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Comparative Analysis of Application of Seismic Wave Reflection Method in Advanced Geological Prediction

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Abstract: Seismic wave reflection method is an advanced geophysical detection method in tunnel geological prediction. It is more sensitive and effective in detecting geological anomalies such as fault fracture zone and karst. In order to verify the prediction efficacy and accuracy of the seismic wave reflection method with different instruments and equipment (tunnel geological prediction [TGP]/tunnel seismic prediction [TSP]) and different vibration modes (hammering, explosives), a comparison test was carried out in Jinping Tunnel. The test results showed that the time-consumption of the hammering source was short, which can greatly reduce the impact on the construction site; different vibration sources methods of seismic wave reflection can predict the unfavorable geological sections accurately.

Keywords: Seismic wave reflection method; Vibration source; TSP; TGP

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1. Introduction

In recent years, highway tunnel construction has developed rapidly. As a concealed project, tunnel construction is complex and unpredictable, and often encounters areas with complex geological conditions, especially tunnel sites passing through hollow areas, fault structural zones, karst developed areas and dangerous areas with high gas concentration often cause geological disasters such as landslides, mud gushes, and gas explosions during construction. Carrying out advanced geological prediction of tunnels can timely detect the location, type, and possible risks of unfavorable geological bodies in front of the tunnel face. It can prevent possible geological disasters such as tunnel collapse, water gushing, mud inrush and gas explosion. At the same time, through advanced geological prediction, it is possible to grasp the geological structure conditions and surrounding rock grade types within a short distance in front of the tunnel face, and provide a more scientific basis for the construction unit to select excavation methods and support parameter types. To sum up, advanced geological prediction of tunnels has significant economic and social benefits as it increases construction efficiency, reduces construction period, ensures safe and scientific construction, and reduces construction accident losses.

There are many advanced geological prediction methods, which can be mainly divided into three categories: traditional geological analysis method, direct drilling method of face drilling and more advanced geophysical detection method [1-3]. Geophysical advanced geological prediction methods can be divided into long-range prediction and short-range prediction according to different prediction distances. In long-distance forecast, the geological conditions at a distance of 100–200 m in front of the tunnel face is forecasted mainly through elastic wave reflection. By analyzing the kinematics and dynamics characteristics of the reflected wave received by the geophone and obtaining the imaging information of the rock mass structure, the geological conditions in front of the tunnel can be predicted [4]. According to the observation system layout, data processing method, excitation method, etc. [5], seismic wave reflection method can be divided into tunnel seismic prediction (TSP) and tunnel geological prediction (TGP); land sonar two-dimensional advanced prediction such as the negative apparent velocity method and the tunnel seismic wave reflection tomography (TRT), tunnel seismic tomography (TST), horizontal sound probing (HSP), and underground seismic prediction system(USP) [6]; tunnel seismic detection system (TSD), and other advanced prediction methods of space observation methods. The seismic wave reflection method has a long prediction distance and has a better prediction effect on planar structures with different mechanical properties. Therefore, it has been widely used in the advance geological prediction of road tunnels [7].

2. Principle of seismic wave reflection method

The seismic wave signal generated by hammering or small-dose blasting at a specific position in the tunnel propagates in the form of spherical waves along the direction of the tunnel; the seismic wave propagates at different speeds in different rock formations. Seismic waves are generated at different locations by exciting multiple source points. These source points are distributed at specific locations in the tunnel. When the seismic waves encounter abnormal bodies (broken zones, faults, cavities, and many more) in front of the tunnel, the waves will then be reflected to the sensor. The three-axis high-sensitivity sensor will receive the reflected waves (X, Y, Z) from different directions of the abnormal body, so as to obtain a large number of three-dimensional data sets (**Figure 1**). According to the location of the sensor distribution, the propagation direction of the reflected wave of the abnormal body is different from the angle of the sensor at different positions. By calculating the angle and wave velocity of each reflected wave, we can obtain the three-dimensional space position of the abnormal body.

