnidirectionally, and upon encountering geological interfaces, they produce reflected signals. These signals propagate through the surrounding rock and are captured by the geophone array. However, the reality is that the segments and the surrounding rock are not in tight contact, resulting in a gap. When the geophone is mounted directly on the segment (Fig. 6b), the amplitude of the seismic wave signal undergoes significant attenuation as it traverses the air gap. This attenuation leads to a substantially reduced signal-to-noise ratio in the received signal, which in turn, severely compromises the accuracy of seismic imaging. To address this, ensuring optimal contact between the geophones and the surrounding rock is crucial. Given the structure of the segments supporting the tunnel, we have developed a geophone installation method: Initially, an 8 cm deep hole is drilled into the surrounding rock via a grouting hole reserved in the concrete segments. A reinforcement is then inserted and secured with an anchor, and the geophone is attached to the exterior of the steel bar using a magnetic connection (Fig. 6a). To further enhance signal fidelity, the space between the grouting hole and reinforcement is filled with sound insulation cotton, effectively reducing noise interference and improving the quality of seismic data collection.

Practical experience with seismic ahead-prospecting in TBM tunnels

To identify unfavorable geological conditions in advance and mitigate the risks associated with tunnel construction and TBM blockages, continuous advance seismic detection was carried out in the entire tunnel in the study area following the excavation progress. According to gathered statistics, over 240 active source seismic prospecting and TBM drilling source seismic prospecting were conducted. These efforts successfully identified more than 600 unfavorable geological formations, including faults, fractured zones, and joint-dense areas. The findings from these explorations were highly consistent with the actual tunnel excavation outcomes, providing critical data for informed decision-making regarding TBM construction parameters and support structure design. This strategic approach significantly enhanced risk warnings and effectively reduced TBM blockages, thereby addressing critical engineering challenges. Below are several detailed case studies from the detection efforts to further analyze their impact and effectiveness.

A case study of active source seismic prospecting method: section KS63 + 785 to KS63 + 914

Preliminary exploration data indicated that the section from KS63 + 785 to KS63 + 914 was influenced by three nearby faults, presenting complex geological conditions, compromised surrounding rock integrity, and low strength. When the open type TBM reached the KS63 + 785, the first active source seismic survey was conducted. The imaging results suggested that the fractured zone was approximately located near KS63 + 805. As the TBM progressed, the quality of the rock mass steadily deteriorated. At KS63 + 814, a collapse
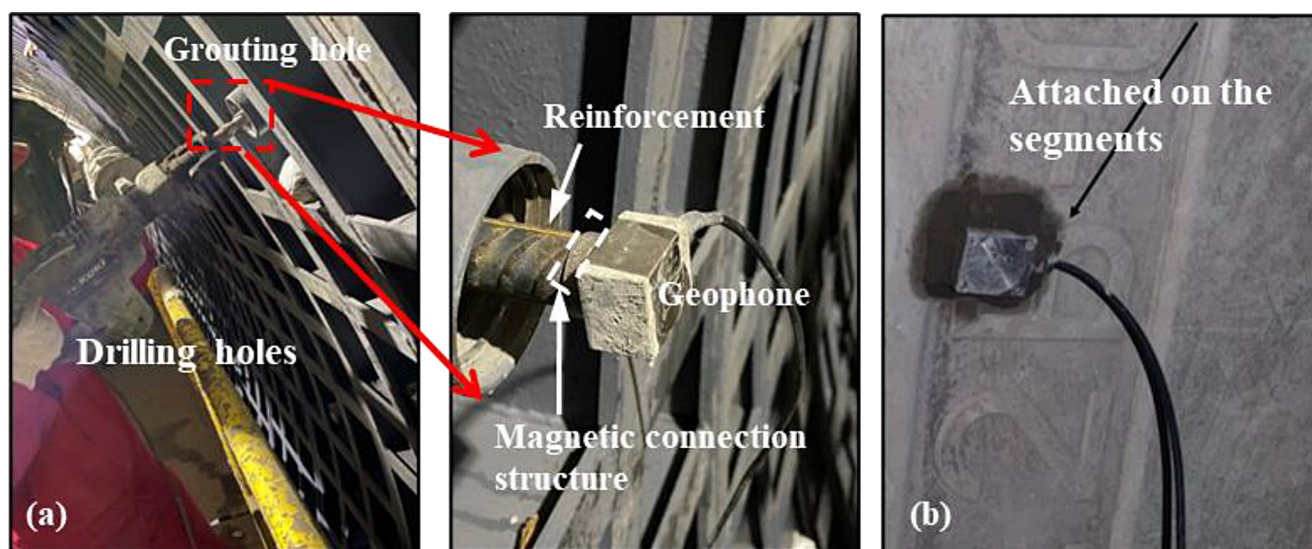

