Chapter

Advanced Geological Prediction

Shaoshuai Shi, Xiaokun Xie, Siming Tian, Zhijie Wen, Lin Bu, Zongqing Zhou, Shuguang Song and Ruijie Zhao

Abstract

Due to the particularity of the tunnel project, it is difficult to find out the exact geological conditions of the tunnel body during the survey stage. Once it encounters unfavorable geological bodies such as faults, fracture zones, and karst, it will bring great challenges to the construction and will easily cause major problems, economic losses, and casualties. Therefore, it is necessary to carry out geological forecast work in the tunnel construction process, which is of great significance for tunnel safety construction and avoiding major disaster accident losses. This lecture mainly introduces the commonly used methods of geological forecast in tunnel construction, the design principles, and contents of geological forecast and combines typical cases to show the implementation process of comprehensive geological forecast. Finally, the development direction of geological forecast theory, method, and technology is carried out. Prospects provide a useful reference for promoting the development of geological forecast of tunnels.

Keywords: advanced geological prediction design, content of advanced geological prediction, method of advanced geological prediction, geological hazard detection, engineering application

1. Introduction

1.1 Main contents and common methods of geological forecast

The advanced geological prediction of the tunnel includes geological analysis and macroscopic geological forecast of the tunnel area, advanced prediction of tunnel geological disasters, and warning of major construction geological disasters [1, 2]. The main forecast content [3–6] is as follows:

1. Stratigraphic lithology forecast, the focus is on prediction of soft interlayers, broken formation, coal seams, and special rock.

2. Geological structure prediction, the focus is on the prediction of the tectonic development of the rock mass integrity, such as faults, concentrated joint band, and fold axis.

3. Unfavorable geological prediction, the focus is on the prediction of karst, man-made tunnels, gas, etc.

4. Groundwater prediction focuses on the prediction of karst conduit water and water-rich faults, water-rich fold axis, and fissure water in water-rich strata.

In response to the abovementioned exploration targets, the researchers have developed geological forecast techniques for various types of construction tunnels. The common methods for geological forecast are geological researching, advance drilling geological prediction, geophysical prospecting prediction in tunnel, advance heading, etc. [7–13], as shown in **Figure 1**.

1.1.1 Hydrogeological survey

The hydrogeological survey method mainly includes the supplementary geological survey of the tunnel surface, the geological sketch of the working face in the tunnel and the geological sketch of the tunnel wall, the underground and surface correlation analysis of the stratigraphic boundary line and the structural line, and the geological mapping.

The hydrogeological survey method is the earliest and most basic method used in various tunnel geological advance prediction methods. The interpretation and use of other tunnel advance prediction methods are based on geological data analysis and judgment. The hydrogeological survey method is based on the existing survey data, the geological survey data supplemented by the surface, and the geological sketch in the tunnel, through the sequence comparison of the geological layers, the stratigraphic boundary line, and the correlation analysis of the subsurface and surface of the stratigraphic tectonic line, the fault elements, and the tunnel geometry. Correlation analysis of parameters, possible precursor analysis of adjacent geological bodies in the tunnel, etc. use conventional geological theory, geological mapping, and geological development trend analysis, etc. to speculate the possible geological conditions ahead of the excavation face. The method has high accuracy in the case where the tunnel has a shallow depth and the structure is not too complicated, but in the case of deep depth and complicated structure, the method is difficult, and the accuracy is poor.

1.1.2 Probe drilling

Probe drilling methods mainly include advanced geological drilling, deepened shot hole detection, and borehole photography.

The **probe** horizontal drilling method is a kind of advanced geological prediction method for obtaining geological information by drilling with drilling equipment or directly using blasting holes to drill ahead in the tunnel excavation working face. The method can directly reveal the lithology, rock structure, groundwater, karst cave and its properties, rock integrity degree, etc., from tens of meters to hundreds of meters in front of the tunnel working face, and can also

