Open Access Library Journal
2025, Volume 12, e14328
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Research on the Application of Advanced Geological Prediction Technology in Tunnel Excavation

Huibing Cheng, Ke Lu*, Yi Liu, Qi Liu, Wenjie Liu, Dengheng Zheng*

Guangzhou Railway Polytechnic, Guangzhou, China
Email: *chbgzrp2022@163.com, *huibingcheng1@163.com

How to cite this paper: Cheng, H.B., Lu, K., Liu, Y., Liu, Q., Liu, W.J. and Zheng, D.H. (2025) Research on the Application of Advanced Geological Prediction Technology in Tunnel Excavation. *Open Access Library Journal*, **12**: e14328.
https://doi.org/10.4236/oalib.1114328

Received: September 22, 2025
Accepted: October 20, 2025
Published: October 23, 2025

Abstract

Tunnel engineering is an underground concealed project with complex and invisible geological and hydrological conditions. Exploring the engineering geological conditions in front of the tunnel face can help reduce blindness during tunnel construction and prevent geological disasters. In order to effectively carry out tunnel engineering under adverse geological conditions, advanced geological prediction technology has been widely introduced and applied. This technology can provide guidance for further tunnel construction, avoiding geological disasters such as water inrush, gas outburst, rock burst, and large deformation during tunnel construction and operation. Therefore, this article systematically summarizes the current situation and application of advanced geological prediction in the construction of mountain tunnels, highway tunnels, subway tunnels, and TBM tunnels, and puts forward prospects for the development of advanced geological prediction technology.

Subject Areas

Transportation Engineering

Keywords

Advanced Geological Prediction, Tunnel Construction, Tunnel Face, Application

1. Introduction

With the rapid development of infrastructure in China, the number of underground engineering projects has increased significantly, leading to a growing number of highway tunnels, mountain tunnels, subway tunnels, and subsea tunnels. Preliminary tunnel surveys are essential for understanding the geological conditions of the construction site. However, drilling methods are time-consuming and cannot fully reflect the hydrogeological conditions or hidden unfavorable geological features. Currently, advanced geological prediction technology is commonly used in tunnel projects under challenging geological conditions. It employs multiple detection methods to probe the geology ahead of the tunnel face, determining the actual geological and hydrological conditions, rock types, lithology, and rock quality. This information guides subsequent excavation and contributes to the safe and smooth progress of tunnel construction [1]. As socioeconomic development continues, the safety and quality requirements for tunnel engineering are becoming increasingly stringent. Therefore, using advanced geological prediction methods to supplement data obtained from drilling is crucial [2] [3].

2. Overview and Current Status of Advanced Geological Prediction Technology

Advanced geological prediction in tunnels provides guidance for subsequent construction to avoid disasters such as water inrush, gas outburst, rockburst, and large deformations during construction and operation, ensuring safety and smooth progress. The main aspects of advanced prediction in tunnel construction include:

1) Prediction of unfavorable geology and hazards: identifying the presence of water inrush, mud outburst, rockburst, harmful gases, etc., within a certain range ahead of the face, determining their extent, scale, and nature, and proposing construction measures or recommendations;

2) Hydrogeological prediction: forecasting the magnitude and variation of water inrush in the tunnel and evaluating its impact on environmental and hydrogeological conditions;

3) Prediction of faults and fracture zones: determining the location, width, occurrence, properties, and filling material of faults, assessing whether they are water-bearing, and evaluating their stability to propose construction strategies;

4) Prediction of surrounding rock classification and stability: verifying whether the rock class ahead of the face matches the design, assessing stability, and providing recommendations for design modifications, support adjustments, and secondary lining timing;

5) Predicting the content, composition, and dynamic changes of harmful gases in the tunnel [4].

The main methods of advanced geological prediction include: horizontal drilling, advanced pilot tunneling, fault parameter prediction, geological projection, geological mapping and prediction in the main tunnel, comprehensive analysis, and geophysical methods. This paper focuses on geophysical methods used in advanced geological prediction for tunnels [5].

