Application of TETSP in advance prediction of water and mud inrush in karst tunnel

Wei Li¹, Wei Wang², Jun jie Li³, mingming Ouyang¹

¹Chongqing Survey Institute, Chongqing 400020, China;
²Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Science, State key laboratory of resource and environmental information systems, Beijing 100101, China
³Zhejiang Design Institute of Water Conservancy and Hydroelectric Power, Hangzhou 310002, China

Email: wangwei@igsnrr.ac.cn

Abstract. Water and mud inrush are easy to occur in the process of karst tunnel driving, in order to reduce the risk of tunnel construction, TETSP is used in the prediction of karst cave, water gushing and mud gushing in a karst area of Longxing tunnel. The characteristics of TETSP geophone, detection principle and arrangement of observation system are introduced. The signal-to-noise ratio of TETSP data under blasting and hammering is compared. The corresponding unfavorable geology abnormal law of TETSP is summarized. Several conclusions are drawn as follow. Firstly, the TETSP geophone with direct coupling method has high installation efficiency and can obtain the original waveform with high signal-to-noise ratio. Secondly, the seismic reflection data collected by blasting is higher quality than that by hammering excitation. Thirdly, the abnormal law of the corresponding TETSP of large-scale karst cave and dissolution fracture zone present as that the P-wave velocity and S-wave velocity are low but Poisson's ratio is high. The prediction results of TETSP are consistent with the actual excavation of the tunnel which provide an important reference for the safe construction of the tunnel.

1. Introduction

Longxing tunnel is located in the middle of new area in Chongqing City near the Yangtze River. Its purpose is to connect the main residential areas, traffic hubs and the main public activity centers of the city. It is the main passenger and freight transportation line of the whole city, which is of great significance to promote the development and construction of the areas along the line. Longxing tunnel is designed as a separate double tunnel. The length of the left line of the tunnel is 3292m, the length of the right line is 3307m, and the maximum buried depth is about 381m. It is a deep buried extra long tunnel with a net width of 15.6m and a net height of 5.0m. The line of Longxing tunnel passes through Mesozoic Permian, Upper Triassic sandstone, carbonaceous shale, and Jurassic middle and lower series mud, shale and siltstone stratum. The lithology is mainly clastic rock and soluble carbonate. The hidden characteristics of geological structure and karst phenomenon are obvious along the line, and the underground water resources are rich. The tunnel construction may encounter fault fracture zone and strong water rich water induced area. Due to the bad geological conditions such as fault fracture zone and karst cave, the collapse, water gushing, mud bursting and other accidents may occur. The
advanced geological prediction method can provide information for the prevention of disastrous accidents in the tunnel, and can also provide information for the tunnel construction scheme.

The advanced prediction methods of tunnel are mainly divided into advanced drilling method, heading method and geophysical prospecting method. Although the detection results of excavation are intuitive, it has a great impact on tunnel construction, which is mostly used for the verification of geophysical method. The geophysical method is based on the physical properties of rock masses. According to the different physical fields of excitation observation, the advanced geological prediction methods of tunnels are divided into direct current method\cite{1}, electromagnetic method such as transient electromagnetic method(TEM\cite{2}), ground penetrating radar(GPR\cite{3}), and seismic wave method such as tunnel seismic prediction(TSP\cite{4}), trilooop electrocial tunnel seismic prediction(TETSP\cite{5}), tunnel geological prediction(TGP\cite{6}), tunnel reflection tomography(TRT\cite{7}), aerospace geophysical instrument tunnel-3D(AGI-T3\cite{8}), tunnel seismic tomography(TST\cite{9}), and nuclear magnetic resonance method(NMR\cite{10}) as well as complex frequency conductivity method\cite{11} which is in the research stage.

When there is water in front of the tunnel, the electric field and electromagnetic field are easy to produce obvious anomalies. Therefore, the electrical method is suitable for the prediction of unfavorable geological conditions in the tunnel where groundwater is developed. However, its detection distance is short and it is easy to be interfered by metal bodies such as excavators, trolleys and pumps in the tunnel. The seismic wave method has high sensitivity for detecting broken and weak rock mass, diversified seismic wave excitation modes such as blasting, hammering and shock source, long prediction distance and strong anti-interference ability. It is suitable for the exploration of unfavorable geological conditions of various tunnels. The differences of seismic wave prediction methods in different regions are mainly reflected in the source selection and the design of seismic observation system, but the data processing process is roughly the same, all of which are filtered wave, velocity pick-up, wave field separation and migration imaging are used to extract effective reflection signals in specific directions. The advantage of TETSP over other earthquake prediction methods is that its geophone is directly coupled with the tunnel rock mass, so the data acquisition efficiency and accuracy are higher. There are few reports on the application of TETSP. This paper analyzes the geological prediction effect of TETSP in karst development section of Longxing tunnel in Chongqing City, introduces the layout of TETSP observation system, and summarizes the abnormal laws of geophysical prospecting corresponding to unfavorable geological conditions such as karst cave and karst fracture zone, which provides guarantee for the safety of tunnel excavation.