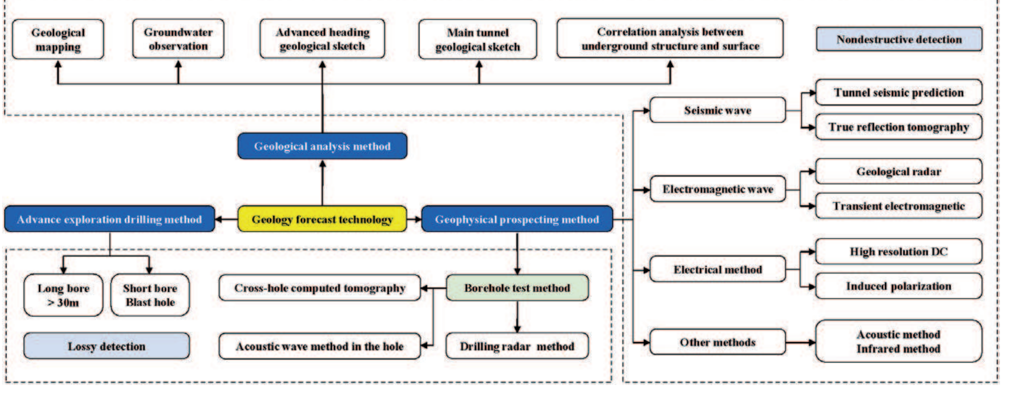

Figure 1.
Common methods for geology forecast of tunnels.

be obtained through core test. Quantitative indicators such as rock strength are applicable to the main unfavorable geological sections that have been basically identified. For undetermined unfavorable geological sections, the unsatisfactory leakage of unfavorable geological bodies is often caused by the problem of "one hole seeing."

1.1.3 Geophysical prospecting

Geophysical methods mainly include elastic wave reflection method (seismic wave reflection, horizontal acoustic wave profile method, negative-vision velocity method, and very small offset high-frequency reflection continuous profile method), electromagnetic wave method (geological radar, transient electromagnetic), and electrical method (high-resolution DC method, induced polarization method, etc.).

The geophysical prospecting is based on the physical difference between the target geological body and the surrounding medium, such as electrical, magnetic, density, wave velocity, temperature, radioactivity, etc., and the spatial distribution of the underground geological body is determined by observing changes in natural or artificial physics. The scope is a physical exploration technology that solves geological problems. The method is fast, comprehensive, accurate, and economical. It is a nondestructive testing method, which mainly includes seismic wave reflection method, electromagnetic wave method, and electric method.

1. Seismic wave reflection: The basic principle of seismic wave reflection method is to use the characteristics of reflected waves generated by seismic waves in uneven geological bodies to predict the geological conditions in front of and around the tunneling face. At present, the main methods include tunnel seismic prediction (TSP), tunnel reflection tomography (TRT), and terrestrial sonar.

2. Electromagnetic wave method: The electromagnetic wave method is a detection method for detecting the distribution of underground medium by using ultrahigh frequency electromagnetic waves, including geological radar method and transient electromagnetic method.

3. Electrical: The electrical method uses the distribution characteristics and laws of the DC electric field to detect the surface of the face and the surrounding underground medium. The common methods used in tunnel advance prediction include induced polarization method and high-resolution direct current method.

4. Drilling test: The borehole test method combined with **leading** horizontal drilling and geophysical methods can make the geophysical approach closer to the exploration target and away from the tunnel interference source, thus achieving good detection results. Drilling test methods include cross-hole CT, acoustic wave method in borehole, and borehole radar method.

1.1.4 Advance heading method

The advance heading prediction method mainly includes the parallel advance heading method, the positive hole advance heading method, etc.

The advance heading prediction method is used to excavate a parallel heading in the tunnel or on the side of the tunnel, through geological conditions revealed in advance heading, geological theory, and mapping method to predict the geological conditions of the main tunnel. The advance heading prediction method includes parallel advance heading method and positive hole advance heading method. The two tunnels with small line spacing can be parallel heading to each other; the tunnel excavated first can predict the geological conditions of the tunnel excavated after. Because of its large cross section, the advance heading method can reveal the geological conditions in front of the positive hole more comprehensively and accurately, but it takes a long time and has high economic cost.

2. Geology forecast design

2.1 Geology forecast design

The tunnel engineering should carry out corresponding geology forecast design at each design stage, and the selection of prediction methods should be compatible with the construction method. The geology forecast design can be implemented by referring to the following steps, as shown in **Figure 2**:

1. The geological survey method is adopted to investigate the engineering geological and hydrological conditions in the area and obtain unfavorable geological structures, special geotechnical areas, and possible geological problems.

