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The Practice of Forward Prospecting of Adverse Geology Applied to Hard Rock TBM Tunnel Construction: The Case of the Songhua River Water Conveyance Project in the Middle of Jilin Province

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ABSTRACT

An increasing number of tunnels are being constructed with tunnel-boring machines (TBMs) due to the increased efficiency and shorter completion time resulting from their use. However, when a TBM encounters adverse geological conditions in the course of tunnel construction (e.g., karst caves, faults, or fractured zones), disasters such as water and mud inrush, collapse, or machine blockage may result, and may severely imperil construction safety. Therefore, the advance detection of adverse geology and water-bearing conditions in front of the tunnel face is of great importance. This paper uses the TBM tunneling of the water conveyance project from Songhua River as a case study in order to propose a comprehensive forward geological prospecting technical system that is suitable for TBM tunnel construction under complicated geological conditions. By combining geological analysis with forward geological prospecting using a three-dimensional (3D) induced polarization method and a 3D seismic method, a comprehensive forward geological prospecting technical system can accurately forecast water inrush geo-hazards or faults in front of the TBM tunnel face. In this way, disasters such as water and mud inrush, collapse, or machine blockage can be avoided. This prospecting technical system also has reference value for carrying out the forward prospecting of adverse geology for potential TBM tunneling and for ensuring that a TBM can work efficiently.

1. Introduction

Hard rock tunnel-boring machines (TBMs) carry many advantages: They are highly efficient; they can complete high-quality tunnels; they bring remarkable economic benefits; and they can guarantee a favorable working environment and hygienic conditions. As a result, TBMs are widely employed in tunnel construction [1,2]. An overwhelming majority of developed countries now deploy TBMs to construct tunnels. In China, an increasing number of tunnels are also being constructed by TBM [3–5]. Although TBMs possess the significant advantages mentioned above, their ability to adapt to complicated geological conditions is poor. During TBM tunneling under complex conditions such as fault fractured zones or karst areas, serious engineering accidents can occur, such as machine blockage, tunnel collapse, or water inrush [6,7]. Accidents such as these can result in huge losses in a project. For example, a major delay (280 d) in TBM tunneling was caused by a minor shear zone filled with water in Indian-controlled Kashmir [8]. In addition, it took nearly 12 years to complete TBM tunnel construction of the diversion tunnel for the Dul Hasti Hydroelectric Project after several incidents of water and mud inrush occurred [9,10]. Therefore, in order to address serious engineering accidents due to adverse geo-hazards, studies have been performed all over the world on methods and techniques of forward geological prospecting as applied to TBM tunneling. Due to the strong electromagnetic interference generated by TBM instruments and metal structures [11,12], many geophysical methods cannot be applied effectively to TBM tunneling. Moreover, there is limited observation space available for geological prospecting in TBM tunnels. The German company Geo Exploration Technologies GmbH (GET) developed the bore-tunneling electrical ahead monitoring (BEAM) technique [13], which is based on the focused frequency domain-induced polarization method. The Geo-Forschungs-Zentrum (GFZ)

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German Research Centre for Geosciences developed a seismic forward prospecting system called the integrated seismic imaging system (ISIS) [14], which can obtain the reflection intensity within a certain range in front of the tunnel face and conduct analysis and interpretation. Generally speaking, due to the complex detection conditions in TBM tunneling, the main usable forward geological prospecting methods are the seismic wave method and the resistivity method. The seismic wave method has a better detection effect for the fractured zone of surrounding rock; however, it has poor sensitivity for water bodies. At present, the resistivity method cannot achieve three-dimensional (3D) positioning and shape characterization of water-bearing structures. In fact, there is no integrated detection technique that can achieve the identification of adverse geology such as fractured zones and their water-bearing situation. This paper introduces a method of 3D seismic forward geological prospecting that adopts a 3D observation mode suitable for hard rock TBM tunnel construction, and that can precisely detect a fault fractured zone in front of the tunnel face. We also propose a method of forward geological prospecting by 3D induced polarization that can be applied to hard rock TBM tunnel construction. A forward-focusing observation mode can increase the detection range and reduce the influence caused by a TBM. This method can be used to obtain a 3D image of water-bearing structures in front of the tunnel face, which can help the forward prospecting of adverse geology during TBM tunnel construction under complicated adverse geology.