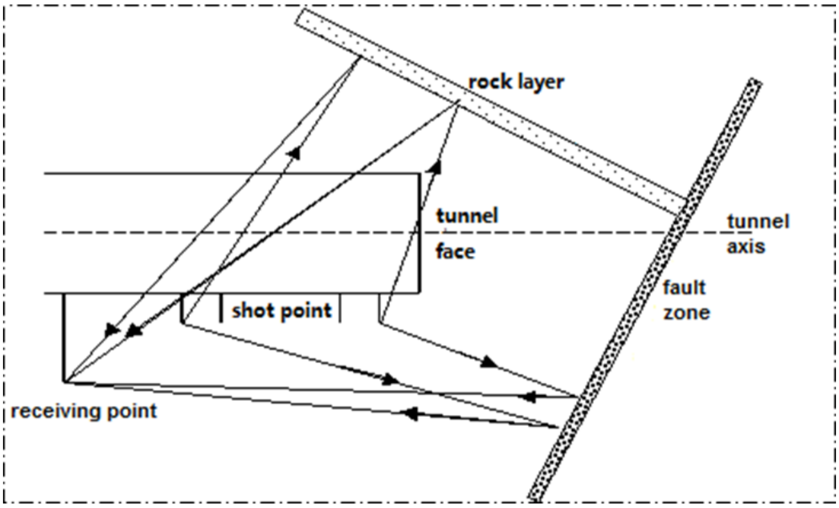

Figure 1. Schematic diagram of the principle of seismic wave reflection method

3. Comparative analysis of application effect

3.1. Instrument efficacy analysis

G4216 Yanjiang Expressway is the largest single-invested expressway in China. The bridge-tunnel ratio of the Yibin-Jinyang section is as high as 92%, of which the tunnel accounts for 70%. The nature of the tunnel is complex and vulnerable, and the unfavorable geological conditions of the cave body are unfavorable, and it is facing a relatively large construction risk. Therefore, the safety and progress of the Yanjiang high-speed tunnel project are the key to the construction of the expressway. Advanced geological prediction of the tunnel is the most important means of information construction, which provides the basis for the dynamic design and safe construction of the tunnel. In order to compare the efficacy and accuracy of long-distance prediction by seismic wave reflection method, the Chief Engineering Office of Yanjiang Yijin Company established relevant third-party testing units and instruments to conduct comparison tests in the left tunnel of XJ8 Jinping Tunnel. The main instruments and equipment and observation methods are shown in **Table 1**. Four sets of seismic wave reflection instruments were used for the test, two sets of TGP206G instruments were excited by explosive vibration sources; two sets of TSP (YWZ11-Z/305plus) instruments were excited by a hammering vibration source.

Table 1. Instrument and equipment layout and efficiency comparison table

Serial number	Instrument	Observation method	Vibration source	Excitation points	Receiving point	Duration forecast
1	TGP206G-1	Side wall line	Dynamite	24	2	• 1 hour for 4 drilling rigs/4 workers to complete the drilling of the blasthole. • 5 minutes for 1 blasthole to charge the data. • 120 minutes/2 hours for 24 blastholes. Total time spent: approximately 3 hours
2	TGP206G-2	Side wall line	Dynamite	24	2	• 1 hour for 4 drilling rigs/4 workers to complete the drilling of the blasthole. • 5 minutes for 1 blasthole to charge the data. • 120 minutes/2 hours for 24 blastholes Total time spent: approximately 3 hours
3	T SP YWZ11-Z	Side wall line	Hammering	24	2	• Acquisition array layout and instrument connection time is 10 minutes. • Acquisition parameter setting and trial acquisition time is 2 minutes. • Data acquisition time is 14 minutes. • 4 minutes to pack up the instrument and equipment Total time spent: 30 minutes/half an hour

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Serial number	Instrument	Observation method	Vibration source	Excitation points	Receiving point	Duration forecast
4	TSP305plus	Side wall line	Hammering	24	2	• 10 minutes for geological observation, layout of measuring points, and instrument connection • 3 minutes for turning on the equipment and parameter setting, • 15 minutes for data collection • 5 minutes for confirming data and sorting out equipment Total time spent: 33 minutes