Fig. 6 Installation of geophone: (**a**) Fixed on the surrounding rock through grouting holes, (**b**) Fixed directly on the pipe segment

occurred in the rock mass above the TBM cutterhead, causing gravel and large rocks to flood into the cutterhead and jam the machine (Fig. 7). Following this incident, to quickly devise an effective solution to assist the TBM, a second active source seismic survey was performed at KS63 + 814. The subsequent data processing produced a 3D seismic reflection image that closely correlated with the results of the initial seismic survey.

Figure 8 displays the seismic migration imaging results from two seismic surveys, indicating the presence of two fractured zones within the exploration profile: from KS63 + 805 to KS63 + 830 and from KS63 + 840 to KS63 + 860. The imaging shows no reflections in the KS63 + 785 to KS63 + 805 section, suggesting that the surrounding rock is relatively intact and structurally stable. In contrast, the KS63 + 805 to KS63 + 830 segment exhibits dense positive and negative reflections, indicating poor rock quality and a developed structural surface, characteristic of a fractured zone. The subsequent section from KS63 + 840 to KS63 + 860, while still showing numerous positive and negative reflections, displays fewer than the previous area, suggesting a slight improvement in rock quality. However, this area still presents a risk of instability. Finally, the section from KS63 + 860 to KS63 + 914 shows no reflections, indicating good quality and stable conditions of the surrounding rock.

The actual outcomes of the tunnel excavation, as depicted in Fig. 8c and 8d, and 8e, reveal that the areas near KS63 + 820 and KS63 + 830 exhibited fractured zone and occurrences of falling blocks, aligning with the anticipated distribution of the fractured zone. As excavation progressed to KS63 + 845, the exposed lithology consisted of purple-red tuffaceous siltstone, characterized by low strength. Correspondingly, the imaging map for this area displayed prominent positive and negative reflections. Thus, the excavation findings corroborate the earlier exploration results, confirming the accuracy of the geological predictions in guiding the tunneling efforts.

A case study of active source seismic prospecting method: section KS67 + 255 to KS67 + 355

The section from KS67 + 255 to KS67 + 355 was excavated using an open type TBM. Prior excavation results indicated poor surrounding rock quality in this area. To ensure the safe progression of the TBM, active source seismic exploration was conducted on the KS67 + 255 section, followed by data processing. The resulting migration imaging, displayed in Fig. 9, provides detailed insights into the geological structure. The imaging reveals distinct positive and negative reflections from KS67 + 255 to KS67 + 275, suggesting the presence of a fractured zone. Between KS67 + 275 to KS67 + 315, the reflections are sporadic and no significant structural anomalies are evident in the surrounding rock, implying generally good rock quality. Conversely, the section from KS67 + 315 to KS67 + 355 exhibits clear positive and negative reflections, indicating potential fractures.