Through an analysis of the cases of the TBM tunnels in the Songhua River water conveyance project, we propose a comprehensive forward geological prospecting technical system that can be applied to TBM tunnel construction; this system integrates geological analysis, the 3D induced polarization method, and the 3D seismic method. Selecting a forward geological prospecting method according to specific engineering-related geological conditions allows highly efficient detection of adverse geology and good adaptation to the characteristics of TBM tunnel construction. When applied to TBM tunnel construction, this comprehensive forward geological prospecting technical system was able to detect fault fractured zones and water-bearing structures. Its use enabled the TBM tunnels of the water conveyance project from Songhua River to be constructed efficiently.

2. Comprehensive forward geological prospecting technical system for TBM tunnels

If TBM tunnels are constructed through geological structures in which water-enriched karsts are developing, they may encounter the risk of water inrush caused by water-bearing and water-conductive structures such as karst caves and karst conduits. If TBM tunnels are constructed through geological structures where faults develop, there is a potential for collapse and machine blockage because of the poor quality of the rock. Thus, it can be seen that water-bearing structures in karsts and fault fractured zones are the major concerns in TBM tunneling. To address these typical adverse geological structures in TBM tunnels, 3D induced polarization and 3D seismic methods are respectively employed in the comprehensive forward geological prospecting of TBM tunnels.

Typical construction features of TBM tunnels include a rapid tunneling speed and tight construction processes. Because a limited time is available for forward prospecting, a geological prospecting system must be able to detect typical adverse geological structures quickly and accurately while maintaining the TBM tunneling speed. Based on engineering geology information, we propose the comprehensive forward geological prospecting ideas shown in Fig. 1. Geological analysis forms the basis of our forward geological prospecting scheme, and 3D induced polarization and 3D seismic forward geological prospecting are its key methods.

The comprehensive forward geological prospecting technical system for TBM tunnels addresses the following aspects:

- Prospecting basis: Conducting an engineering geological analysis results in an awareness of the geological and geographic conditions of geological structures, lithology, faults, fractured zones, and/or catchment areas.
- Geological conditions: Macroscopic geological analysis determines high-risk sections with developed adverse geological structures such as lithological interfaces, fault fractured zones, caves filled with water and mud, karst channels, and underground rivers.
- Prospecting methods: The 3D seismic method can be used to identify fault fractured zones and lithological interfaces within 100 m. If an anomaly is detected by the 3D seismic method, the 3D induced polarization method can then be used to determine the water-bearing condition of the geological structure within 30 m.
- Constrained inversion: A 3D induced polarization constrained inversion can be conducted by incorporating the anomalous structure from the 3D seismic prospecting results as a constraint. The constrained inversion can both reflect the position of adverse geological structures such as faults and karst caves and determine their water-bearing condition.

Thus, the comprehensive forward geological prospecting technical system for TBM tunnels helps to avoid the occurrence of geo-hazards such as collapse, machine blockage, and water and mud inrush.

Induced polarization exploration is based on the chargeability differences among various mediums. This method is sensitive to water-bearing structures such as water-filled karst caves and water-conductive channels, and is suitable for the forward prospecting of water-bearing structures in a TBM tunnel environment. Fig. 2 shows an arrangement of current electrodes and measuring electrodes for the 3D induced polarization forward geological prospecting mode as applied in TBM tunnels. This arrangement is a focusing and sounding observation mode that relies on the movement of identical polarity current electrodes and is suitable for TBM tunneling. The current electrodes are on the TBM shield and sidewall in order to supply current, the measuring electrodes are on the cutterhead. Among them, a current electrode on the TBM cutterhead supplies power, and measuring electrodes on the cutterhead collect data. All the electrodes are flexible coupling electrodes. Each current electrode ring has four identical polarity current electrodes.

