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Real-time geological prediction technology based on TBM rock-breaking seismic source HSP method and engineering practice

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ABSTRACT: In order to overcome the geological adaptability challenges encountered in TBM construction and avoid blind tunneling through unfavorable geological conditions that were not clearly identified beforehand, the implementation and innovation of geological detection methods during the construction phase are particularly critical. It has become a consensus to fully utilize TBM to carry out advanced geological prediction techniques suitable for TBM construction. This paper focuses on the real-time geological prediction technology based on the TBM rock-breaking seismic source HSP method, which involves mounting the HSP forecasting equipment on the TBM to complete the processes of rock-breaking vibration, acoustic wave information collection, data processing, anomaly identification, and interpretation. This results in automatic information collection, intelligent data processing, intelligent anomaly recognition, and real-time interpretation of the results. As TBM excavation progresses and the thickness of the geotechnical layer decreases, a data processing technology based on multiple forecast result iterations is proposed to improve accuracy.

1 INTRODUCTION

With the rapid development of major infrastructure projects in China, the number of long, deeply buried tunnels crossing rivers and seas steadily increases. The safe, efficient, and environmentally friendly TBM (tunnel boring machine) method is increasingly applied in tunnel construction due to its advantages in tunneling speed, minimal disturbance to surrounding rock, and enhanced tunnel construction quality.

However, the TBM construction method necessitates a TBM structure that occupies substantial tunnel space, resulting in a weak response capability or low treatment efficiency when facing unknown unfavorable geological bodies. Once unfavorable geological bodies are encountered, the safety of personnel, machinery, tools, and construction progress are at significantly greater risk compared to the drilling and blasting method.

Given the spatial characteristics of TBMs and the interference factors—such as vibrations, metal bodies, and electromagnetism—that affect geophysical prediction signal sources, researching appropriate and effective geological exploration technologies has become a key focus area for scholars. Focusing on the differences in the physical characteristics of unfavorable geological conditions, such as speed, density, electrical properties, and rock temperature, the geophysical prediction prediction technologies specifically dedicated to or suitable for TBM tunnels include elastic wave reflection methods for non-blasting seismic sources, such as HSP (horizontal sonic/seismic profiling)[1], ISP(integrated seismic prediction) [2], SAP (seismic ahead prospecting)[3], TST(tunnel seismic tomography) [4], and TSWD (tunnel seismic while drilling)[5]; electrical (magnetic) methods, such as BEAM(bore-tunneling electrical ahead monitoring) [6], TEAM(tunneling electrical ahead monitoring) [7], TIP (time increased probability)[8], and CFC(complex frequency conductivity) [9]; and the RTP(rock-mass temperature probing) method [10]. This paper elaborates on the real-time geological prediction technology based on the TBM rock-breaking seismic source HSP method and highlights its application in the Xianglushan TBM Tunnel of Water Diversion Project in Central Yunnan, and the Daliangshan TBM tunnel on the Leshan–Xichang Expressway. These insights can serve as a reference for advanced geological prediction in similar projects.

2 DIFFICULT ISSUES AND METHOD SELECTION FOR GEOLOGICAL PREDICTION IN TBM CONSTRUCTION

2.1 *Analysis of Geological Risks of TBM Tunnels*

Long tunnels increases the risk for TBMs of encountering geological hazards like water or mud inrushes and collapses, which can potentially lead to jamming or trapping accidents and even casualties. Many typical disasters and accidents have been reported in China and other countries. In mild cases, TBM jamming or mechanical damage may occur, while in severe instances, the entire TBM may need to be scrapped, leading to serious consequences such as abandonment of the TBM construction and even casualties.