Figure 10a depicts an excavation sketch of this segment, highlighting a pronounced fracture zone between KS67 + 250 and KS67 + 264, aligning with the seismic results. Near KS67 + 280, a collapsed cavity adjacent to the arch is visible, with a significant accumulation of stones above the steel mesh evident in the on-site photograph (Fig. 10c). Additionally, two faults near KS67 + 330 correspond with areas of intense reflection in the imaging results. These observations further verify the effectiveness of seismic ahead prospecting technology in predicting and identifying geological conditions during tunnel excavation.
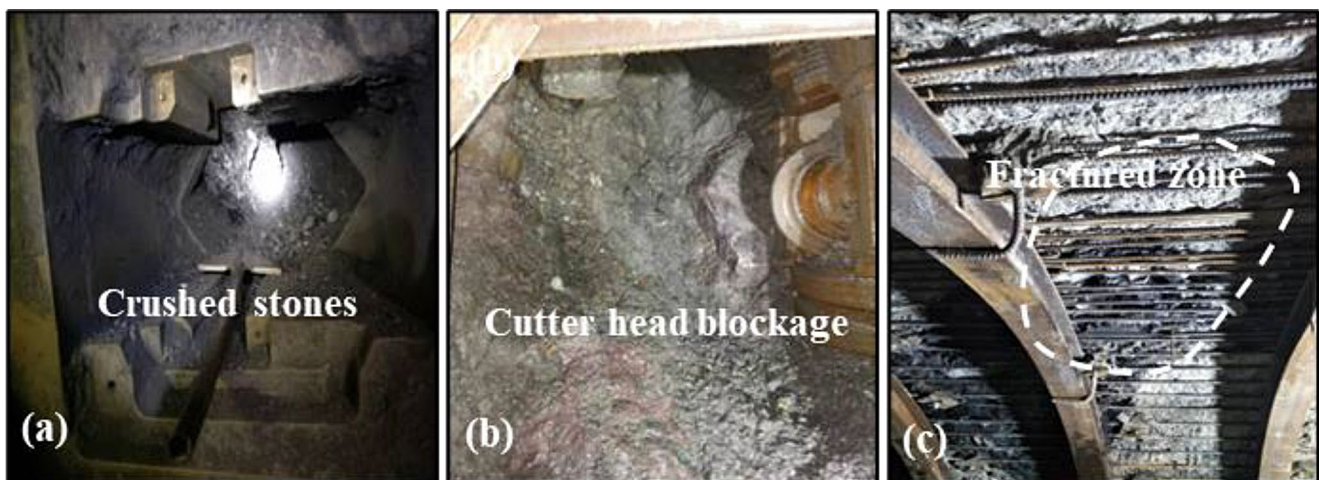

Fig. 7 The site conditions of TBM jamming at KS63 + 814. (**a**) The cutter head is filled with gravels, (**b**) Cutter head blockage, (**c**) Fractured zone