Electric-field interference from the TBM body is the major problem encountered during 3D induced polarization prospecting in TBM tunneling. When detecting, the TBM stops tunneling, the cutterhead backs off by 10–20 cm, and TBM grippers retract. The focusing effect of the electric field powered by the identical polarity current electrodes set around the tunnel face causes the current from the middle of the tunnel face to point forward. A proportion method for processing observation data can be used to eliminate the electric-field interference from a TBM. The data collection process is as follows: Firstly, the first current electrode ring on the shield and the middle current electrode on the cutterhead supply power while the measuring electrodes collect data. Next, the second current electrode ring supplies power while the measuring electrodes collect data. This process continues until the 10th to 15th current electrode rings have moved backward by 60 m. The proportion coefficient for removing the electric-field interference from a TBM can be obtained from numerical simulations and field tests; multiplying the observation data by the proportion coefficient removes the electric-field interference from the TBM to a certain extent.

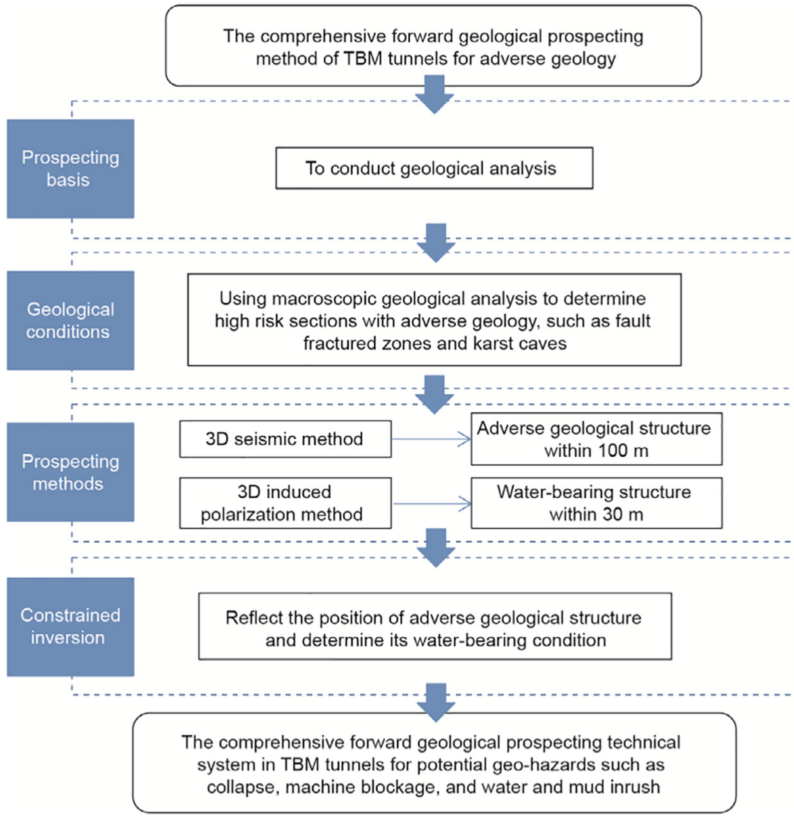

Fig. 1. A technical system of comprehensive forward geological prospecting in TBM tunnels.

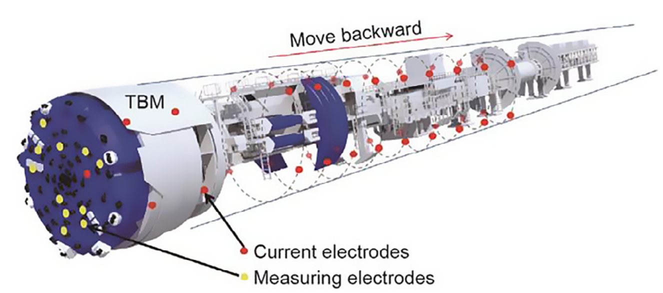

Fig. 2. Schematic diagram for 3D induced polarization forward geological prospecting in TBM tunnels.