2.1. TSP Advanced Prediction Technology

The TSP (Tunnel Seismic Prediction) system uses the characteristics of seismic waves reflected from heterogeneous geological bodies to predict geological conditions ahead of and around the tunnel face. This method employs multi-wave and multi-component detection technology to identify changes in rock properties ahead, such as irregular bodies, discontinuities, faults, and fracture zones. During data acquisition, about 20 blast holes are drilled at equal intervals along one sidewall of the tunnel, while two sensor holes are drilled on both sidewalls to place geophones in casings. Each charge is detonated sequentially, and signals reflected from any wave impedance interface ahead of the face, as well as direct waves, are received by two three-component geophones. This process takes approximately one hour. Data processing with TSP win software yields the distribution patterns of P-waves and S-waves. The analysis process includes: data adjustment → bandpass filtering → first break picking → pick processing → shot energy balancing → Q estimation of direct wave attenuation → reflection extraction → P- and S-wave separation → velocity analysis → depth search → reflection interface extraction, etc. The final output is a 2D or 3D result showing reflective interfaces intersecting the tunnel axis and their geological interpretation. Based on density values, physical and mechanical parameters of the rock mass can be calculated, and the engineering classification of the surrounding rock can be determined. Practice shows that this method effectively predicts distances of 100 - 200 m. By analyzing reflection wave velocities, time-depth conversion can be performed to determine the spatial location and scale of reflective interfaces based on the intersection angle with the tunnel axis and the distance from the face. Combined with the dynamic characteristics of P- and S-waves, the nature of geological bodies can be inferred [6] [7].

2.2. Seismic Negative Apparent Velocity Method

This method applies the Vertical Seismic Profile (VSP) technique to nearly horizontal tunnels, using seismic reflection characteristics to predict geological conditions in the surrounding rock near the excavation face. Excitation points are arranged within a certain range along the sidewall, and vibration signals propagate through the surrounding rock. When the wave impedance of the rock layer changes, part of the seismic signal is reflected back. When the reflective interface is perpendicular to the survey line, the reflected waves and direct waves exhibit a negative apparent velocity on the record. The intersection of their extensions indicates the location of the reflective interface. Analysis of both longitudinal and transverse waves helps understand changes in lithology and hardness on either side of the interface [8].

2.3. TST Advanced Prediction Technology

The TST (Tunnel Seismic Tomography) advanced prediction system uses visual seismic reflection imaging technology to predict the geological conditions within a range of 150 m - 200 m in front of the tunnel face. It can accurately predict the location, scale, and properties of geological objects such as fault zones, fracture zones, karst development zones, and changes in rock engineering categories. This method uses a multi-channel high-precision seismometer for data acquisition, and the processing software is the inverse scattering synthetic aperture imaging system. It fully utilizes the kinematic and dynamic characteristics of seismic reflection waves and scattered waves, and has various functions such as directional filtering, rock wave velocity scanning, geological structure directional scanning, velocity offset imaging, absorption coefficient imaging, travel time inversion imaging, etc. It comprehensively predicts geological conditions from multiple aspects such as the mechanical properties and integrity of rock masses [9].

The TST software includes four major modules: seismic data preprocessing, directional filtering, offset imaging, and velocity scanning. The preprocessing function includes: noise and interference removal; Filtering and surface wave cleaning; Wavelet analysis and signal enhancement; Seismic wave energy absorption spectrum analysis; Pick up seismic wave travel time. The offset imaging function includes: velocity scanning analysis and rock engineering category discrimination; Direction scanning and structural orientation analysis; Geological interface velocity migration imaging; Rock integrity absorption migration imaging; Seismic wave travel time geological interface inversion imaging; Intelligent recognition of fractures and broken zones.