Fig. 8 (**a**) The seismic migration results in the XZ-plane for the section from KS63+785 to KS63+885, (**b**) The seismic migration results in the XZ-plane for the section from KS63+814 to KS63+914, (**c**) Fractured zone, (**d**) Fall-blocks, (**e**) Purplish red tuffaceous siltstones
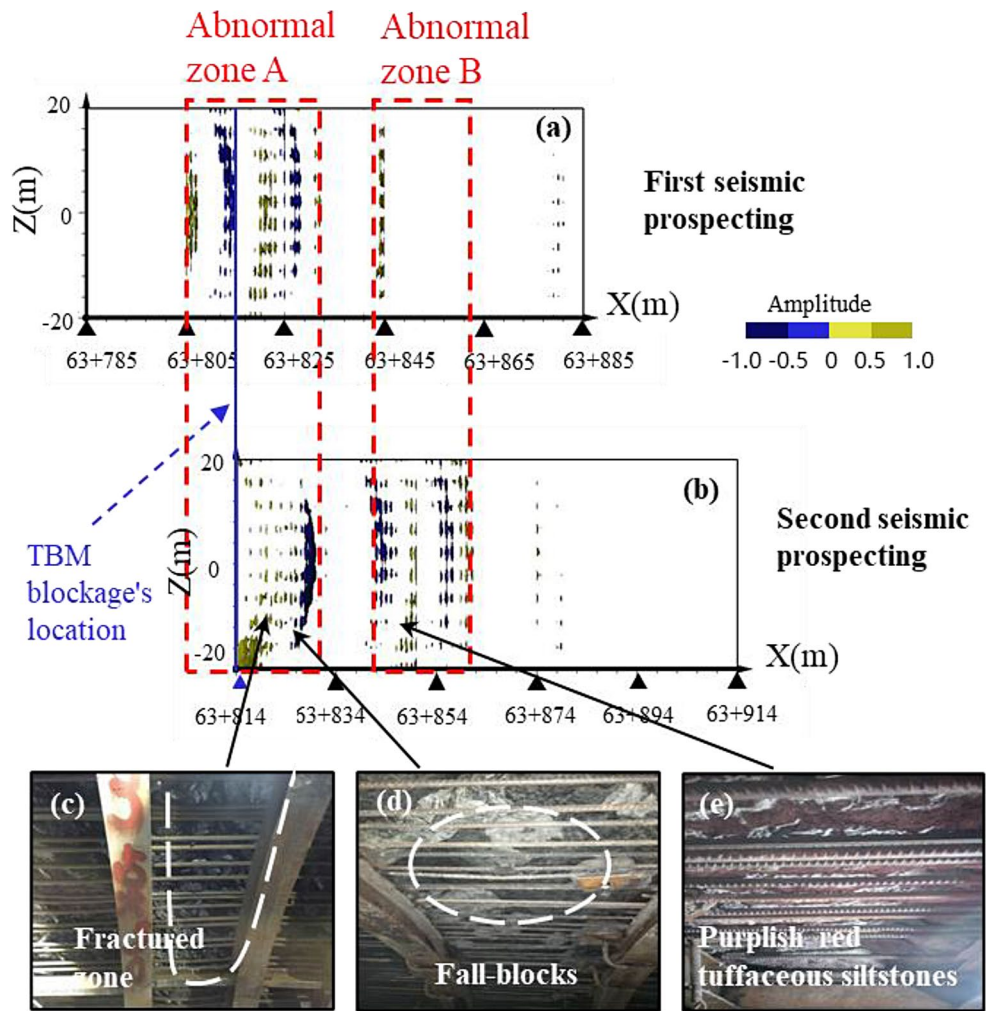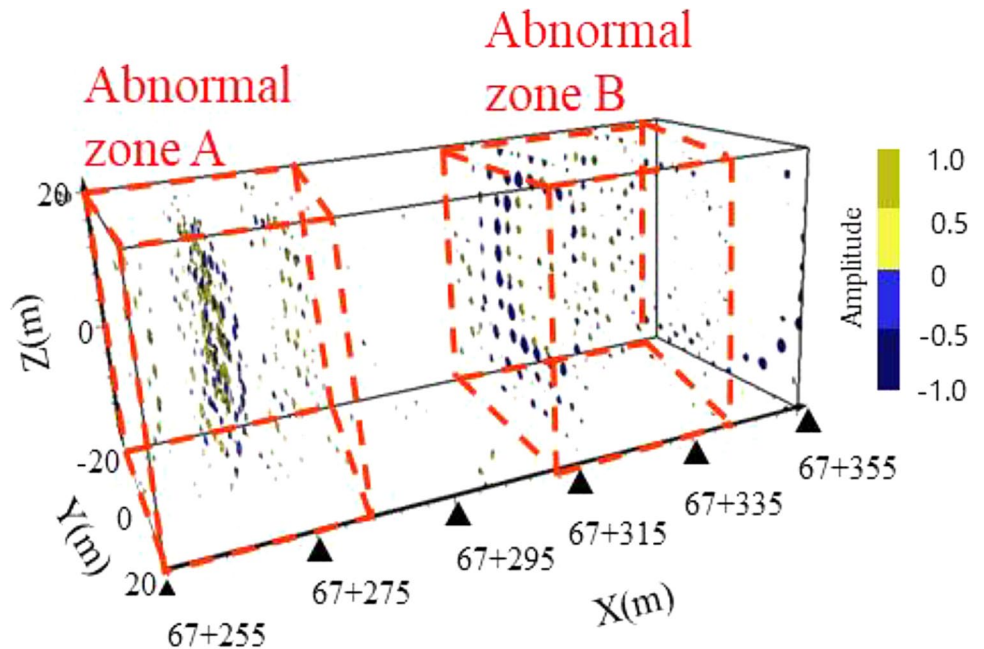