2.2 *Characteristics of TBM Construction and Difficult Issues for Geological Prediction*

The characteristics of TBM construction technology and its unique spatial structure impose restrictions on the application of various traditional prediction methods. The main reasons include:

(1) The TBM fully occupies the working face, restricting the visibility of working face conditions to portions only observable through the cutter holes and reserved manholes. Consequently, traditional methods such as GPR (ground penetrating radar) and transient electromagnetic methods, which require measuring lines to be positioned on the working face, cannot be implemented;

(2) Due to the narrow space, for the prediction method that requires drilling holes for receiving sensors and field source excitation, hole drilling is not only time-consuming but also inconvenient, and it often causes significant noise interference;

(3) Among seismic wave methods, the prediction method that utilizes explosive blasting vibrations as the seismic source carries the risk of damaging the TBM. Additionally, the process is time-consuming and generates dust, which can adversely affect the construction environment;

(4) The direct current method is constrained by spatial limitations, and the detection equipment can restrict the detection distance. As a result, it often facilitates only short-distance detection, which does not align with the rapid tunneling requirements of TBM operations. Consequently, this method is typically utilized as a supplementary detection technique in critical risk areas;

(5) The current suction effect of the TBM's metal body can impact both the detection distance and effectiveness of electrical methods. Furthermore, the required contact electrodes may be hindered by the supporting structure, making their arrangement inconvenient or even impossible. It is essential to implement integrated installation and targeted design to complete the detection;

(6) The TBM construction procedures are closely interconnected, and the tunneling is fast, necessitating that the geological prediction is completed in a short timeframe, with results submitted timely.

When selecting geological detection methods for TBM construction, it's essential to consider the effectiveness of the method, the feasibility of implementation, the convenience of operation, and the timeliness of results. The purpose is to determine the optimal prediction method that aligns with the specific construction environment and engineering requirements.

2.3 *Selection of Prediction Method*

The selection of a geophysical prediction method for advanced geological prediction in tunnels focuses on the physical characteristics of unfavorable geology, the required prediction distance, and the tunnel environmental characteristics to identify the most suitable method. An analysis is provided below in several aspects:

(1) Analysis of field source type and excitation form

The field source types typically utilized in geological prediction during tunnel construction include the elastic wave field, electric field, electromagnetic field, and temperature field. Given the characteristics of the TBM body and the space, the elastic wave field and electric field are two types of field sources that are well suited for the TBM environment.

The excitation modes of the elastic wave field encompass both active and passive sources. Active sources include explosive seismic sources and various forms of hammering, such as manual, hydraulic, electric, and pneumatic hammering. Passive sources include cutter rock-breaking seismic sources and environmental noise seismic sources. The excitation modes of the electric field include both DC (direct current) and AC (alternating current) power supplies. Due to the low resistivity of the TBM metal, power is typically supplied primarily through contact electrodes.

(2) Analysis of integration mode of prediction equipment

A key technology for enhancing intelligent prediction is the automatic acquisition of physical field sensing information. The integration of prediction equipment with TBMs is essential for establishing a pathway for this automatic acquisition. The HSP method for TBM construction employs vibration signals generated during the rock mass shearing by the cutterhead and cutters as the seismic source. The detection equipment is installed within the TBM chamber and is controlled via an upper computer, allowing for effective detection. These methods introduced innovations in equipment arrangement, field source acquisition, equipment adaptability, and data processing algorithms. By mounting the equipment or sensors onto the TBM, they enhance intelligent prediction in the TBM construction environment.

(3) Analysis of prediction length and result timeliness

It is clear that the accuracy and effective application of prediction results are critical factors in evaluating the prediction quality. For efficient TBM construction, the prediction length and timeliness of results should be fully considered when selecting the prediction method. Therefore, the long-distance prediction or short-distance real-time (or quick result acquisition) prediction method will be more suitable for TBM construction.

Based on the aforementioned three considerations, this paper will elaborate on the HSP method, which employs TBM rock-breaking vibrations as the seismic source. The equipment utilized in this method is mounted on the TBM, enabling real-time prediction without requiring any shutdowns. The characteristics of this method and its application in several key TBM projects in China will be discussed below.