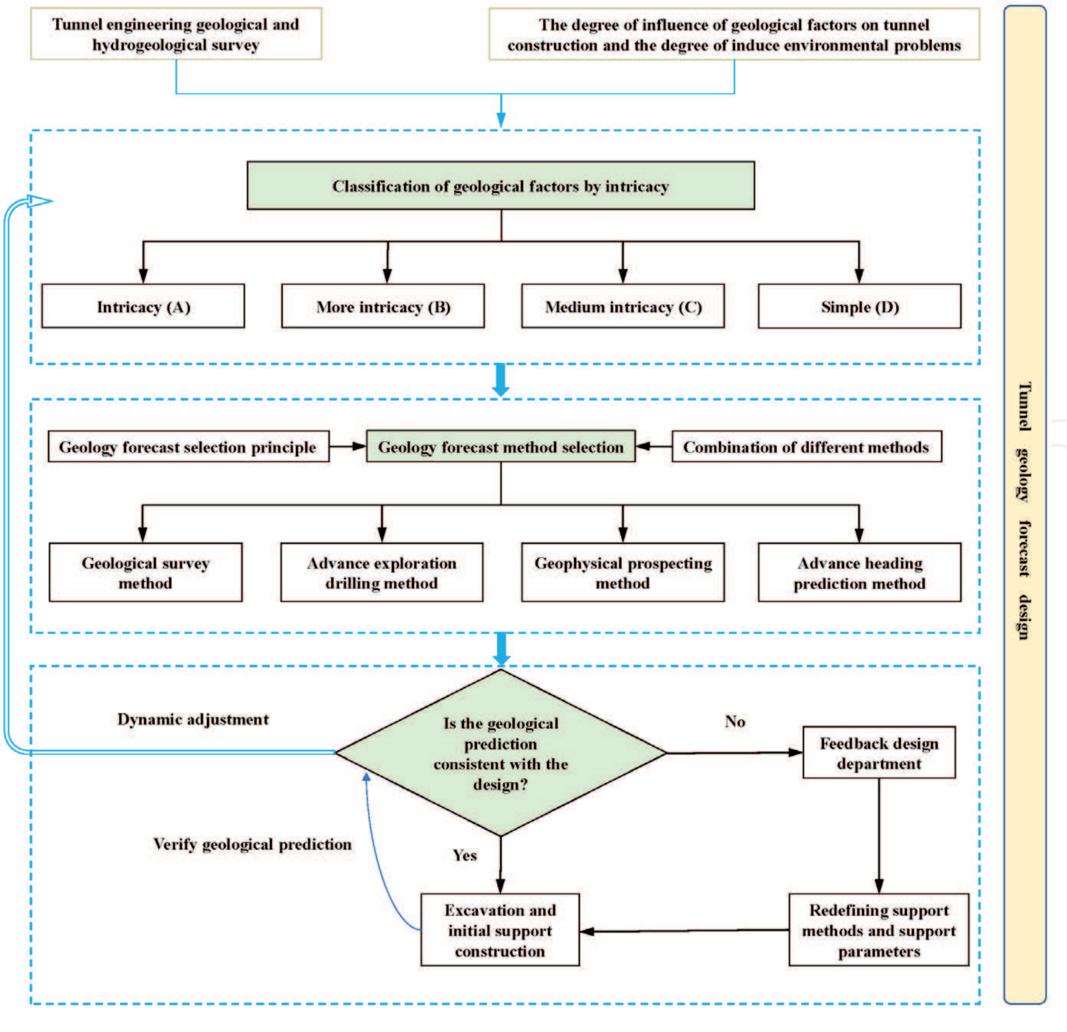

Figure 2.
Flow chart of tunnel geology forecast design.

2. Based on the results of geological surveys, obtaining the classification of geological factors by intricacy.

3. According to the condition of classification of geological factors by intricacy and the selection principle of the geology forecast method, the corresponding advanced prediction methods are selected.

4. In the process of tunnel excavation, according to the results of geology forecast and actual geological condition dynamic, adjust the tunnel classification of geological factors by intricacy and geology forecast design.