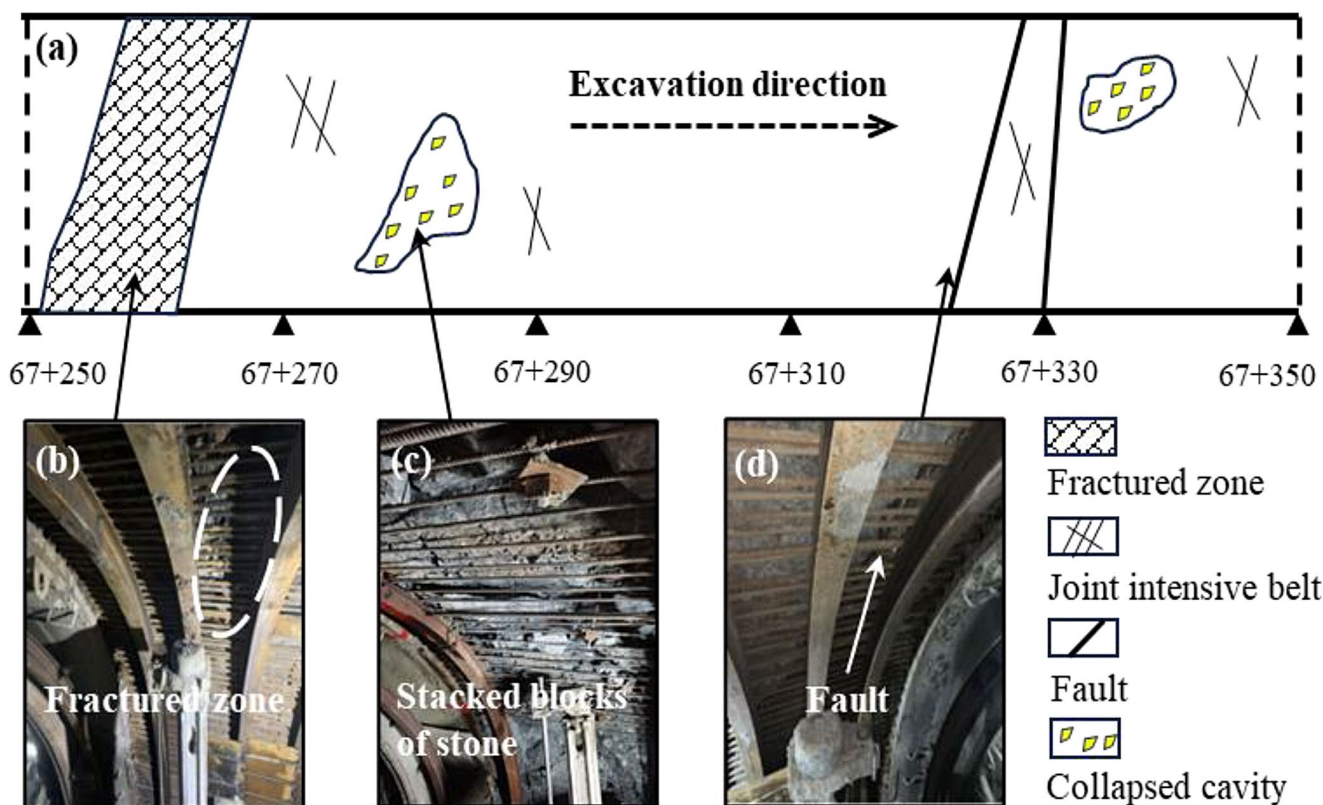**Fig. 9** 3D imaging from KS67+255 to KS67+355 by detection with the active source seismic prospecting method

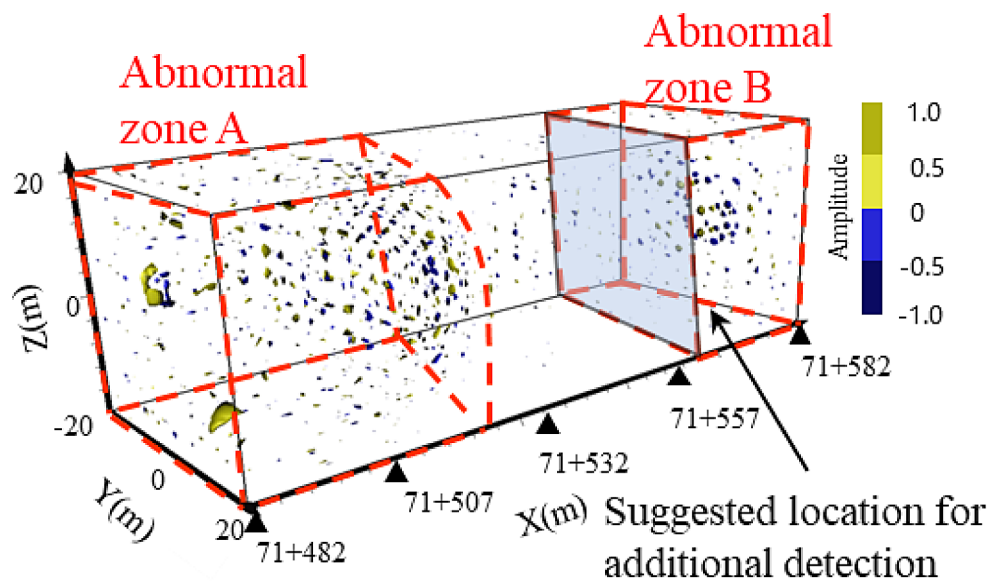**Fig. 10** TBM excavation results. (**a**) Geological sketch map of the excavation area, (**b**) Fractured zone, (**c**) Joint intensive belt, (**d**) Fault