3 REAL-TIME GEOLOGICAL PREDICTION TECHNOLOGY BASED ON ROCK-BREAKING SEISMIC SOURCE HSP METHOD

3.1 *Theoretical Framework*

(1) Seismic wave reflection theory

The HSP method is grounded in the theory of seismic wave reflection, which is utilized to detect unfavorable geological bodies characterized by differences in seismic wave impedance within the media. As indicated by Formula (1), when there is a disparity in the product of density and longitudinal wave speed between an unfavorable geological body and the surrounding rock, a reflection phenomenon will occur. A greater disparity results in more pronounced reflection characteristics. Common types of unfavorable geology include fault structural zones, densely jointed zones, and karst strata. They exhibit differences in seismic wave impedance. Through reflection wave imaging, the locations, scales, and filling properties of unfavorable geological bodies can be effectively detected.

$$R_{12} = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1} \tag{1}$$

where, R_{12} denotes the reflection coefficient, ρ represents the strata density, and v is the longitudinal wave speed of the strata.

(2) Seismic interferometric imaging technology

According to the reciprocity theory of Green's function [11], seismic data collected from any two receiving points can be utilized for deconvolution processing to derive their Green's function.

For receiving points in the same domain, the convolution formula in the frequency domain is given below:

$$u(r_a, s, w) = W(s, w)G(r_a, s, w) \tag{2}$$

where: G is the Green's function and W is the frequency domain source function. The cross-correlation is performed for seismic information collected at the two points. Then, their frequency domain formula is as follows:

$$C_{ab} = |W(s)|^2 G(r_a, s) G * (r_b, s) \tag{3}$$

where, $|W(s)|^2$ is the influence factor of the seismic source, which varies with the changes in seismic source s, and the asterisk indicates the conjugate. According to the equation, the cross-correlation C_{ab} is influenced by the energy spectrum $W(s)$. The frequency domain formula for the deconvolution of receiving points a and b is given below:

$$D_{ab} = \frac{u(r_a,s)}{u(r_b,s)} = \frac{G(r_a,s)G*(r_b,s)}{|G(r_b,s)|^2} \tag{4}$$

Information $u(r_a, s)$ and $u(r_b, s)$ is recorded at points a and b, and cross-correlation is performed for seismic information collected at the two points. The influence of source function characteristics on the processing results is eliminated through deconvolution. The extracted seismic signals consist of the causal part, the non-causal part, and the impulse response.

Thus, if the seismic signals recorded by two different free geophones are cross-correlated, a new seismic signal can be generated, incorporating the causal part, the non-causal part, and the impulse response. The causal part corresponds to that of seismic waves recorded by an observation system utilizing one geophone as the virtual source and the other as the geophone. Consequently, wave field separation and speed imaging can be achieved without prior knowledge of the seismic source characteristics.

3.2 *Technical Scheme for Real-time Prediction*

Based on theoretical analysis and considering the requirements for TBM construction, spatial characteristics, and geological prediction, an HSP real-time prediction technology is proposed, which utilizes the rock-breaking vibrations from TBMs as the seismic source. The detection scheme is illustrated in Fig. 1.