2.2 Classification of geological factors by intricacy (hazard)

Considering comprehensively the geological and hydrogeological conditions of the tunnel, the influence degree of the possible geological hazards on the tunnel construction and environment classifies the geological factors by intricacy. Tunnel classification of geological factors by intricacy (hazard) is shown in **Table 1** [3]. The purpose of the tunnel classification of geological factors by intricacy (hazard) is to determine the depth (accuracy) of geological prediction and exploration; to select different exploration methods and means (and their combination); determining the relevant technical requirements, workload, and so on; to complete the geology forecast design of tunnel construction; and to realize scientific planning and controllable management of geological prediction in tunnel construction.

2.3 Advanced geological prediction method selection

The advanced geological prediction can generally adopt long-distance forecast, medium and long-distance forecast, and short-distance forecast. The choice of forecast length and forecast method should meet the following requirements:

1. Long-distance forecast: If the forecast length is more than 100 m, geological survey methods, elastic wave reflection methods, and **probe** drilling of more than 100 m can be used.

2. Medium and long-distance forecast: If the forecast length is 30–100 m, geological survey methods, elastic wave reflection methods, transient electromagnetic methods, and **probe** drilling of 30–100 m can be used.

3. Short-range forecast: If the forecast length is <30 m, geological survey methods, elastic wave reflection methods, electromagnetic wave methods (geological radar method), electrical methods (high-resolution direct current method and tunnel-induced polarization method), and **probe** drilling <30 m can be used.

2.4 Forecast method in typical bad geological body prediction

2.4.1 Fault

1. The geological survey method can further verify the nature, occurrence, location, and scale of the fault.

2. The seismic wave reflection method can determine the approximate position and width of the fault within the tunnel.

Influencing factor		**Degree of intricacy**			
		Intricacy (A)	**More intricacy (B)**	**Medium intricacy (C)**	**Simple (D)**
Geological intricacy	Karst development	Strong development	Medium development	Weak development	Feeble development
	Water and mud gushing	Extra-large water inrush	Larger water inrush	Medium water inflow	Small water inflow
	Fault stability	Large fault fragmentation zone, poor self-stabilization capacity, rich in water	Medium-sized fault zone, weak, medium-to weak rich in water may cause medium-sized collapse	Small- and medium-sized faults, weakly rich in water, may cause small collapses	Small- and medium-sized fault, water-free, and drop block
	Ground stress	Extremely high stress ($R_c/\sigma_{max} < 4$)	High stress (R_c/σ_{max} = 4–7)	—	—
	Gas influence	Gas outburst: gas pressure $P \geq 0.74$ MPa	High gas: gas emission in the whole work area ≥ 0.5 m^3/min	Low gas: gas emission in the whole work area < 0.5 m^3/min	No
	Geological factors on tunnel construction	Endangering construction safety	Security risks	May have security issues	Local security issues may exist
	Environmental problems	May cause major environmental disasters	Improper construction	General environmental problems	No

where Rc is the rock uniaxial saturated compressive strength (MPa) and σ_{max} is the maximum geostress value.

Table 1.
Classification of geological factors by intricacy (hazard).

3. High-resolution direct current method, electromagnetic wave method, and tunnel-induced polarization method can detect the development of groundwater in fault zone.

4. **Probe** drilling can predict the exact location and scale of the fault, the material composition of the fracture zone, and the development of groundwater.

2.4.2 Karst

1. The geological survey method can analyze the law of karst development and grasp the regional geological conditions.

2. The seismic wave reflection method can be used to ascertain the structural planes such as faults and the karst morphology that is large enough to be detected.

3. High-resolution direct current method, electromagnetic wave method, etc. can qualitatively detect karst water.

4. Tunnel-induced polarization method to find out the three-dimensional location, scale, and shape of karst and the size of static reserves.

5. **Probe** drilling can combine the short-range fine detection results to find out the karst scale, development characteristics, water pressure, and so on.

2.4.3 Coal seam gas

1. The geological survey method can further verify the position and thickness of the coal seam and analyze and determine the mileage position of the coal seam.

2. The geophysical method can determine the approximate location and thickness of the coal seam within the tunnel.

3. **Probe** drilling can calibrate the exact position of each coal seam and grasp its occurrence and gas condition.