2.4. Horizontal Sound Wave Profiling (HSP) Method

It is an advanced prediction method developed using the principle of borehole seismic profiling (ABSP) and corresponding software. The principle is to radiate high-frequency seismic waves of a certain frequency into the rock mass. When the seismic waves encounter the impedance interface, they will undergo refraction and reflection, and the spectral characteristics will also change. By detecting the reflected signal (receiving seismic waves in the frequency band of sound waves), the propagation characteristics can be obtained, and the rock mass characteristics in front of the working face can be understood. The arrangement of seismic sources and detectors not only causes minimal interference to the construction site away from the excavation surface, but also ensures clear recording, high signal-to-noise ratio, and clear reflection phase axis due to the reflection wave being located outside the direct wave and surface wave continuation phase [10].

During observation, seismic sources and detectors are installed on both sides of the tunnel, and two observation methods are designed according to their relative positions: fixed excitation points (or receiving points) and excitation and receiving points staggered and oblique. The earthquake source is located at the far end of the target object for prediction, and the distance between the receiving points adopts a small path spacing and multiple channels of reception, forming a "horizontal acoustic profile". The method of combining time difference and frequency difference with geology is used to determine the spatial orientation of the reflection surface and "project" it onto the profile, thereby determining the spatial position and properties of the reflection surface. Its characteristic is that the reflected wave paths received by each detection point are equal, the combination of reflected waves is the same as the reflection interface shape, the image is intuitive, and the observation does not affect the excavation of the palm face [11].

2.5. TRT True Reflection Tomography Technology

TRT (True Reflection Tomography) is a seismic reflection imaging method that uses reflected seismic waves from uneven surfaces in rock mass for advanced detection. It adopts a spatial multi-point excitation and reception observation method, and its detection and excitation points are spatially distributed to fully obtain spatial field wave information, thereby greatly improving the positioning accuracy of adverse geological phenomena ahead; Its key data processing technologies are velocity scanning and offset imaging, which do not require travel time. Therefore, it has high accuracy in determining the position of the reflection interface in the rock mass, rock wave velocity, and engineering classification, and also has a large detection distance [12].

2.6. Land Sonar Method

Land sonar method is the abbreviation for "continuous profile method of high-frequency elastic wave reflection with extremely small offset distance on land", which can explore geological construction hazards such as small and medium-sized caves, medium and small faults (fractures) in narrow sites and exposed bedrock conditions. It applies the principle of seismic reflection method and absorbs some elements of ground penetrating radar and underwater acoustic method; To address some of its key issues, other fields of technology such as computing and seismic measurement have been adopted, gradually enriching and maturing it. During the measurement, a seismic wave excitation reception system with extremely small offset distance is used, and single point measurement is carried out or a detector is installed symmetrically on both sides of the excitation point to excite two receivers at once. Then, the time curves of each measuring point are assembled into a time profile to delineate unfavorable geological bodies such as faults, large joints, rock interfaces, veins, water inflow layers, and caves based on the same phase axis and spectral interpretation. The land sonar method can receive elastic wave signals of 10 - 4000 Hz without distortion [13] [14]. Due to the ability to collect reflection signals with a wide frequency range, the data can be processed using a windowed bandpass filtering method to extract information from different spectra and highlight reflection images of exploration objects of different scales. Capable of conducting precise geophysical exploration 150 meters away from the tunnel face, providing information on medium and small caves, faults (fractures), intersecting faults, dip angles, and inclinations within the exploration range; This method has the advantages of high resolution, avoiding many interference waves, high reflected wave energy, good exploration effect of karst and caves, and simple and easy to distinguish images [15].

2.7. Surface Wave Method

This method includes steady-state and transient approaches. The steady-state method places a vibrator on the tunnel face, controlled by a computer to generate waves of different wavelengths. Two sensors receive vibrations from different directions, and the computer calculates the propagation velocity of surface waves for each wavelength. Based on the principle that the detection depth of surface waves is half the wavelength, the distribution of average surface wave velocities at different depths is obtained. Different media have different surface wave velocities, and variations in velocity distribution reflect changes in geological structures such as faults and groundwater. The transient method has not been reported in practical applications due to array length limitations [16].