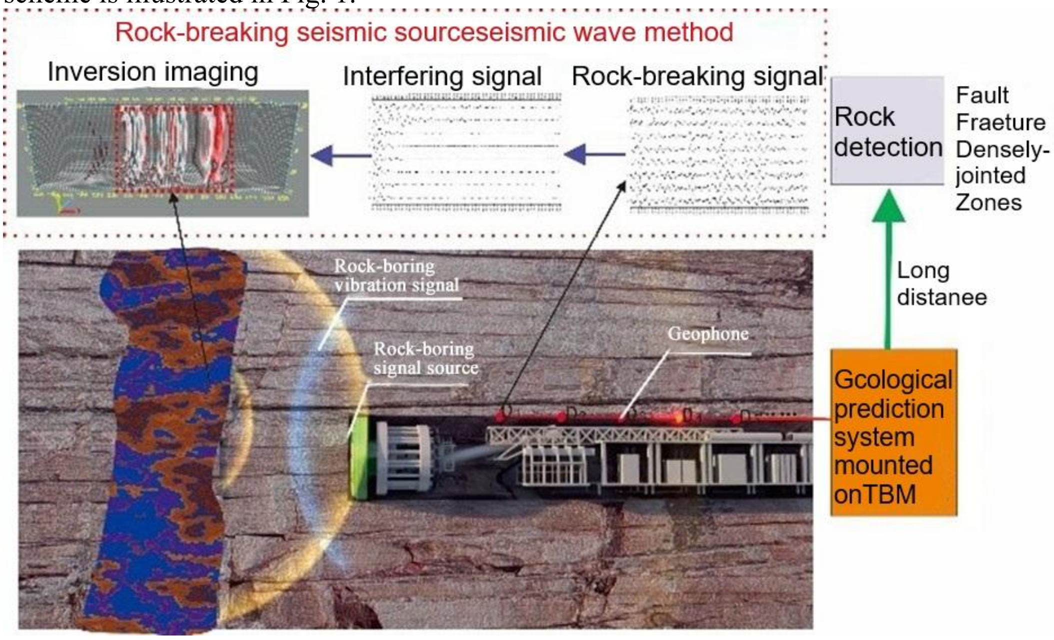

Fig.1 Schematic diagram of HSP detection layout

This technical scheme effectively utilizes the rock-breaking seismic source to implement real-time predictions of unfavorable geological bodies up to 100 meters ahead. Its real-time performance is primarily enabled through the following aspects:

(1) The TBM continues tunneling without interruption during the detection process;

(2) The HSP equipment is mounted on the TBM, allowing for the automatic interaction of basic data such as mileage, tunnel diameter, and coordinates;

(3) After the geophone layout and automatic parameter settings are completed, detection can be initiated with a single click. The system automatically acquires data for a minimum of 8 minutes, followed by data processing, virtual source establishment, ellipsoid imaging, anomaly picking, and result display, all according to the built-in processing workflow, with the entire process taking approximately 10 to 12 minutes.

(4) The resulting data is automatically stored in a database, enabling iterative analysis of adjacent detection results through human-computer interaction.

Field signal acquisition involves using 6 signal receiving geophones installed along the tunnel profile and 1 noise receiving geophone mounted on the TBM body (structural beam) to continuously gather a sufficient amount of vibration information (typically no less than 8 minutes, with more than 1000 data recording channels per test) while the TBM is fully advancing. Furthermore, the signal data undergoes various analyses, including time-domain waveform analysis, spectral analysis, filtering, correlation interference analysis, reflection imaging, time-depth conversion, extraction of anomalies from geophysical prediction, and geological interpretation. From the installation of geophones to the output of results, the entire process takes approximately 20 to 25 minutes, allowing for preliminary results to be obtained on the TBM construction site.

By pre-setting acquisition parameters (sampling rate, acquisition duration, etc.), equipment parameters (spatial coordinates of geophones), data processing (filtering parameters, interferometric data channels, etc.), and inversion parameters (initial wave velocity, anomaly picking threshold, etc.), functions such as automatic data acquisition, immediate processing, and intelligent identification of rock-breaking signals are executed. Data processing encompasses spectral analysis and filtering, the establishment of a virtual seismic source, 3D imaging, and anomaly picking and interpretation, which collectively yield preliminary results for geological predictions. If geophysical prediction images reveal a significant unfavorable geological body, manual intervention is invoked for precise processing, ultimately enabling the detection of the location, scale, and nature of the unfavorable geological body ahead of the working face, thereby guiding safe TBM operations.

3.3 *Key Technologies of Data Processing*

During TBM tunneling, rock-breaking vibration signals are generated and captured by receiving geophones amidst the interference from cutters and the filtering effects of the strata. The unfavorable geological body ahead of the working face can be detected through effective signal selection and preprocessing, correlation interferometry, virtual source extraction, and focused imaging. The key processing technologies are described below.