2.5 Advanced geological prediction design content

The advanced geological prediction design of the tunnel firstly evaluates the complexity of the geological complex (hazard) of the tunnel and clarifies the risk events and risk levels. The assessment of the complexity of the geological complexity of the tunnel can initially determine the causes, possibilities, and consequences of various risks. Secondly, according to the complexity of the tunnel and the risk assessment after the prediction plan is made, the prediction grading can be reasonably determined. In the case of complex high-level sections, several geophysical methods with complementary physical parameters should be comprehensively implemented. Targeted advance drilling can be carried out purposefully according to the results of geophysical exploration, and we should give full play to the advantages of geophysical exploration and drilling so that we can achieve accurate and resource-saving objectives. Finally, the forecasters were requested to adopt advanced data collection and processing methods, strive to improve the level and accuracy of the prediction, further investigate the engineering geological and hydrogeological conditions in front of the tunnel excavation face, guide the smooth progress of the project construction, and reduce the probability of a geological disaster occurring. The advanced geological prediction design relies on the assessment of the complexity of the tunnel geological (hazard) and can be divided into the following four levels, as shown below:

A-level forecast: Based on the geological survey method, integrated seismic wave reflection method (TSP, TRT, etc.), electromagnetic wave method (GPR, GPR, etc.), electrical method (high-resolution direct current method), and other methods conduct comprehensive prediction. According to the comprehensive prediction conclusion, the advanced prediction method is used to verify the comprehensive prediction conclusion. For water-rich layer, detection methods such as transient electromagnetic method (TEM) and tunnel-induced polarization (TIP) should be added to qualitatively locate and estimate the water-bearing structure and supplemented with information such as targeted drilling to detect water pressure to guide the design and construction.

B-level forecast: Based on the geological survey method, mainly seismic wave reflection method (TSP, TRT, etc.), and supplemented by electromagnetic wave method (GPR), electric method (high-resolution direct current method), etc., conduct comprehensive prediction. Adopting **probe** drilling method verifies the forecast conclusions. When it is found that the engineering geological conditions of the local section are complicated and rich in water, it is implemented according to the requirements of class A.

C-level forecast: Based on the geological survey method, the seismic wave reflection method is mainly used to detect the important geological (layer) interface, fault fracture zone, karst cave, or geophysical anomaly section by electromagnetic wave method and high-resolution direct current method. The drilling method is adopted to verify the prediction conclusion.

D-level forecast: Geological survey method is the main method, supplemented by seismic wave reflection method, and if necessary, geological radar and high-resolution direct current method can be used for detection, and **probe** drilling method can be used to verify the prediction conclusion.

In addition, for the coal seam gas, hydrogen sulfide and other harmful gas forecasts according to the tunnel situation select special equipment to carry out the forecast work.

Each type of advance forecasting technology has different characteristics in terms of scope of application, detection distance, and recognition accuracy. According to the geological and geophysical characteristics of the unfavorable geological bodies, the comprehensive advanced geological prediction technical system of the whole process of bad geology can be adopted, which is guided by geological analysis, combined with geology and geophysical exploration, drilling, combining inside and outside the cave, and combining different geophysical methods [8, 9].

The design documents for advanced geological forecast shall be prepared and shall include the following main contents [3]:

1. Tunnel engineering geology and hydrogeological conditions, highlighting the bad geology and special geotechnical, possible major engineering geological problems, and geological risks.

2. Classification of geological complexity.

3. The purpose of advanced geological prediction.

4. The design principle of advanced geological forecast and forecast scheme should (piecewise) forecast the content, method selection, and combination

of the different methods, technical requirements (the same kind of forecast method or overlap between the different forecast method length, hole angle and length, etc.), and in advance, when need should be of meteorological springs, important points and main water hole (flow rate is >1 L/s water point), such as rivers flow observations plan, technical requirement, etc.

5. Technological requirements for the implementation of advanced geological forecast (if necessary).

6. Safety measures for geological forecast work in advance.

7. The workload of geological forecast in advance and the time occupied by the working face.

8. Budget estimates for advanced geological forecast.

9. Other issues requiring explanation.

3. Comprehensive advanced geological prediction design example

3.1 Project overview and hydrogeological analysis

The typical geological disaster prone area of Chenglan railway in western Sichuan is an important part of China's railway "five vertical and five horizontal" planning network. The Yuelongmen tunnel, one of the landmark projects of the Chenglan railway, spans two areas of Anxian and Maoxian. The geological structure at the Longmenshan fault is particularly complex. The maximum depth of the tunnel is 1445 m, the length of the right line is 20,042 m, and the length of the left line is 19,981 m [14–16].