2.8. Ground Penetrating Radar (GPR) Technology

Using high-frequency electromagnetic waves in the form of wideband short pulses, they are transmitted forward from the palm surface through a transmitting antenna. When encountering abnormal geological bodies or medium interfaces, they are reflected and returned, received by the receiving antenna, and recorded by the host to form a radar profile. Due to the propagation of electromagnetic waves in a medium, their path, electromagnetic field strength, and waveform will change with the electromagnetic characteristics and geometric shape of the medium they pass through. Therefore, based on the characteristics of the received electromagnetic waves, such as travel time, amplitude, frequency, and waveform, the spatial position or structural features of the interface or target body in front of the palm can be determined through radar image processing and analysis. Given the integrity of the current rock mass, a distance of 30 m can be predicted; When the rock is incomplete or there are structural conditions, the predicted distance becomes smaller, even less than 10 m. The effectiveness of radar detection mainly depends on the difference in electrical properties of different media, that is, the dielectric constant. If the difference in dielectric constant between media is large, the detection effect is good. Due to its sensitivity to cavities, water bodies, etc., this method is widely used in karst areas. The disadvantage is that during testing inside the cave, there are often many interference factors that can cause false anomalies and lead to misjudgments. In addition, its predicted distance is limited, generally not exceeding 30 m, and it takes up the working time of the palm face [17].

2.9. Infrared Water Detection Method

All objects emit invisible infrared energy, with magnitude proportional to the object's emissivity. Emissivity depends on the material and surface condition of the object. When the media ahead and around the tunnel face are uniform, the measured infrared field is normal. When hidden water-bearing structures or water are present, their field strength superimposes on the normal field, causing distortion. This helps determine the presence of water-bearing structures within a certain range ahead [18].

2.10. BEAM Method

BEA (Bore-Tunneling Electrical Ahead Monitoring), This is currently the only international electrical method for advanced prediction. It is an excitation polarization method that focuses on the frequency domain of current. Its biggest feature is to emit a barrier current through a peripheral ring electrode and a measurement current inside, so that the current can be focused into the rock mass to be detected. By obtaining a parameter PFE (Percentage Frequency Effect) related to the electrical energy storage capacity of the pores in the rock mass, the integrity and water content of the rock mass ahead can be predicted; Another feature of it is that all devices are installed on the cutting head (measuring electrode) and outer steel ring (shielding current) of the shield excavator, and can also be installed in front of the drilling and blasting method construction drill bit (measuring electrode) and on both sides of the steel frame (shielding current). As the tunnel is excavated, continuous results are obtained, and the PFE curve in front of the face is timely processed to predict the characteristics and water content of the rock mass ahead [19], Information on some methods is shown in Table 1.

Table 1. Comparison of key near-surface geophysical detection methods.

Method	Typical Detection Depth	Resolution	Key Advantages	Typical Constraints & Limitations
Electrical Resistivity Tomography (ERT)	Medium-Deep (tens to hundreds of meters)	Medium-Low	Highly sensitive to water content and lithological changes; relatively portable equipment.	Resolution decreases significantly with depth; susceptible to shielding by shallow low-resistivity layers; strongly influenced by topography.
Ground Penetrating Radar (GPR)	Shallow (<30 m)	Very High	Extremely high resolution; rapid data acquisition.	Shallow penetration; signal attenuates rapidly in conductive media (e.g., clays, saline water).
Seismic Methods	Medium-Deep (tens to kilometers)	Medium (Vertical)/Low (Horizontal)	Great depth of investigation; provides mechanical properties (e.g., wave velocity) of rock mass.	High cost and operational complexity; susceptible to environmental noise; relatively low horizontal resolution.
Land Sonar	Shallow-Medium (<50 m)	High	Very small offset allows for high-resolution profiling; effective in noisy environments.	Limited penetration depth; ineffective in loose, unconsolidated layers; requires careful sensor coupling.
Cross-hole Tomography	Inter-borehole region	Very High (between boreholes)	Provides detailed imagery between boreholes; resolution superior to surface methods.	Requires two or more boreholes, making it very costly; provides a “slice” of information, not ideal for regional surveys.