(1) Signal selection and preprocessing

Multi-source interferometry continuously collects a substantial amount of data during TBM tunneling, which inevitably introduces construction noise.

By analyzing time and frequency domain signals, the system deletes abnormal high-amplitude data. Additionally, it removes high-frequency and low-frequency interference through frequency domain filtering. It is important to clarify that during the data processing, it is neither feasible nor realistic to pursue complete noise filtering and removal. Maximum efforts should be made to ensure that reasonably effective time-frequency domain signals are not filtered out; occasional noises can be mitigated through techniques such as focusing and iteration.

(2) Virtual source extraction

Seismic interferometry is employed to perform interferometric processing on the selected filtered signals received along the tunnel profile. The data will contain reflection information. By applying speed analysis and focused imaging, stratigraphic distribution information can be derived.

(3) Focused imaging

The core concept of focusing is to maximize energy. Based on the principle that the sum of distances from two focal points of an ellipsoid to any point on its surface is constant, the reflected wave fields are spatially superimposed at different speeds. This results in the optimal speed, where the reflection energy spectrum in the anomalous area focuses most strongly. Consequently, a final 3D spatial reflection energy spectrogram of the strata is formed.

(4) Automatic anomaly identification

Through focused imaging and calculation, the spatial position of the point with the maximum focused energy can be identified during the iteration process. By analyzing the area covered by the energy group, the spatial position and scale of the anomaly can be determined. Leveraging experience and prior geological information, the anomalous areas are clustered and diminished to facilitate the automatic identification of anomalies, leading to preliminary prediction conclusions.

4 ENGINEERING APPLICATION

4.1 *Xianglushan TBM Tunnel of Water Diversion Project in Central Yunnan*

(1) Project overview and geological conditions

The Xianglushan Tunnel is located in the Hengduan Mountains of northwestern Yunnan, with a total length of 62.596 km. It represents the most typical key and challenging components of the Water Diversion Project in Central Yunnan. In the tunnel area, the exposed geology primarily consists of sandstone and mud shale interbedded with coal streaks from the Permian basalt and Heinishao formations.

(2) Case analysis

Real-time advanced geological prediction was conducted using the HSP method, focusing on fault structural zones encountered by the TBM. Geophones were arranged along the upper tunnel profile of the operation platform, positioned between the gripper and the main equipment chamber. Three geophones were placed on each side—left and right—to continuously collect rock-breaking signals for over 10 minutes while the TBM was fully advancing. The prediction mileage ranges from DLI54+000 to DLI53+631, resulting in a prediction distance of 369 meters (average of 4 detection results). For the prediction results, TBM tunneling parameters, and revealed conditions, please refer to Fig. 2.