Seismic prospecting is a detection method that is based on differences in the physical properties of seismic wave propagation and reflection in different mediums. This method is highly sensitive to fault fractured zones and lithology interfaces, and is suitable for the forward prospecting of adverse geology in TBM tunnels. Fig. 3 [15] shows an arrangement of shot points (S) and geophones (A) for the 3D seismic forward geological prospecting mode in TBM tunnels. When conducting this method, the shot points (S1–S10) are respectively hammered, and the geophones (A1–A20) record seismic data.

3. Practical experience with comprehensive forward geological prospecting of TBM tunnels

3.1. Project profile

The water conveyance project from Songhua River in the middle of Jilin Province covers Changchun, Siping, and Liaoyuan, along with 11 county-level cities and the urban areas of the counties under their administration, and 26 towns near the water conveyance line, which can draw water directly from the line. This project is a long-distance water conveyance project between towns. The length of the main line is 263.58 km. As shown in Fig. 4, the project involves TBM tunnels, which comprise the general main line. The overall direction of the general main line is from northeast to southwest, and the landform is characterized by low hills. The local vegetation is well developed. The elevation ranges in 264–484 m, and the maximum burial depth of the tunnel is 260 m. The accumulated length of the gully is around 3229 m. Because of the complex geological conditions, forward geological prospecting was necessary in order to ensure the safety and efficiency of the TBM tunnel construction.

3.2. A case study of forward geological prospecting by the 3D induced polarization method: Section K66+824 to K66+794

Section K71+046 to K63+975, one of the TBM tunnel construction sections of the general main line, is a long limestone section that passes through hills and river valleys. According to geological analysis, the surface comprises hills and valleys with abundant surface water and groundwater, such that karst development is relatively likely to happen along the direction of the valley. There are non-dissolution rock layers within these strata, which have a certain restrictive influence on the scale of karst development. Based on geological analysis, the karst development in this section is mainly small-scale karst structures with adequate groundwater. Using the TBM forward geological prospecting technical system, the key prospecting subjects in this section are karst and other water-bearing structures. When the TBM excavation reached K66+824, forward geological prospecting was conducted using the 3D induced polarization method. The results of the inversion imaging are shown in Fig. 5.

As shown in Fig. 5(a), the background resistivity value of the surrounding rock was 2800–3000 Ω·m, and there was a lower