3. Application of Advanced Geological Prediction Technology in Tunnel Construction

3.1. Application of TSP203 Seismic Reflection Wave Method in Jiayan Water Conservancy Hub Project

Drill holes on the support surface of the long stone slab tunnel, bury explosives at the design depth, and detonate the explosives to form seismic waves. The seismic waves propagate in the rock and soil layers and reflect back to the seismic wave signal when encountering special media. Use the receiving end to collect signals and obtain key data such as the propagation speed, waveform, and direction of the seismic waves. Then, TSPW in processing and evaluation software is applied for data processing and analysis to obtain geological information ahead of excavation. The longest distance for advance prediction can reach 150 m. If the geological conditions of the long stone tunnel are poor, reducing the prediction distance appropriately can improve the accuracy of advance geological prediction. In addition, seismic waves have two forms, one is surface waves, which propagate on the surface of an object. The other type is body waves, which are divided into two types: longitudinal waves. The characteristic of this wave is that it vibrates in the same direction as the propagation, and when it stretches the medium, it makes the medium sparse, while when it compresses, it makes the medium compact; When transverse waves propagate in a medium, the vibration is perpendicular to the direction of propagation and can shear the medium [20].

3.2. Application of Geological Radar Detection in Subway Tunnels

The subway tunnel adopts X3M RAMAC ground penetrating radar detection, which is composed of a radar host and a 100 MHz shielded antenna. The detection range each time is not more than 30 m in the direction of the tunnel face excavation (not more than 20 m in weak surrounding rock), and the overlap length is not less than 3 m, and not less than 3 m above the arch top. The geological radar detection construction is composed of one detection personnel and 2 - 5 auxiliary personnel. During the detection process, at least two parallel measurement lines are arranged on the upper and lower steps of the tunnel face for detection and data collection. Later, engineering and technical personnel process the collected raw data through software and issue a mining method tunnel ground penetrating radar report. Targeted measures are taken based on the detection report during on-site construction [21]. The ground penetrating radar host and 100 MHz shielded antenna are shown in **Figure 1**.

Figure 1. Ground penetrating radar host and 100 MHz shielded antenna diagram.

3.3. Application of 3D Seismic Wave Advanced Geological Detection System in TBM Tunnel Excavation

The 3D seismic detection system mainly consists of 12 detectors, 8 seismic sources, and 3 main units. The detectors are arranged at a distance of about 4 meters between groups, and are located at a distance of 12 - 32 meters behind the cutterhead. One detector is installed on each side of the lower part of the tunnel, and 8 seismic sources are set up in 3 groups, arranged at a distance of about 3 meters behind the cutterhead, and installed at the upper part of the trolley. The 3D seismic method utilizes the downtime of TBM tunneling machines for advanced geological prediction and detection. During detection, the detector is quickly installed on the tunnel wall, and the host controls the detector for detection. After the detection is completed, the detector and source are retracted. The principle of earthquake detection technology is that the seismic waves emitted by the seismic source have different wave impedances in different surrounding rocks or media. When the seismic source emits seismic waves, some of them are transmitted to the rock mass in front, while others are reflected, and the reflected part is received by highly sensitive sensors arranged behind. If there are weak, fractured zones, or faults inside the surrounding rock ahead, the difference in wave impedance is significant and the reflected wave is obvious. If the rock type inside the surrounding rock ahead is hard and the surrounding rock is intact or relatively intact, the reflected wave is not obvious [22].

4. Conclusion and Future Directions

4.1. Conclusion

In summary, the detection technology for advanced prediction of tunnel construction in China has developed rapidly, among which geophysical methods have become an important component and play an important role in various tunnel construction processes. Nowadays, tunnel advance prediction mostly combines geological survey methods with various geophysical methods, systematically processing and comprehensively analyzing geological geophysical data. In order to improve the accuracy of advanced detection and prediction, some geophysical techniques still need to be further improved. It is expected to obtain three-dimensional rock properties, provide more accurate and effective engineering geological data for tunnel construction, and further guide tunnel construction.