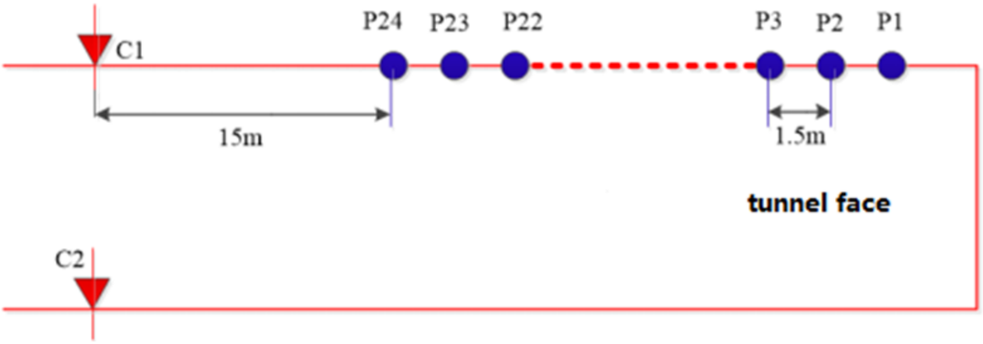

Figure 2. TGP on-site detection layout

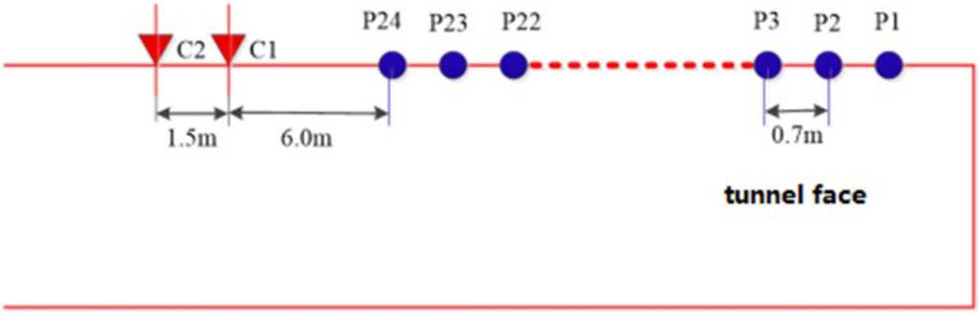

Figure 3. On-site detection layout of TSP seismic wave reflection method

The TGP measuring line was laid on the left side wall of the tunnel face, about 1.5m above the ground, and a total of 24 blastholes were arranged 1.5 m away from each other to stimulate P1–P24; two receiving points C1 and C2 were located on the left and right side walls, respectively; the offset distance was 15 m (**Figure 2**), and the prediction distance was 150 m. The TSP measuring line was laid on the left side wall of the tunnel face, about 1.5 m above the ground, with a total of 24 hammering points P1–P24, with a distance of 0.7 m between each point; two receiving points; C1 and C2, with a distance of 1.5 m between each other, and the moving distance was 6 m (**Figure 3**); and the prediction distance was 100 m.

Advance geological prediction by seismic wave reflection method is a comprehensive technical work, in which the source is an important link, and the signal acquisition quality and detection distance are all restricted by the source [8]. At present, the seismic sources used in advanced prediction at home and abroad are mainly divided into two categories: one is the expansion point source, such as explosives and spark sources; the other is the surface impact source, such as hammering, controlled shock source, and many more [9]. The maximum energy that can be excited and generated of different sources in order from strong to weak are explosive sources > electric spark sources > vibrators > hammering; in which the order would be reversed in terms of convenience of use. Explosive sources are the most frequently used, and the development and application of many advanced geological prediction technologies based on seismic wave methods are based on them, but they are strictly controlled and have great limitations. The comparison test of the seismic wave reflection method used explosive sources and the hammering sources respectively. Affected by the control of explosives, the source of explosives has been gradually replaced by digital electronic detonators from traditional electric detonators. In the advanced geological prediction of the TGP seismic wave reflection method, it is necessary to scan codes one by one to activate blastholes, which takes a long time. It can be seen from **Table 1** that it takes about 3 hours for the advanced geological prediction of the TGP explosive seismic source from the layout and drilling to the data acquisition, whereas it only takes 30 minutes from the layout of the collection array to the data collection for the advanced geological prediction using TSP hammering source. Therefore, seismic wave reflection method using hammering source is better than explosive source in terms of efficacy.

3.2. Comparative analysis of prediction results

This prediction comparison test was carried out in the left tunnel of XJ8 Jinping Tunnel, the pile number of the tunnel face is ZK41+444, and full-section excavation was carried out. The surrounding rock of the tunnel face was mainly blue-gray limestone, with a gently dipping, nearly horizontal layered, thin-to-medium-thick layered structure, and the weathered surface was light grayish white, mainly moderately weathered. Based on the hammering sound and rebound, the harder rock has more well-developed joints and fissures, which are mainly structural and weathered types, and the width of the fissures is mainly micro-extensive, mostly filled with mud, and the interlayer bonding force and stability are poor; the surrounding rocks were generally broken, showing massive to sub-massive structure. Moreover, the arch and the surrounding rock of the vault were easy to fall off or collapse, underground fissure water had been developed, the tunnel face was wet, and the vault top was sporadically dripping. The grade of the surrounding rock was evaluated comprehensively on site to be grade IV (**Figure 4**).