2. The principle and data acquisition of TETSP

TETSP receives seismic wave signal by micro blasting in a certain distance behind the tunnel face. The seismic wave propagates around in the form of spherical wave in the rock mass. When encountering the interface of wave impedance difference, part of the wave is reflected back from the interface. By processing the received reflection data, the velocity information of rock mass in front of the tunnel is obtained. The layout of TETSP observation system is shown in figure 1. One receiving hole is arranged on the left and right walls of the tunnel, and the number of twenty-four blasting holes are arranged on one side of the tunnel wall. The distance between the blasting holes is 1.5 m and they are placed on the same plane with the receiving holes. The receiving holes are inclined upward about $5^\circ \sim 10^\circ$ with a diameter of 50 mm ~60 mm, and the blast holes are inclined downward about $10^\circ \sim 20^\circ$ with a diameter of 38 mm ~ 45 mm. The distance between each hole and the bottom of the tunnel is 1.0 m~ 1.2 m.

![Figure 1. Layout of TETSP observation system](image-url)
3. The analysis of TETSP acquisition data under different seismic sources

The TETSP detector can be installed on a special metal rod as shown in figure 2. The TETSP detector is loaded with a retractable metal wheel, and the metal rod is pushed into the drilling hole to complete the geophone installation. The installation time of TETSP detector is less than two minutes. However, the traditional speed detector needs to be led into the receiving hole with casing, and then filled with grease. The installation time of the detector is as follows more than ten minutes. TETSP adopts acceleration sensor with high sensitivity of 2.5V/g, in which TSP and TRT are 1V / g, and AGI-T3 is 0.6V/g.

![Figure 2. Direct coupling sensor of TETSP](image)

There are two kinds of seismic sources used in TETSP, namely, hammering mode and blasting mode. Figure 3 shows the data test results of a TETSP prediction of different sources in Longxing tunnel, as shown in figure 3, the TETSP waveform of blasting source is clear and the direct wave is obvious, but the waveform collected by hammer source contains strong high-frequency background interference, so blasting source should be given priority in TETSP data acquisition.

![Figure 3. Comparison data collected by TETSP in different seismic sources](image)

4. The typical forecast cases of TETSP

4.1. Karst cave and water inflow forecast

Figure 4 shows the prediction results of TETSP in section YK3 + 979 ~ YK3 + 879, in which Y represents the right line of the tunnel and K represents kilometre. As shown in figure 4, the longitudinal wave and transverse wave velocities of rock mass in TETSP detection section are generally low, the former is about 3500 m/s ~ 3900m/s, the latter is between 2000 m/s ~ 2150 m/s, and Poisson's ratio is about 0.25 ~ 0.3, which is relatively high, indicating that the rock mass dissolution is developed and the groundwater content is high, in which, the longitudinal and transverse wave velocities in section YK3 + 922 ~ YK3 + 887 are very small, it is speculated that the corrosion in this section is more developed and the water yield is larger. The actual excavation of the tunnel shows that the rock mass in YK3 + 979 ~ YK3 + 879 section is limestone with developed dissolution fissures, which are fragmentary in some parts and filled with clay. The underground water in YK3 + 979 ~ YK3 + 923 section is mainly like raindrop. Since YK3 + 923, the water yield of rock mass has increased, mainly in the form of gushing and seepage, and locally in spray shape as shown in figure 5. The geological conditions revealed by excavation are consistent with the results of TETSP analysis.
4.2. Prediction of mud inrush in karst cave

The ZK2 + 534 ~ ZK3 + 861 section of Longxing tunnel is mainly composed of limestone and dissolution breccia. Z represents the left line of the tunnel. The breccia is mainly composed of sandstone and calcite, with limestone lens locally. The breccia cementation is general and the core is broken. The occurrence of strata in ZK2 + 703 ~ ZK3 + 861 section changes greatly, structural fractures are developed and core is strongly dissolved, and there are a lot of dissolution pores and caves expose on the surface.