4.2. Future Directions

The field of engineering geophysics is rapidly evolving, driven by advancements in computational power and data science. Two interconnected trends are poised to significantly enhance the capabilities and impact of the methods discussed:

AI-Assisted Data Processing and Interpretation: Artificial Intelligence (AI), particularly deep learning algorithms, is transforming how geophysical data is handled. Convolutional Neural Networks (CNNs) are being trained to automate labor-intensive tasks such as noise filtering, feature identification (e.g., automatic picking of first arrivals in seismic data), and direct inversion. For instance, AI models can now be trained to recognize the distinct signatures of cavities, utilities, or reinforcing elements in GPR images with high accuracy and speed, reducing subjectivity and enhancing reproducibility.

Integrated 3D Geological Modelling: The future lies in moving beyond the interpretation of single-method datasets. The integration of multiple geophysical methods (ERT, Seismic, GPR) with direct information from boreholes, field mapping, and geotechnical testing through joint inversion and data fusion techniques is becoming standard. This multi-parametric approach mitigates the inherent non-uniqueness of geophysical solutions and enables the construction of more reliable and detailed "Digital Twin" models of the subsurface. These integrated 3D geological models provide a powerful platform for visualizing and analyzing geological risks throughout the entire lifecycle of an engineering project, from initial design and construction to long-term monitoring and maintenance.

Funding

This work was supported by the New Talent Research Project of Guangzhou Railway Polytechnic [No. GTXYR2208].

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Cui, X., Liu, B., Zhao, P., Wang, J., Liu, C. and Wang, H. (2025) Comprehensive Advanced Geological Prediction Technology and Application of Tunnels. *International Conference on Mechatronics and Intelligent Control* (*ICMIC* 2024), Vol. 13447, 846-851. https://doi.org/10.1117/12.3045226

[2] Liu, M. and Gan, Q. (2023) Applied Research of Comprehensive Advance Geological Prediction in Daluoshan Water Diversion Tunnel. *Scientific Reports*, **13**, Article No. 9162. https://doi.org/10.1038/s41598-023-36090-8

[3] Chen, G., Wu, Z., Wang, F. and Ma, Y. (2010) Study on the Application of a Comprehensive Technique for Geological Prediction in Tunneling. *Environmental Earth Sciences*, **62**, 1667-1671. https://doi.org/10.1007/s12665-010-0651-y

[4] Youzhong, L. (2017) The Application of Geological Advanced Prediction in Tunnel Construction. *IOP Conference Series*: *Earth and Environmental Science*, **61**, Article ID: 012007. https://doi.org/10.1088/1755-1315/61/1/012007

[5] Chen, H. and Liu, S. (2019) Advanced Geological Prediction Technology of Tunnel Based on Image Recognition. *Arabian Journal of Geosciences*, **12**, Article No. 601. https://doi.org/10.1007/s12517-019-4832-z

[6] Chen, D., Wang, X., Bai, J., Chu, Y., Wang, X., Zhao, J., *et al.* (2025) An Overview of Ahead Geological Detection Technologies in Tunnels. *European Journal of Remote Sensing*, **58**, Article ID: 2503240. https://doi.org/10.1080/22797254.2025.2503240

[7] Fu, X., Wu, M., Tiong, R.L.K. and Zhang, L. (2023) Data-Driven Real-Time Advanced Geological Prediction in Tunnel Construction Using a Hybrid Deep Learning Approach. *Automation in Construction*, **146**, Article ID: 104672. https://doi.org/10.1016/j.autcon.2022.104672

[8] Dong, X., Zhu, J., Wang, Q., Xu, Y. and Guo, Y. (2023) A Technical Study of Advanced Geological Prediction of Tunnels under Complex Geological Conditions. *Ac-*

ademic Journal of Architecture and Geotechnical Engineering, **5**, 52-57.