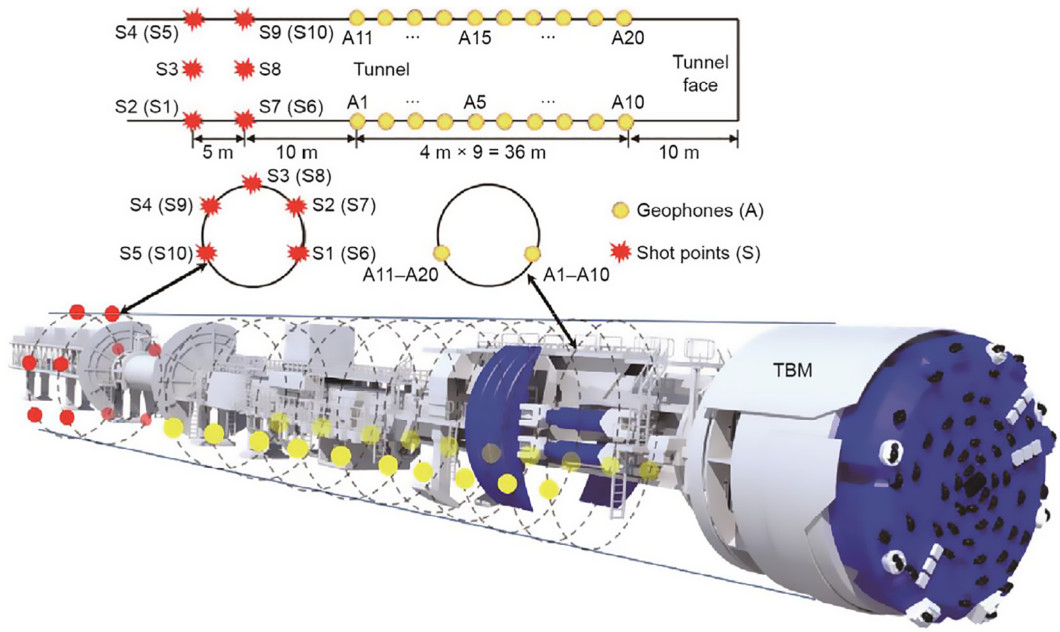

Fig. 3. Schematic diagram of 3D seismic forward geological prospecting in TBM tunnels [15].

Fig. 4. A planimetric map of the general main line of the Songhua River water conveyance project in Jilin Province.

induced polarization zone in the tunnel face and on its left side. In order to present the position and shape of the low-resistance body more directly in 3D induced polarization imaging, the image whose resistivity was less than 500 Ω·m was selected from the 3D inversion images. In addition, Fig. 5(b) clearly shows that the inversion region has two low-resistance regions: R1 and R2. R1 is within $Y = -3$–7 m and Z = 0–3 m from the tunnel face, while R2 has a larger space and is within $Y = -10$–0 m and Z = 8–28 m from the tunnel face. The following geological inferences can be drawn from the 3D induced polarization method of prospecting: Firstly, from K66+824 to K66+816, there is a spherical low-resistance region on the right side of the tunnel face, which can be inferred to be a water-bearing cavity; secondly, from K66+816 to K66+796, there is a larger, ellipsoidal-shaped space that is a low-resistance region in front of the tunnel face, which can be inferred to be a water-filled karst cave or channel, and which presents the risk of a larger scale water inrush.

As shown in Fig. 5(c) and (d), when the TBM excavation reached K66+810, a water-flowing fracture was discovered on the left side of the tunnel face from the middle to the right sidewall, with water inflow of about 200 $m^3 \cdot h^{-1}$. Thus, the excavation results are basically coincident with the prospecting results from 3D induced polarization.

3.3. A case study of forward geological prospecting by the 3D seismic method: Section K39+501 to K39+401

Section K38+963 to K44+329 of the general main line passes through middle and low hills. Below the surface is bedrock with homogeneous lithology—mainly granite in the Fanjiatun Formation of the lower series of the Permian System. As shown in the initial prospecting data, this section had developed more than 20 fault structures. Based on the geological analysis, the 3D seismic method was applied for forward geological prospecting in this section. When the TBM excavation reached K39+501, forward geological prospecting was conducted using the 3D seismic method. Eventually, the 3D seismic reflection image shown in Fig. 6 was acquired using the migration imaging method.

As shown in Fig. 6, the migration imaging results from the 3D seismic method revealed a dense positive and negative reflection zone in the section from K39+431 to K39+401, which can be considered to be a fractured area. The following geological inferences can be made: Firstly, no clear positive and negative reflection is visible in the section from K39+501 to K39+431, so the surrounding rock has no obvious abnormal structure in this section; secondly, two clear positive and negative reflections are visible in the section from K39+431 to K39+401, so fractures of the surrounding rock are developed and micro fractures can be discovered in this section. Moreover, in the section from K39+421 to K39+401, it is possible that fall-blocks and collapses will be encountered due to the weak interfaces.

As shown in Fig. 7(a), when the TBM excavation reached K39+428, an interface of soft and hard rock was discovered on the left sidewall in the tunnel. As shown in Fig. 7(b) and (c), when the TBM excavation reached the section from K39+418 to K39+407, a fractured zone, joint and fracture development, and local fall-blocks were discovered, all of which are basically coincident with the prospecting results.