The Yuelongmen tunnel crosses the Longmenshan Central Fault Zone. The tunnel crossing section intersects the mountain range at about 60°. The Yingxiu-Beichuan fault develops multiple secondary faults in the tunnel area. The Guangtongba fault and Gaochuanping fault that the tunnel passes through belong

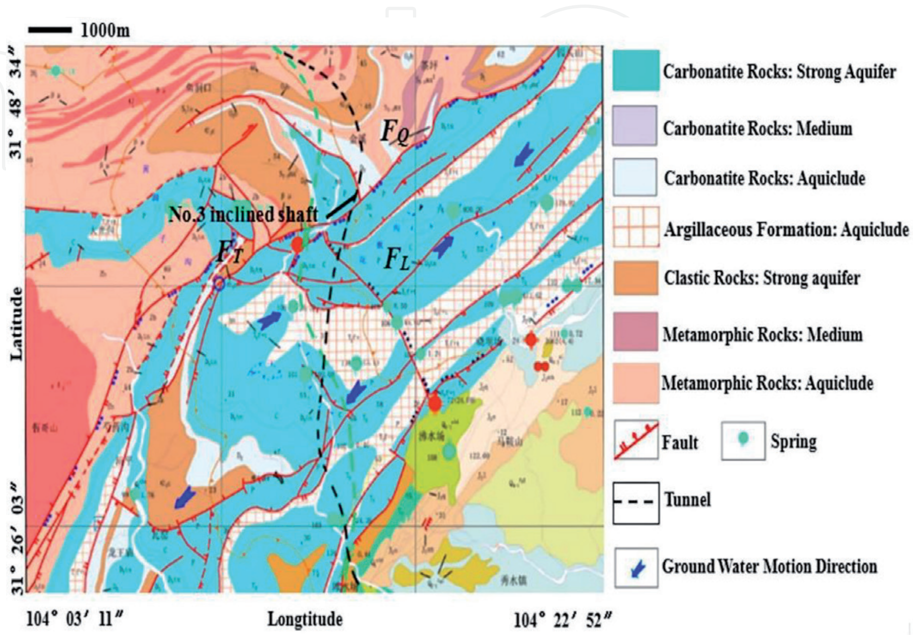

Figure 3.
Hydrogeological plan of the tunnel area of Yuelongmen tunnel.

to its secondary faults. The tunnel also passes through the Qianfoshan fault, the Qianfoshan No. 1 fault, and the Tujiamiao fault. A number of intermountain rivers are developed in the survey area, which is crossing three watersheds. The main surface water in the survey area is intermountain trench water, which is mainly replenished by atmospheric precipitation and partly by bedrock fracture water. The hydrogeological plan of the tunnel area is shown in **Figure 3**.

3.2 Tunnel advanced prediction design

According to the geological survey analysis and comparison of the geological hazard degree classification (**Table 1**), it can be determined that the XJ3K0 + 000–XJ3K0 + 396 segment of the Yuelongmen tunnel should be detected by the class A method of the advanced forecast design, and the seismic wave reflection method (TSP, TRT, etc.) and electromagnetic waves are comprehensively adopted. Methods such as geological radar (GPR, etc.) and electric method (high-resolution direct current method) are used for prediction, and **leading** target drilling is performed to verify the geophysical results.