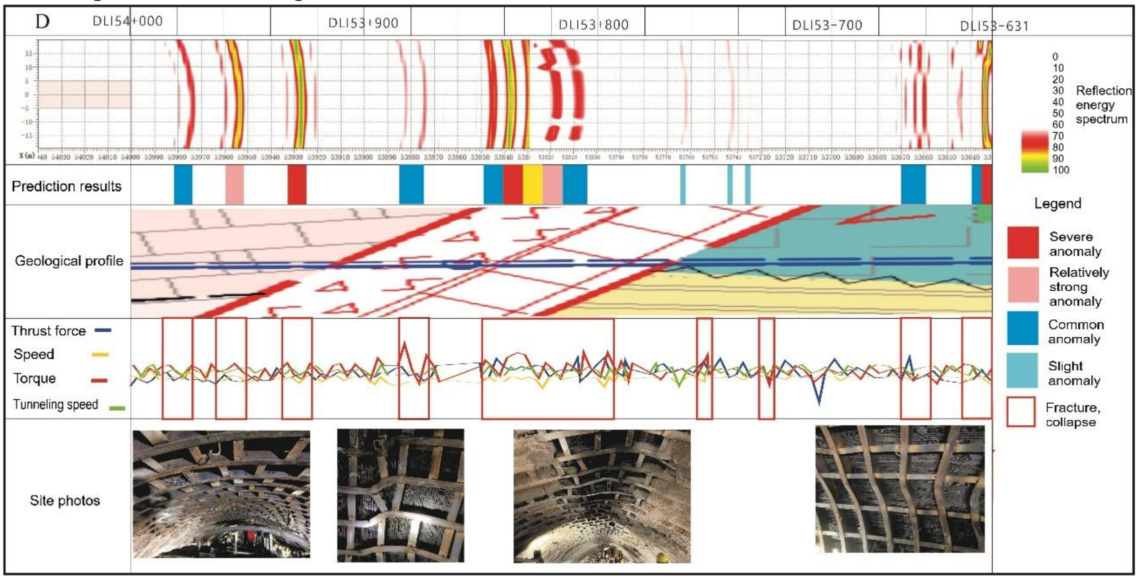

Fig.2 Statistical Analysis of Prediction Results

From the figure, it is evident that there are several strong reflection zones in this test area, characterized by high reflection energy spectrum values (relative). Notably, in the section from DLI53+850 to DLI53+800, there are continuous anomalous areas, indicating risks of spalling or collapse.

(3) Verification after excavation

After excavation, the analysis of tunneling parameters—such as thrust force, speed, and torque—along with the interaction of on-site support structures, indicates a significant influence from the F12 fault. This influence is evidenced by abnormal fluctuations in tunneling parameters and severe deformation of the support structures. The affected area aligns closely with the predicted anomalous area. In particular, within the section from DLI53+850 to DLI53+800, the amplitude of the reflection energy spectrum exceeds 70% of the specified value, with the core exhibiting values approaching the specified maximum. During tunneling and crossing, the tunneling parameters exhibit abnormal fluctuations, and the deformation of the supporting structures is pronounced. However, the length of the predicted anomalous area is shorter than the affected area indicated in the geological profile. The geological conditions of the tunnel are further detailed through prediction.

4.2 *Daliangshan No. 1 TBM Tunnel on Leshan–Xichang Expressway*

(1) Project overview and geological conditions

The Daliangshan No. 1 Tunnel, the dominant works of the Leshan–Xichang Expressway, is situated in the transitional zone between the Yunnan–Guizhou Plateau and the southwestern Sichuan mountainous region, bordering the Sichuan Basin to the northeast. The main tunnel is approximately 15.3 km long and features a cross-sectional layout of one main tunnel plus one parallel adit. The parallel adit was constructed using the TBM method. The tunnel traverses eight geological formations, including Jialingjiang, Leikoupo, and Xujiahe. It encounters several unfavorable geological conditions, such as karst strata, rock bursts, water inrush, significant deformation, and gas presence. The tunnel crosses through limestone and basalt water-rich sections and intersects F1 and F2 faults multiple times, which posed a substantial risk of water inrush.

(2) Case analysis

The focus was placed on the detection of the section from DK87+680 to DK87+220, covering a length of 460 m (average of 5 detection results). Geophones were arranged on both sides along the upper tunnel profile of the operation platform, positioned between the gripper and the main equipment chamber. In this case, the TBM will traverse basalt primarily classified as Grade III and IV.

Fig. 3 clearly shows several strong reflection zones in this test area, characterized by high reflection energy spectrum values (relative). There are extensive anomalous areas in the sections from DK87+680 to DK87+620 and from DK87+520 to DK87+500, where the prediction indicates risks of spalling or collapse. Additionally, several smaller anomalous areas are present, where the prediction suggests that they are local fracture areas. There is a possibility of local collapse.