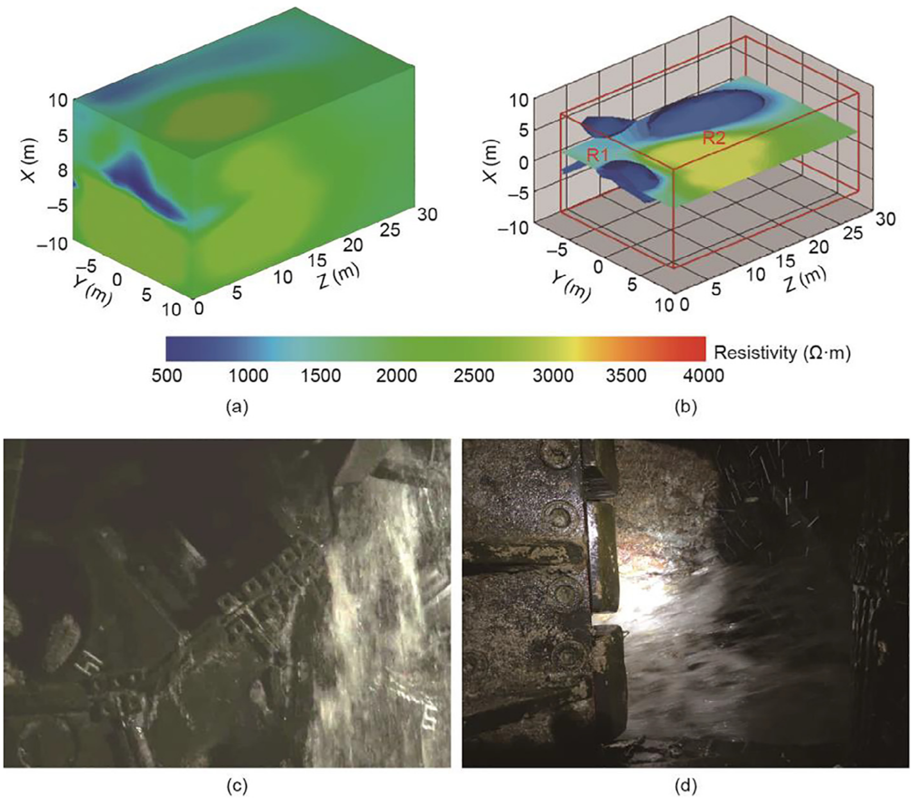

Fig. 5. Prospecting results using the 3D induced polarization method, and excavation discoveries. (a) 3D inversion imaging; (b) the selected low-resistance body; (c, d) photographs of water inrush discovered during the excavation.

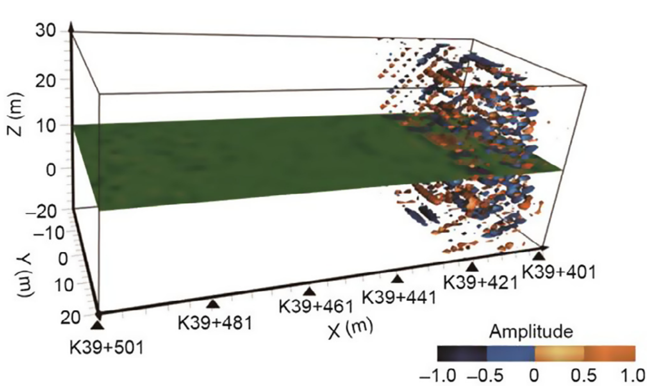

Fig. 6. 3D prospecting imaging using the 3D seismic method.

3.4. A case study of comprehensive forward geological prospecting: Section K39+788 to K39+688

According to surface reconnaissance, an influence belt of faults consisting of granite is crossed by the TBM tunneling route from K39+788 to K39+688. In this section, the buried depth is relatively shallow, and the surface consists of a gully with many catchment areas, including a large catchment area with adequate groundwater. According to the TBM forward geological prospecting technical system, under these complicated geological conditions, both the 3D seismic method and the 3D induced polarization method should be comprehensively applied. First, the 3D seismic method should be applied to detect the fractured zone. Based on the 3D seismic detection results, the 3D induced polarization method should be applied to detect the water-bearing condition of the fractured surrounding rock in this area.