Figure 4. Photos of the surrounding rock conditions of ZK41+444 tunnel face

TGP206G explosive source and the TSP hammering source were used respectively to carry out advanced geological prediction work on the tunnel face ZK41+444. Through data processing, the main results are shown in **Figures 5–7**.

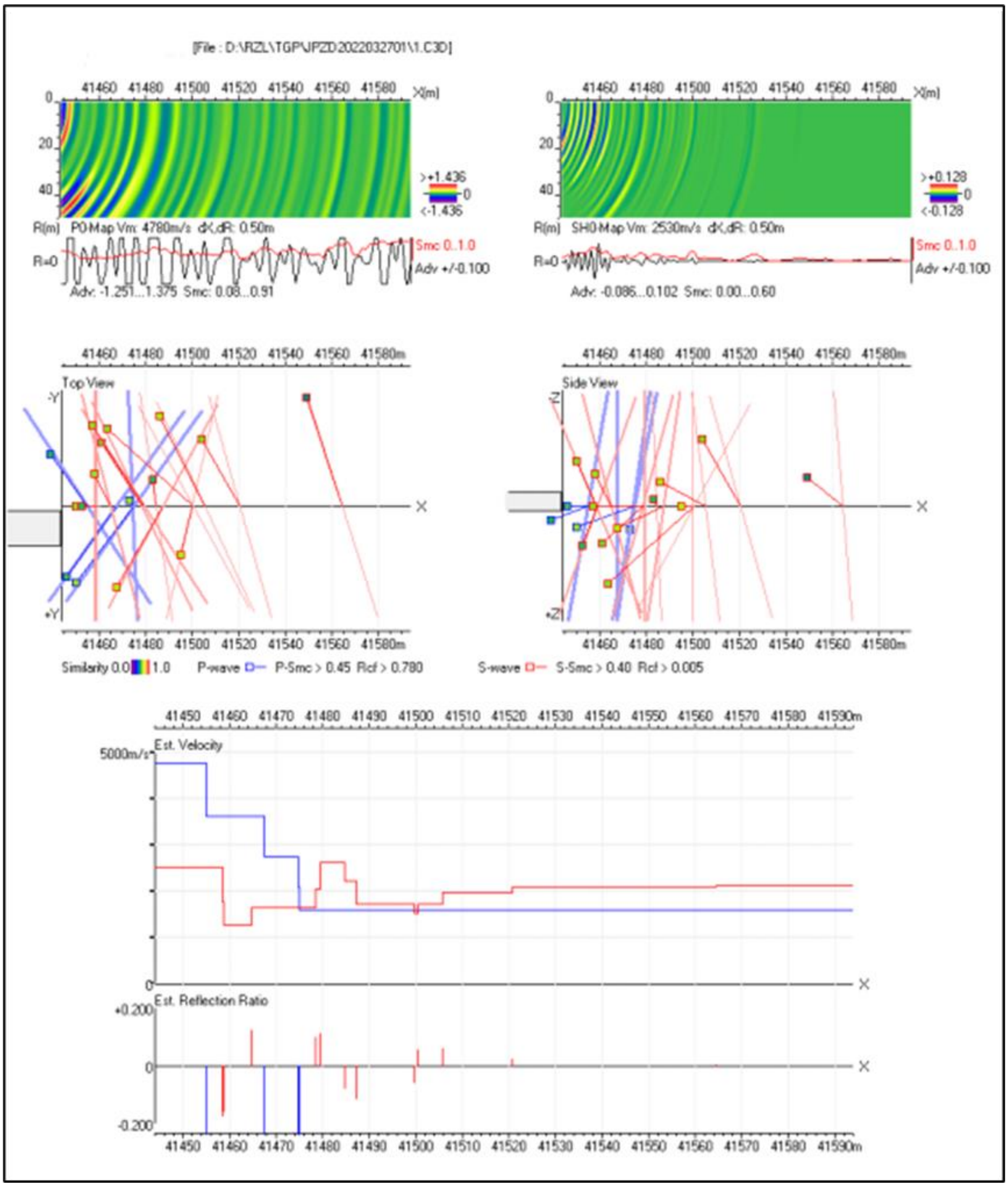

Figure 5. Reflection interface diagram of TGP ipsilateral diffraction migration imaging (TGP206G)