3.3 Implementation of comprehensive geological prediction in typical water-rich section

3.3.1 Geological analysis of 3# inclined shaft in Yuelongmen tunnel

The 3# inclined shaft of Yuelongmen tunnel is located at the interface of D2K97 + 700 on the left side of Yuelongmen tunnel. The whole field is 2025 m, and the maximum buried depth is 872 m. The location is a more weathered hilly landform, overlying the Quaternary Holocene alluvial pebble soil, silt-splitting layer silty clay, slope residual coarse breccia, breccia, and block stone. In the lower Devonian system, the Wushan group is a dolomitic limestone, the first subgroup of the Silurian group of the Silurian, the Carboniferous phyllite limestone, and the black carbonaceous slab of the lower Longmaxi group. There are also interbedded with thin-layer siliceous rocks, Ordovician Zhongtong Baota Formation marl, crystalline limestone, Cambrian Qingqing Formation limestone, siltstone, apatite, Sinian Lower Juejiahe Formation Siliceous rocks, shale, carbonaceous shale, limestone, dolomite, and fault breccia. Among them, the XJ3K0 + 396–XJ3K0 + 273 segment is dominated by the Cambrian Qingping Formation limestone, and the rock is hard, but the karst is moderately strong, the joints are developed, and the surrounding rock is broken. Therefore, when the 3# inclined shaft of Yuelongmen tunnel digs into XJ3K0 + 396, water inrush occurs, and the amount of water inflow is about 1000 m^3/h.

3.3.2 Comprehensive advanced geological prediction analysis

In order to understand the geological conditions in front of the tunnel face, the TSP method is used to make a large-scale preliminary judgment on the geological body in front of XJ3K0 + 393. The prediction conclusion is that the whole section of XJ3K0 + 393– + 273 is hard but is formed by karst development. The rock is relatively broken, and there is more water between the cracks of XJ3K0 + 393– + 379, XJ3K0 + 374– + 354, and XJ3K0 + 344– + 330. Based on the TSP prediction conclusion and the geological analysis (**Figure 4**), the 3# inclined well fracture of Yuelongmen tunnel is developed and is water-rich. The geological radar method is used to focus on the location, scale, and development of the fracture. The induced polarization method and transient electromagnetic are used. The method carries out detailed detection of the water-rich position and scale of the rock formation.

Comprehensive analysis of TSP, geological radar, transient electromagnetic, and tunnel-induced polarization detection results combined with the geological conditions of the tunnel can be an accurate quantitative judgment of the geologic body in front of the XJ3K0 + 393 face: in general, the front of the face. The surrounding rock within 47 m is generally poor, and the fracture is developed and rich in water, but the water-rich area is uneven. The full section of 0–15 m in front of the face is almost rich in water, while the main middle left side of 16–30 m is rich in water; the 31–47 m side is rich in water in the middle right side. Using the different data of the induced polarization half-life, the estimated static water reserve within 70 m in front of the face is 700 m^3. In order to further verify the geological and water-rich conditions in front of the face, further advance drilling operations were carried out. Comparing the three detection results, it is found that the three detection methods are consistent with the prediction results of the water body. In particular, the polarization method not only determines the spatial position of the water body but also determines its distribution pattern, which can guide the drilling operation well [17–19].

3.3.3 Advanced targeted drilling detection

According to the comprehensive prediction conclusion, four **probe** drill holes were applied at the face of the face to verify the comprehensive geophysical findings. The **probe** drilling position is shown in **Figure 5**.

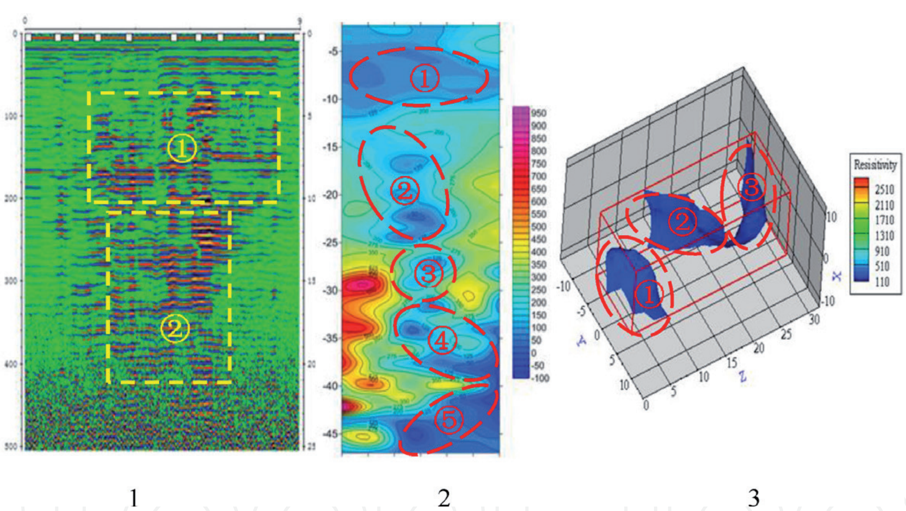

Figure 4.
Comparison of detection results. (1) Geological radar detection results; (2) transient electromagnetic detection results; (3) excited excitation detection result (hole body range extraction map).