When the TBM excavation reached K39+788, the 3D seismic method was applied for advance detection, and a 3D seismic reflection image (Fig. 8) was produced. As shown in Fig. 8, from K39+788 to K39+770, a positive and negative reflection predominantly appears; however, from K39+746 to K39+688, this reflection appears sporadically. Therefore, it can be inferred that the section from K39+788 to K39+770 is a fractured zone that carries the risk of fall-blocks and cavity collapses.

In the image, the fractured zone ranges from K39+788 to K39+688. In order to further detect the contents of the fractured zone, 3D induced polarization was applied for forward geological prospecting. Fig. 9 shows the resulting inversion imaging.

As shown in Fig. 9(a), within the detection area, the background resistivity value of the surrounding rock generally ranged in 3000–3200 Ω·m. In addition, a low-resistance area was present on the right side and at the tunnel face. Fig. 9(b) provides a sectional drawing of the inversion. In this figure, the low-resistance area is visible in the right part of the tunnel face, with $Y = 0–10$ m and $Z = 0–20$ m. The low-resistance area is very large; however, the resistivity here is quite high, at about 1200 Ω·m. Thus, an inference can be drawn from the detection results obtained by 3D induced polarization: From K39+788 to K39+768, the fractured surrounding rock contains water. During the tunneling process, therefore, the phenomena of large-scale water-dripping and linear running of water are likely to occur in the surrounding rock around the arch crown.

During the process of TBM tunneling from K39+788 to K39+768, a fractured zone appeared. That area contained a joint fissure with several fall-blocks and collapsed cavities, as shown in Fig. 10(a). Fig. 10(b) shows large-scale water seepage appearing at the arch crown, mainly in the form of linear running fissure water rather than large-scale water inrush. Thus, the results of the tunneling agreed well with the results of the comprehensive forward geological prospecting.

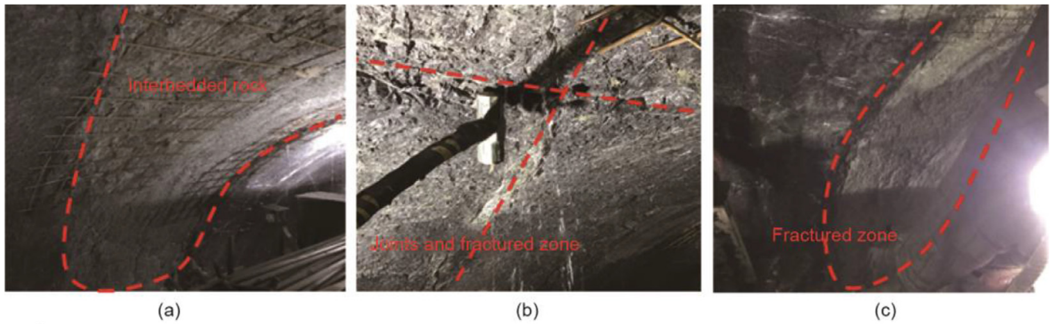

Fig. 7. TBM excavation results. (a) Lithology interface; (b) joints and fractured zone; (c) fractured zone.

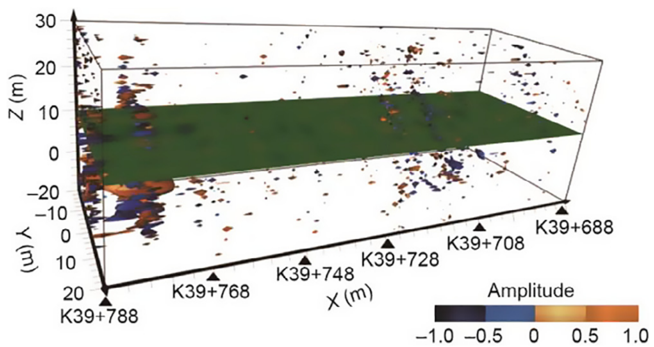

Fig. 8. 3D imaging from K39+788 to K39+688 by detection with the 3D seismic method.