Fig. 11 3D imaging from KS71 + 482 to KS71 + 582 by detection with the TBM drilling source seismic ahead prospecting method

A case study of TBM drilling source seismic prospecting method: section KS71 + 482 to KS71 + 582

The section from KS69 + 635 to KS71 + 704.1 was constructed using a single shield TBM. Preliminary exploration data indicated that the lithology within this stretch was complex and the rock mass quality was notably poor. Given the use of concrete segments for support in this section, direct observation of the surrounding rock was not feasible, making it challenging to ascertain information on rock mass integrity, quality, and lithology. Consequently, it was difficult to infer geological conditions in the unexcavated area ahead of the tunnel face. Additionally, the confined space rendered traditional geological exploration

methods, such as advance drilling, impractical. Thus, continuous seismic ahead prospecting was deemed necessary to provide essential data for determining appropriate support strength for the surrounding rock and for selecting TBM construction parameters. This analysis focuses on the TBM drilling source seismic ahead prospecting carried out in the KS71 + 482 section.

The three-dimensional seismic reflection image, displayed in Fig. 11, shows seismic migration imaging for this area. The section from KS71 + 482 to KS71 + 522 exhibits dense positive and negative reflections, suggesting that it is an area with developed fractured zones. The section from KS71 + 522 to KS71 + 562 shows sporadic positive and negative reflections, which could indicate potential rock falls. Meanwhile, the section from KS71 + 562 to KS71 + 582 displays pronounced positive and negative reflections, indicating a deterioration in rock quality that suggests it is a potential fractured zone. To gain a more comprehensive understanding of the geological conditions within this section, additional exploration of the KS71 + 562 segment is recommended.

Conclusion

To address the challenges of geological ahead prospecting in complex tunnel environments caused by various types of TBM excavation, this paper introduces a multi-source seismic ahead prospecting strategy, which has been successfully implemented in a water diversion tunnel in Northwest China. In conclusion:

(i) Active source seismic prospecting and TBM drilling source seismic prospecting were successfully conducted in sections excavated by the open type TBM and the single shield TBM, respectively. The results from these explorations showed good consistency with actual excavation outcomes, providing vital references for ensuring the safe operation of TBMs and for designing tunnel support systems.

(ii) Active source seismic prospecting is conducted during TBM shutdown periods to avoid interference from construction noise. The signals used in this method, such as from hammers or explosives, are strong and regular, resulting in high-quality, accurate data imaging. Conversely, TBM drilling source seismic prospecting is performed during the excavation process. While it offers the benefit of real-time detection, the imaging accuracy is compromised due to the complex wave field generated by rock breaking. To satisfy the engineering requirements for efficient TBM excavation, it is advisable to implement a dual-technology approach

for joint detection: using TBM drilling source seismic prospecting to initially identify the extent of unfavorable geological formations during excavation, and complementing this with active source seismic prospecting during TBM downtime to precisely map the distribution of these formations. This comprehensive approach will further improve the accuracy of geological ahead prospecting.

(iii) The multi-source seismic prospecting strategy proposed in this study is applicable to tunnels constructed with various TBM types—including open type, single shield, and double shield TBMs—in rock formation environments. This strategy offers broad applicability and practical value, effectively enhancing geological prediction and risk management in TBM tunnel construction.

Declarations

Competing interest We know of no conflicts of interest associated with this publication, and there has been no personal relationships or significant financial support for this work that could have influenced its outcome.

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