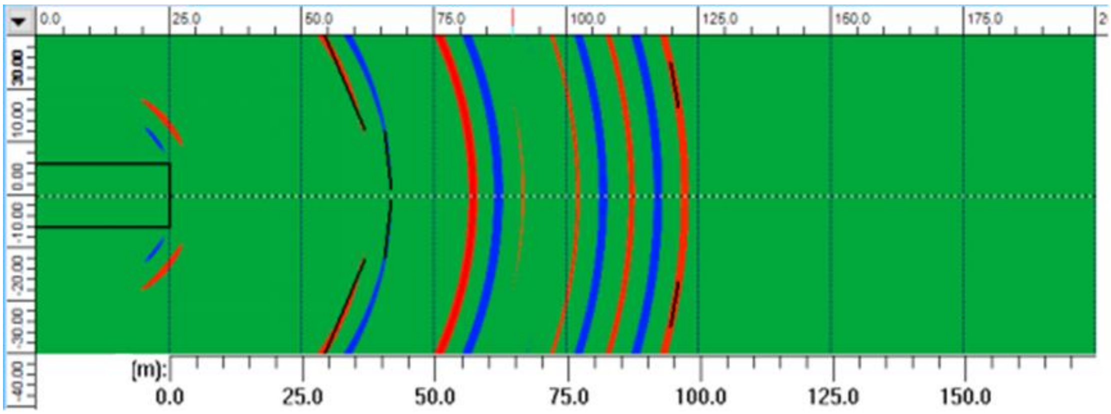

Figure 6. TSP method P-wave reflection interface display forecast map (YWZ11-Z)