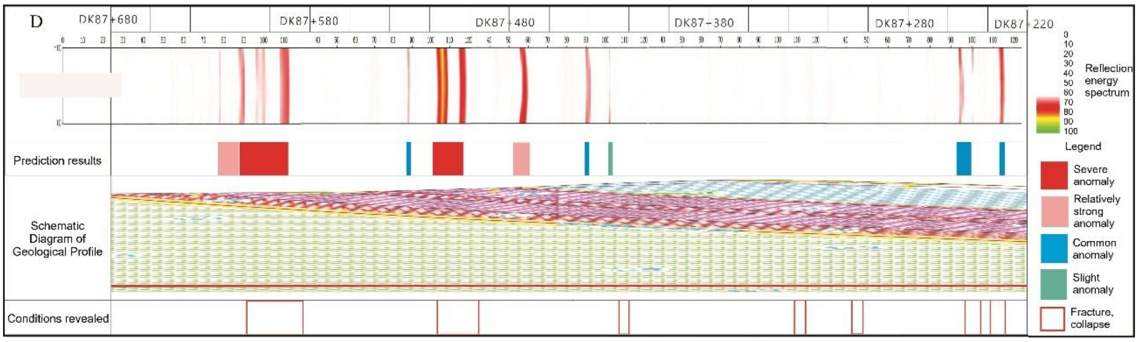

Fig.3 Statistical Analysis of Prediction Results

(3) Verification after excavation

According to the verification conducted after excavation, the construction of sections from DK87+635 to DK87+580 and from DK87+520 to DK87+495 encountered fractured rock masses and developed groundwater. This resulted in crown collapse and the formation of cavities of a significant scale in the surrounding rock. The results generally align with the anomalous sections identified by the prediction, though there is a slight discrepancy in position, attributed to the differences between stratigraphic anisotropy and the speed inversion model. Nevertheless, this long-distance prediction effectively identifies unfavorable geological bodies that could cause disasters.

4.3 *Summary of Application*

The HSP method, which utilizes vibration signals generated from rock mass shearing by the TBM cutterhead and disc cutters as the excitation source, exhibits the following characteristics:

(1) It enables convenient field tests without the need for blasting or hammering. Additionally, it does not require TBM shutdown, ensuring that construction is not affected.

(2) The deployment of detection points is highly adaptable, allowing for their arrangement at any position along the tunnel profile.

(3) It achieves a short on-site test duration. Geophones can be installed in approximately 10 minutes. Once in place, they can continuously collect rock-breaking signals for no less than 8 minutes.

(4) The object under detection meets the requirements of the long-distance seismic wave method, with an effective detection distance of up to 100 m. Unfavorable geological bodies, including karst strata, weak interbeds, fractured strata, faults, densely jointed zones, water-rich structural zones, boulders, and bedrock relief, can be effectively detected.

(5) The equipment can be installed without the need to modify the TBM. It is suitable for various types of TBMs, including open-type TBMs and those with single or double shields.

5 CONCLUSION

It has become a consensus to fully utilize TBMs to implement advanced geological prediction technology. Previous studies have devised solutions through geophysical prediction methods, such as electrical methods and elastic wave methods, by analyzing the characteristics of TBM construction technology and the structure of the TBM body. In light of the key and difficult issues in TBM geological prediction, this study examines the critical factors of geophysical prediction methods, including the field source type and excitation form, the integration mode of prediction equipment, and the prediction length and result timeliness. Additionally, it celebrates the theory and key technologies of real-time geological prediction based on the TBM rock-breaking seismic source HSP method. This method has led to key technical breakthroughs, including automatic information collection, intelligent data processing, intelligent anomaly identification, and real-time result interpretation. The technology has been successfully implemented in the TBM construction of several projects such as the Xianglushan Tunnel of Water Diversion Project in Central Yunnan and the Daliangshan No. 1 Tunnel on the Leshan–Xichang Expressway. It has produced positive results and has played a significant role in enhancing the efficiency of TBM construction, underscoring its considerable importance.

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