Figure 6 shows the prediction results of TETSP in section ZK2 + 682 ~ ZK2 + 782. As shown in figure 6, the longitudinal wave and transverse wave velocities of rock mass are relatively low, and the variation is small. The former is about 3860 m/s and the latter is between 2140 m/s ~ 2200 m/s, which indicates that the rock mass in the TETSP detection section is generally developed with water bearing caverns. Since ZK2 + 707, the transverse wave velocity gradually decreases and Poisson's ratio increases gradually. It is speculated that the water content of rock mass is relatively high. Tunnel excavation shows that section ZK2 + 682 ~ ZK2 + 782 is mostly dissolution breccia with broken rock mass. There are strand like water seepage in some tunnel sections. The surrounding rock is easy to soften when encountering water, and its self stability is very poor. Mud inrush appears in ZK2 + 700 tunnel face as shown in figure 7 with a volume of about 1000 m3, and the maximum length of mud inrush is nearly 50m away from the tunnel face. Compared with the actual excavation results, although the TETSP prediction results can accurately reflect the engineering geological conditions of the rock body in front of the tunnel, it can not identify the pile number range where mud inrush may occur. Therefore, the advance prediction work in karst development area should be combined with geological
According to the data, the corresponding pre-drilling work should be carried out to improve the prediction accuracy more effectively.

![Figure 6. Prediction results of TETSP in ZK2+682~ZK2+782 section](image)

**Figure 6. Prediction results of TETSP in ZK2+682~ZK2+782 section**

![Figure 7. Mud bursting of tunnel face in Pile ZK2 + 700](image)

**Figure 7. Mud bursting of tunnel face in Pile ZK2 + 700**

5. Conclusion
Firstly, the directly coupled TETSP geophone with the tunnel wall has high installation efficiency, about 1/5 of that of the conventional advanced prediction method. The original waveform collected by TETSP is clear at the first break. When the water injection effect in the borehole is good, the seismic reflection data with high signal-to-noise ratio can be obtained. Strong high-frequency acoustic interference is easy to occur under the artificial hammering excitation mode. Therefore, explosive source should be preferred for TETSP prediction.

Secondly, TETSP has a good effect in the prediction of unfavorable geological conditions such as karst cave, water inrush and fracture zone, and its anomaly law is reflected in the low P-wave velocity and high Poisson's ratio.

Thirdly, the accuracy of advanced prediction can be further improved by combining the interpretation of TETSP results with geological data, and using the comprehensive prediction method verified by advanced geological drilling method in TETSP abnormal area.

Acknowledgments
This work was supported by the National Natural Science Foundation of China (41641040) and the Instrument Development Project of Chinese Academy of Sciences (YJKYYQ20170033)

References
[1] Yang, J. H Yan, C. B and Miao, D (2019) Comprehensive advanced geological prediction methods for tunnel construction with double shield TBM[J]. *Journal of Engineering Geology*, **27**(2): 250－259.
[2] Qin, L Zhang, Q. C (2019) Physical simulation of tunnel advance geological prediction by transient
electromagnetic method[J]. Modern Tunnelling Technology, 56(6): 46－51.

[3] Jiang, J. G Liu, C and Chen, Y (2019) Study on GPR forward modeling and its application in advanced geological prediction of fault water-rich zone[J]. Journal of Railway Science and Engineering, 16(11): 2801－2808.

[4] Zheng, J. D Chen, S. L and Li, D.Y (2019) Classification of surrounding rock based on seismic exploration and its application[J]. Journal of Henan Polytechnic University(Natural Science), 38(01): 54－60.

[5] Yao, W Fu, N. Y and Lu, X. L (2019) Application of a new geophone and geometry in tunnel seismic detection[J]. Sensors, 19(5): 1246－1260.

[6] Zhou, Y. D Zhang, B and Geng, Z (2019) Stability analysis of soft rock surrounding tunnel based on Hoek-Brown strength criterion[J]. Journal of Engineering Geology, 27(5): 980－988.

[7] Fan, X. F Chen, J and Yue, Z. P (2019) Advanced geological prediction and inspection in the construction of metal mine roadway based on TRT system: an example from Xulou iron mine[J]. China Mining Magazine, 28(02): 80－85.

[8] Zhao, G. J LI, J. J and Jiang, Z. G (2018) Application of AGI-T3 to advance geological prediction for construction of water conveyance tunnel[J]. Water Resources and Hydropower Engineering, 49(6): 164－170.

[9] Feng, X. L Chen, F M and Xie, M (2014) Application of TST geological probing technique in TBM excavation in Neelum-Jhelum Hydropower Station[J]. Yangtze River, 45(01): 66－68.

[10] Zhao, X. L (2019) Numerical simulation of excitation field and engineering application of tunnel magnetic resonance sounding[D]. Changchun: Jilin University, 1－79.

[11] Chen, F M Xie, M and Jiang, H (2015) Application of complex-frequency conductance technique in advance water exploring of tunnels[J]. Yangtze River, 46(21): 50－54.