4. Conclusions

Using the water conveyance project from Songhua River as an example, this paper introduced a field-tested practical application of a comprehensive forward prospecting technical system for TBM tunnel construction that combines geological analysis, the 3D induced polarization method, and the 3D seismic method. In conclusion:

(1) Ideas for comprehensive forward geological prospecting were established, based on comprehensive geological analysis and forward geological prospecting by means of the 3D induced polarization method and the 3D seismic method. These ideas were then applied to the complicated environment of TBM tunneling. The technical system for comprehensive forward geological prospecting was used during TBM tunnel construction.

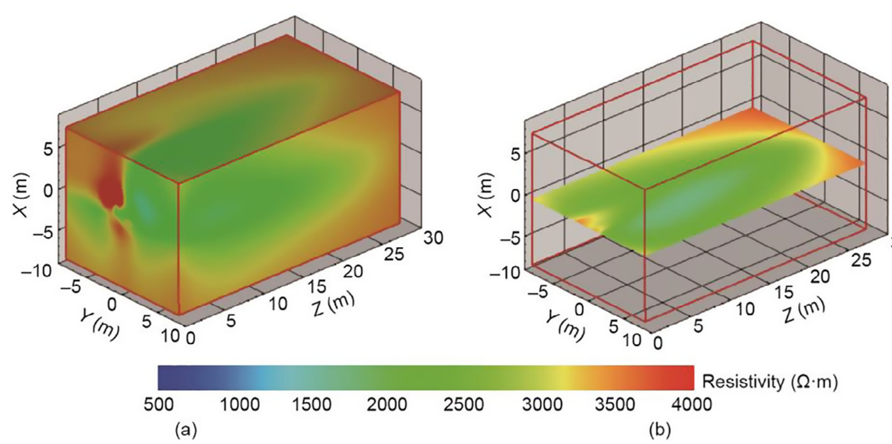

Fig. 9. Prospecting results using the 3D induced polarization method. (a) 3D inversion imaging; (b) section slice for $X = 0$.

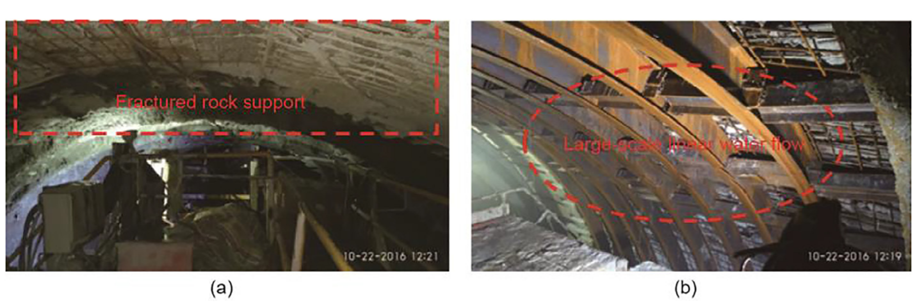

Fig. 10. Images of the surrounding rock after excavation. (a) Primary support of the fractured surrounding rock; (b) large-scale linear fissure water running in the surrounding rock.

(2) The comprehensive forward geological prospecting technical system was successfully applied to TBM tunneling during the Songhua River water conveyance project. Based on geological analysis, the 3D seismic method was first employed to detect faults; the 3D induced polarization method was then used to detect the water-bearing structure. During TBM tunneling, the prospecting results were validated by the excavation results. This process verified the effectiveness of the comprehensive forward prospecting system for TBM tunneling, indicating that these results have significance for TBM tunnel construction.

(3) Further development of forward geological prospecting technologies for TBM tunneling, relevant imaging theory, and a TBM-installed detection system with the characteristics of integration, automation, and real-time monitoring are suggested as a direction for further development. Moreover, both the 3D seismic method and the 3D induced polarization method can be applied to shield machine tunneling when improvement has been achieved in aspects such as the fast attenuation of seismic waves and interference reduction.

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Compliance with ethics guidelines

Shucai Li, Lichao Nie, and Bin Liu declare that they have no conflict of interest or financial conflicts to disclose.

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