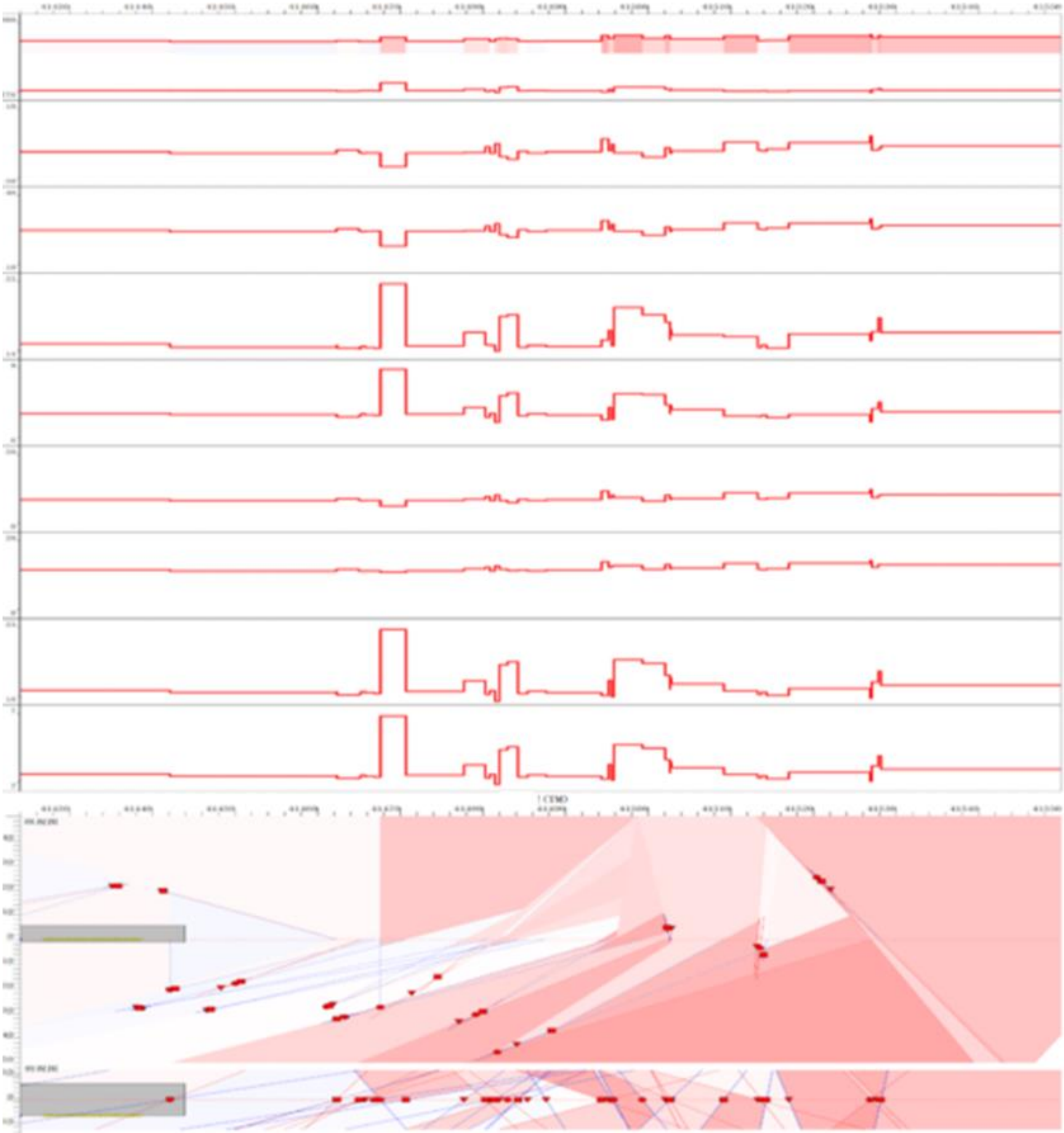

Figure 7. TSP method reflection horizon and physical and mechanical parameters result map (TSP305 PLUS)

The main forecast conclusions are shown in **Table 2**.

Table 2. Statistics table of TSP advanced geological prediction results

Serial number	Instruments/sources used	Forecast range and length	Forecast conclusion	Unfavorable geological body range
1	TGP206G/Dynamite	ZK41+444–ZK41+544	Grade IV surrounding rock	• There was a weak interface near ZK41+464, ZK41+477–ZK41+487, multiple weak interfaces near ZK41+510–ZK41+528, and a weak interface near ZK41+540. It was speculated that the rock mass in this mileage segment was broken and developed fissures or dissolved cavities. There may be seepage of dissolved water, local strands of water may flow out, poor interlayer bonding.
2	TGP206G/Dynamite	ZK41+444–ZK41+544	Grade IV surrounding rock	• In the mileage section ZK41+455–ZK41+470, there were locally developed dissolved fracture zones, weak interlayers and dissolved pipes on the right middle side, and the cracks and interlayers were mostly filled with mud and sand. • In the mileage section ZK41+474–ZK41+480, there were dense cracked broken zones locally on the right-middle side. • In the mileage section ZK41+485–ZK41+510, there were locally dissolved broken cracked zones, dissolved pipes, or dissolved cavities developed on the right middle side, and the cracks and interlayers were mostly filled with mud and sand, the groundwater is relatively developed, and the local karst pipeline water is exposed. Therefore, during the excavation process, it was necessary to pay attention to the impact of ZK41+467, ZK41+487, ZK41+499, ZK41+508 anomalies on the tunnel. • The ZK41+516–ZK41+528 mileage section had locally developed dissolved cracks and broken zones, and local weak interlayers, it was inferred that in the ZK41+560–ZK41+572 mileage section, there were locally developed dissolved cracks and broken zones, and local weak interlayers.

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Serial number	Instruments/sources used	Forecast range and length	Forecast conclusion	Unfavorable geological body range
3	TSP YWZ11-Z /hammering	ZK41+444–ZK41+544	Grade IV surrounding rock	• In the vicinity of ZK41+482, ZK41+486, ZK41+498, and ZK41+508, the joints and fissures in the ZK41+519–ZK41+541 section were relatively developed, with some areas having densely developed joint and fissures or interbed with weak interlayers. The surrounding rocks were relatively broken, and karst was relatively developed. Dissolved structures such as dissolved pores, dissolved pipes, and caves had developed. Groundwater had developed, showing seepage or strands.
4	TSP305PLUS/hammering	ZK41+444–ZK41+544	Grade IV surrounding rock	• ZK41+465–ZK41+471, ZK41+477–ZK41+486 sections had strong reflective surfaces, and it was speculated that dissolved fissures, pipes, or joint fissures had densely developed. Groundwater had developed in the sections, and strands of water may occur nearby. ZK41+494–ZK41+503, ZK41+509–ZK41+518, ZK41+526–ZK41+530 may have had dense joint fissures or dissolved fissures and pipelines.

Geological sketches of the face of ZK41+444–ZK41+544 were drawn by professional geologists. According to the sketches of the face of the site, the surrounding rocks of ZK41+444–ZK41+544 were mainly limestones. The rocks were mostly hard rocks that were thin to medium-thick, with broken rock mass, well-developed joints and fissures, local mud inclusions in the fissures, and poor bonding between structures, which make them Grade IV. The differences between the sketches were the degree of fragmentation of the surrounding rock and the development of underground fissure water. The situation of the surrounding rocks at section ZK41+444–ZK41+516 was similar. After ZK41+516, the surrounding rock became thin layered, and the overall integrity became poor. At the same time, ZK41+477 began to develop fissure water, at ZK41+497–ZK41+533, it became drizzling water, and there was no crack water after ZK41+533.