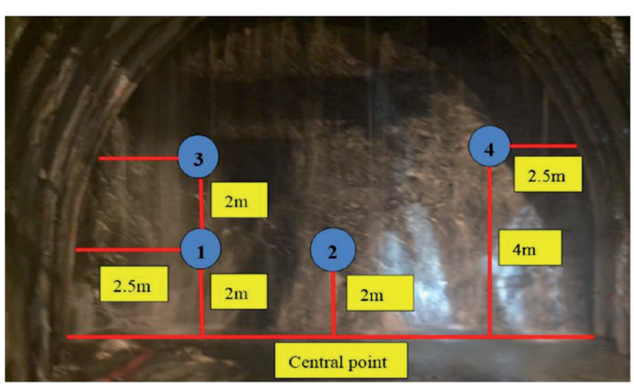

Figure 5.
Position of the lead drilling hole.

The verification of the on-site lead drilling indicates that the forecast results are in good agreement with the drilling results and the water-bearing structures predicted in the forecast conclusions are also verified by the disclosure. The forecast results also optimize the location and quantity of targeted drilling, which not only reduces the number of boreholes for the construction unit but also effectively covers the detection of unfavorable geology.

3.3.4 Excavation result verification

During the excavation of the tunnel, XJ3K0 + 393–XJ3K0 + 378 paragraph, the water surge appeared in the middle and lower part of the face, and a certain depth of water appeared in the bottom plate. In the XJ3K0 + 377–XJ3K0 + 368 paragraph, there is water in the left and middle of the face, and there is water in the XJ3K0 + 367–XJ3K0 + 363 section. The water inflow has an increasing trend (**Figures 6** and 7). The distribution of water content in rock mass is almost always consistent with comprehensive advanced geological prediction, which confirms the accuracy of comprehensive advanced geological prediction.

3.4 Tunnel construction measures

The results of comprehensive geophysical exploration combined with geological analysis and advanced targeted drilling show that there are no large caves or karst pipelines within the effective geophysical range and the main unfavorable

Figure 6.
Water inrush in the tunnel after the advanced drilling.

Figure 7.
Water inrush after tunnel excavation.

geology is dominated by bedrock fissure water. The geological integrity of the surrounding rock in front of the face is poor; the bedrock fissure is relatively developed and rich in water. Therefore, according to the requirements of tunnel construction safety, quality, schedule, and environmental protection, the Yuelongmen tunnel 3#, the sloped limestone water-rich section changed the original "full-section curtain grouting" to "advanced peripheral grouting" treatment measures, which not only saves time and effort but also speeds up the progress of the project.

Through the implementation of **leading** peripheral grouting measures for the 3# inclined well water-rich section of Yuelongmen tunnel, the risk of inrush water was effectively reduced, and remarkable results were obtained, ensuring the safe and orderly construction of the tunnel.

4. Development and prospect of advanced geological prediction technology

At present, the location, scale, and distribution of most unfavorable geological bodies have been detected by corresponding technologies, but it is still impossible to determine the rock mechanic properties of unfavorable geological bodies, the detection range is mostly limited to two-dimensional plane, the detection effect is not ideal in complex environment with large disturbance, the construction area is occupied and the time-consuming is longer, etc., which are still urgent problems to be solved in the field of advanced forecasting and detection. In addition, the development direction of future advanced geological prediction technology is the ultra-long **leading** horizontal drilling technology, the advanced geological prediction method while drilling, the fine imaging technology of multi-physical field information joint inversion, the quantitative technology of advanced prediction, the real-time advanced prediction technology, and the intelligent interpretation technology of advanced prediction [20–23]. At the same time, in order to obtain more accurate quantitative information in the tunnel, it is necessary to combine advanced geological prediction and surface exploration technology; use aviation electromagnetic exploration technology and system and intelligent geologic deep drilling; adapt to complex environmental geophysical techniques as breakthrough points; and form the comprehensive exploration and prediction technology that includes space-borne remote sensing, airborne exploration, and surface geophysical exploration and intelligent drilling. These could improve the ability of obtaining geological information and provide guidance for safe and efficient tunnel construction.

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