[9] Li, S., Li, S., Zhang, Q., Xue, Y., Liu, B., Su, M., *et al.* (2010) Predicting Geological Hazards during Tunnel Construction. *Journal of Rock Mechanics and Geotechnical Engineering*, **2**, 232-242. https://doi.org/10.3724/sp.j.1235.2010.00232

[10] He, N. and Zhang, X. (2023) Excavation and Construction Technology of Diversion Tunnel under Complex Geological Conditions. *Applied Sciences*, **13**, Article No. 11538. https://doi.org/10.3390/app132011538

[11] Ji, T., Qu, Z. and Tian, H. (2020) Advanced Geological Prediction Technology Based on Tunnel Face Borehole Drilling. *Journal of Highway and Transportation Research and Development* (*English Edition*), **14**, 78-85. https://doi.org/10.1061/jhtrcq.0000745

[12] Wang, C.L., Bai, M.Z., Du, Y.Q. and Kuang, X. (2013) Application Analysis of Comprehensive Advanced Geological Prediction in Karst Tunnel. *Applied Mechanics and Materials*, **405**, 1309-1313. https://doi.org/10.4028/www.scientific.net/amm.405-408.1309

[13] Kong, F., Lu, D., Ma, Y., Li, J. and Tian, T. (2022) Analysis and Intelligent Prediction for Displacement of Stratum and Tunnel Lining by Shield Tunnel Excavation in Complex Geological Conditions: A Case Study. *IEEE Transactions on Intelligent Transportation Systems*, **23**, 22206-22216. https://doi.org/10.1109/tits.2022.3149819

[14] Yao, S., Liu, Q., Duan, R., Liu, Q., Zhao, Y., Wu, Q., *et al.* (2026) Using Active-Source-induced Distributed Acoustic Sensing Signals for Detection of Urban Road Voids. *Measurement*, **257**, Article ID: 118748. https://doi.org/10.1016/j.measurement.2025.118748

[15] Jahanbakhsh, M., Esmaeily, A. and Pour, A.B. (2025) Spatio-Temporal Assessment of Land Use and Land Cover Dynamics in Urmia Lake Basin of Iran: A Bi-Directional Approach Using Optical and Radar Data on the Google Earth Engine Platform. *Advances in Space Research*, **75**, 316-330. https://doi.org/10.1016/j.asr.2024.09.039

[16] Zhang, Q., Liu, Z. and Tan, J. (2019) Prediction of Geological Conditions for a Tunnel Boring Machine Using Big Operational Data. *Automation in Construction*, **100**, 73-83. https://doi.org/10.1016/j.autcon.2018.12.022

[17] Landage, I. and Arora, K. (2024) Machine Learning Approach to Predict Geology Ahead of Tunnel Boring Machine Face: Review and New Model. In: *International Conference on Inforatmion Technology in Geo-Engineering*, Springer, 369-381. https://doi.org/10.1007/978-3-031-76528-5_37

[18] Wang, K., Guo, W., Shi, S., Zhao, R. and Wang, X. (2023) 3D Geological Model of a Tunnel for Improving Construction Measures: A Case Study. *Geotechnical and Geological Engineering*, **42**, 975-989. https://doi.org/10.1007/s10706-023-02599-y

[19] Tang, S.M., Lin, C.J., Yao, X. and He, C.X. (2012) Research on Advanced Geological Prediction in Highway Double-Arch Tunnel Construction. *Applied Mechanics and Materials*, **193**, 805-809. https://doi.org/10.4028/www.scientific.net/amm.193-194.805

[20] Zhao, J., Shi, M., Hu, G., Song, X., Zhang, C., Tao, D., *et al.* (2019) A Data-Driven Framework for Tunnel Geological-Type Prediction Based on TBM Operating Data. *IEEE Access*, **7**, 66703-66713. https://doi.org/10.1109/access.2019.2917756

[21] Zhong, M. and Wang, Y. (2022) Intelligent Advanced Geological Prediction Model of Tunnel Based on Wavelet Neural Network. In: *Advances in Mineral Resources, Geotechnology and Geological Exploration*, CRC Press, 388-395. https://doi.org/10.1201/9781003319412-55

[22] Yang, J.H., *et al*. (2024) Comprehensive Advanced Geological Prediction Method Based on Multi-Source Information for Double Shield TBM Construction Tunnel and Its Application. *Journal of Basic Science and Engineering*, **31**, 1571-1589.