Table 3. Comparison table of forecast and excavation of ZK41+444, ZK41+477, ZK41+497, ZK41+516, ZK41+533

Excavation results	**No obvious geological anomalies**	**Fissure water**	**Drizzling water**	**Drizzling water with thin surrounding rocks**	**Thin surrounding rocks**
1	It was predicted that there was no abnormality in this section.	ZK41+477–ZK41+487 had strongly reflective interface, which meant that the surrounding rocks were broken, and there might be water seepage from the cracks.	There were multiple weak interfaces in ZK41+510–ZK41+528, which meant that rock mass was broken, and there might be strands of water gushing out.	There were multiple weak interfaces in ZK41+510–ZK41+528, which meant that the rock mass was broken, and there might be strands of water gushing out.	The surrounding rocks were broken.
Consistency analysis	Unanimous	Unanimous	Similar	Similar	Unanimous
Accuracy	**77%**				
2	From ZK41+455 to ZK41+470, there were locally developed fracture zones, weak interlayers, and dissolved pipes on the right middle side, and the gaps and interlayers were mostly refilled with mud and sand.	ZK41+474–ZK41+480 had developed dense fracture zone.	In the right middle part of ZK41+485–ZK41+510, there were dissolved fracture zones, corrosion pipes or dissolved cavities, most of the fissures and interlayers were refilled with mud and sand; groundwater had developed, and water in local karst pipes was exposed.	ZK41+516–ZK41+528 mileage section had locally developed dissolved fracture zone, partially interbedded with weak interlayers.	The surrounding rocks were broken.
Consistency analysis	Unanimous	Similar	Different	Similar	Unanimous
Accuracy	**80 %**				

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Excavation results	**No obvious geological anomalies**	**Fissure water**	**Drizzling water**	**Drizzling water with thin surrounding rocks**	**Thin surrounding rocks**
3	The hardness of the surrounding rock is basically the same as that of the tunnel face, the rock mass is relatively complete, the joints and fissures are well developed, the bonding degree of the structural plane is average, and the stability is poor	ZK41+482, ZK41+486, ZK41 +498 strong reflection interface, surrounding rock broken, groundwater developed	Strong reflection interface of ZK41+498 and ZK41+508, development of dissolved fracture zone and development of groundwater	There were joints and fissures in ZK41+519–ZK41+541, where some areas had dense ones.	There were joints and fissures in ZK41+519–ZK41+541, where some areas had dense ones.
Consistency analysis	Unanimous	Similar	Different	Similar	Unanimous
Accuracy	**79%**				
4	The hardness of the surrounding rocks was basically the same as that of the tunnel face, the rock mass was relatively complete, the joints and fissures were well developed, the bonding between the structural planes was average, and the stability is poor	ZK41+472–ZK41+486 had a strong reflective surface, it was speculated that there might be a dense zone of dissolved fissures, pipes or joint fissures, and groundwater had developed in that area	ZK41+486–ZK41+503 might have dissolved fractures, karst, and well-developed groundwater	ZK41+503–ZK41+521 might have weak interlayers or dissolved fracture zones. There might be rain strands of water on the face after excavation	The surrounding rocks were broken.
Consistency analysis	Unanimous	Different	Similar	Similar	Unanimous
Accuracy	**75%**				

The comparison between forecast results and excavation results is shown in **Table 3**. The advanced geological prediction by seismic wave reflection method carried out using different sources, instruments, and equipment all predicted the surrounding rock 100 m in front of the tunnel face to be Grade IV, which was basically consistent with the geological conditions of the site excavation. The seismic wave reflection method of different instruments and equipment all predict that the ZK41+516–ZK41+533 section has developed fissure water and the surrounding rock was broken. The accuracy of the prediction was above 70%. The main reasons for the discrepancy with the actual excavation are explained below.

(1) Selection of direct wave velocity

In the seismic wave reflection method, the direct wave is received before the reflected wave. For the initial value picking, different personal understandings and selection points will result in different velocity values. The difference in the selection of the direct wave speed will lead to differences in the final results, which will affect the accuracy of the conclusion.

(2) Selection of band-pass filter parameters

Improper selection of band-pass filters will often cause loss of valuable waveform signals, or selection of clutter interference within 300 ms. This requires experience and understanding of the site, and a summary and analysis of the filter selection methods for different strata and different lithologies in order to make a breakthrough.

(3) Selection of forecast distance

Assuming that the data collected were valid, with the same initial value and band-pass filter parameters, different forecast distances were selected for the same data, and comparisons and inferences were made through verification and comparison from multiple excavations. As the forecast distance increases, the forecast accuracy rate decreases linearly [10]. The empirical forecast distance is roughly 100 m for the geologically complex section; the forecast distance for the normal section is between 120 and 180 m.

(4) The impact of excavation footage

The left hole ZK41+444–ZK41+544 of the Jinping Tunnel in the predicted section underwent full-face excavation, and the single-cycle footage was relatively large, so it was difficult to fully reveal the predicted anomalies such as small, dissolved channels, and there were certain differences between the excavation and forecast results.

4. Conclusion

(1) The hammering source seismic wave reflection method is superior to the explosive source in terms of efficacy, 2.5 hours can be saved in one forecast, which greatly reduces the impact on construction.

(2) In this test, the seismic wave reflection method using different instruments and shock modes can predict the subsurface section of ZK41+516 to ZK41+533 in the left tunnel of Jinping Tunnel more accurately, where underground fissure water had developed and the surrounding rock was broken. The seismic wave reflection method is sensitive to geological anomalies with differences in elastic wave impedance and has a good detection effect on unfavorable geological factors that affect the integrity of surrounding rocks (joint fissure development, faults and fracture zones, karst, alteration, and many more).

(3) Although the hammering source is a widely used non-explosive source, its characteristics of weak energy, instability, uncontrollability and poor anti-interference ability should also be considered.

(4) Affected by the subjective factors of the geological description of the tunnel face, the excavation of the surrounding rock was not very accurate, and there were no major adverse geological phenomena in the forecast section. Therefore, more research and improvements need to be done. On one hand, professional geologists need to conduct macroscopic geological understanding analysis; on the other hand, it is also necessary for geophysical exploration personnel with theoretical knowledge and field

experience to carry out geophysical exploration interpretation, eliminate interference anomalies and multiple solutions, and carry out advanced geological prediction truthfully and objectively.

(5) The single geophysical prospecting method utilizes the characteristics of geological body for advanced geological prediction. For example, the seismic wave reflection method uses the difference in wave impedance of the surrounding rock; the geological radar uses the difference in the dielectric constant of the surrounding rock; and the transient electromagnetic method uses difference in the surrounding rock. These methods have their limitations with solutions to them. The comprehensive overdue geological prediction method of geological analysis, geophysical prospecting, and drilling should be used for prediction to improve the accuracy of the forecast and ensure safe construction of the tunnel project.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Gou D, Xie X, 2017, Several Main Methods and Application Research of Karst Tunnel Geological Prediction. Journal of Railway Engineering, 2017, 34(1): 75–80.

[2] Zhang Z, 1981, Engineering Geological Survey, Geological Press, Beijing, 152–200.

[3] Liu Y, Wang Z, Zhou Z, 2009, Research on advance forecast of tunnel geology based on tunnel face catalog. People's Yellow River, 31(8): 94–95.

[4] Zhou L, Qiu D, Fu D, et al., 2016, TSP Tunnel Advanced Geological Prediction Technology and its 3D Results Research and Application. Journal of the Yangtze River Academy of Sciences, 33(10): 72–78.

[5] Li S, Liu B, Sun H, et al., 2014, Research Status and Development Trend of Advanced Geological Prediction in Tunnel Construction. Chinese Journal of Rock Mechanics and Engineering, 33(6): 1090–1113.

[6] Ye Y, 2009, Application of Seismic Angle Migration in Advanced Geological Prediction of Tunnel Construction. Geophysical and Geochemical Prospecting, 33(6): 733–736.

[7] Wu J, Zhou H, Zhang Y, et al., 2021, Comprehensive Advanced Geological Prediction Technology and Application of Highway Tunnels. Journal of Jinan University (Natural Science Edition), 35(2): 182–189.

[8] Xu L, Wang S, Zhang J, 2020, Research on Key Technology of TGP Forecast Data Acquisition. Progress in Geophysics, 35(4): 1618.

[9] Zhao X, Yao Q, Chi J, et al. 2021, Application and Effect Analysis of Non-Explosive Source in Tunnel Geological Prediction. Tunnel Construction (Chinese and English), 41(S1): 153–160.

[10] Zhi G, 2021, Analysis of the Influence of the Accuracy of TSP Advance Geological Prediction Results. Subgrade Engineering, 182(5): 139–143.