Application of Comprehensive Survey Technology in Karst Tunnel

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Abstract. Karst formations and karst water-related issues significantly impact the construction and operation of tunnels that traverse mountainous karst regions. Therefore, developing technical methods to identify the patterns of karst development and the groundwater environment is a key focus in the exploration and assessment of mountainous tunnel projects. This article presents a case study of a karst tunnel that crosses mountains in the western region, highlighting the application of advanced technologies such as cross-hole geophysical exploration and tracer testing. By integrating geophysical exploration with drilling and employing comprehensive survey techniques supported by preliminary and construction surveys, the study successfully identified the rock formations, karst features, and karst water characteristics in the tunnel site area. This approach effectively avoided hidden river channels and provided warnings regarding areas prone to karst fragmentation and collapse. The comprehensive survey technology has enhanced detection techniques for groundwater runoff and aquitards in mountainous karst tunnel regions. Case verification demonstrates that this method is clearly worthy of promotion. However, it does have limitations, including challenges in quantifying groundwater runoff, high costs associated with comprehensive detection, and the need for further research to innovate instrument design and achieve a more integrated technological approach.

Keywords: Comprehensive Survey Technology; Mountainous Karst Tunnel; Groundwater

1 Introduction

The karst region in the western mountainous area comprises more than one-third of the total land area. Tunnel construction in this karst environment faces significant challenges due to the presence of karst formations and karst water. During construction, tunnels often experience issues such as karst collapses, the formation of karst caves, and the influx of muddy water. Additionally, problems like water leakage and side wall failures can occur during tunnel operation. Identifying and mitigating the pathways of karst and karst water is crucial for the successful investigation of karst

W. Nie et al. (eds.), *Proceedings of the 2024 6th International Conference on Hydraulic, Civil and Construction Engineering (HCCE 2024)*, Atlantis Highlights in Engineering 37,
https://doi.org/10.2991/978-94-6463-726-7_14

tunnels. This paper summarizes the comprehensive investigation techniques employed in the geotechnical assessment of the Tunnel in the western mountainous area, focusing on the karst tunnel challenges in western china.

Major survey institutes and numerous scholars are actively exploring survey methods for karst tunnels, examining them from various perspectives. Liu Qian and colleagues discussed the selection of routes and survey points for karst tunnels in mountainous regions, focusing on hydrogeological issues. Sun Zhongke proposed utilizing cross-hole CT and tube wave testing technology to detect karst distribution[1]. Du Yuben and others suggested selecting the spatial location of tunnels based on the angle of the groundwater circulation zone[2]. Fu Kailong and his team analyzed the phenomenon of water inrush in karst tunnels and summarized key considerations for tunnel survey and design[3]. Li Guangwei examined the five major types of karst and proposed principles for route selection in karst areas[4]. Shi Wei and colleagues attempted to accurately detect karst formations using sonar techniques. Jiang Guanghui employed artificial tracing technology to investigate the replenishment and drainage of karst water[5]. Scholars have concentrated on the application of a single method, often overlooking the exploration of new techniques to address engineering challenges associated with the interaction between rocks and water. This article examines the advantages and contextual background of various methods relevant to the project and develops comprehensive survey techniques tailored to specific projects.

2 Project Overview

2.1 Geological Structure

The site is influenced by both the mountain structure and the Huaxia structure. The geological conditions at the site are relatively complex, with the geological structure oriented in a northwest direction. The area exhibits significant folding, characterized by the axis of the Bajiao synclinal core, which trends northwest at an angle of 50°. The southwest wing is oriented between 350° and 75° with a dip of 13° to 67°, while the northeast wing ranges from 220° to 252° with a dip of 10° to 65°. The tunnel traverses diagonally across eight sections, entering from the northeast wing and exiting through the southwest wing.

2.2 Stratum Lithology

The rock layers found in the tunnel site area include limestone, sandstone interbedded with limestone, mudstone, and shale.

2.3 Karst Characteristics

The density of karst depressions is 5.75 per square kilometer, with karst skylights varying in diameter from 15 meters to 50 meters and in depth from 30 meters to 60 meters, predominantly circular or elliptical in shape. Karst vertical shafts are typically located in the runoff sections of underground rivers and adjacent areas where these rivers emerge. Karst water primarily surfaces in the form of underground rivers and descending springs. There are 15 spring points exposed within the alternating rock layers at the base of the slope. At the outlet of the underground river, the water flow is approximately 100 liters per second during the normal water period and about 1 cubic meter per second during the rainy season.

3 Principles of Comprehensive Survey Technology

The investigation of karst tunnels that traverse mountains primarily focuses on detecting groundwater and analyzing rock formations. While traditional survey methods can accurately assess the rock mass quality in underground engineering, they are unable to measure the water resistance of karst water and rock mass without a stable water head.

The comprehensive survey technology integrates hydrological survey methods based on rock formation detection, with the results of rock mass and water body tests mutually supporting each other. The tracer test method introduces local water flow direction detection into the tunnel through regional groundwater tracking. After injecting a tracer into the surface water tunnel, samples are collected from the spring point and borehole to analyze the groundwater runoff layer. Simultaneously, CT scanning and comprehensive logging are conducted in the borehole to study the integrity and permeability of the aquitard, as indicated by the geophysical results.

4 Application of Comprehensive Survey Technology

In order to address the challenges associated with the tunnel, the characteristics of the karst landscape, karst water, and aquifer at the tunnel site have been thoroughly assessed. The exploration of the tunnel employs an integrated exploration technology that includes geological mapping, geophysical exploration, drilling, cross-hole CT tracer tests, hole pressure water tests, palm surface HSP sound wave[6] analysis, and advanced horizontal drilling techniques.

4.1 Geological Mapping

Geological mapping serves as the foundation for investigating karst areas. The tracing method and traversing method are employed to conduct engineering geological mapping. To address the challenges posed by steep terrain, geological mapping has incorporated UAV airborne radar scanning and three-dimensional laser scanning technology to identify geological features such as surface depressions, water caves, and spring points. The integration of human and machine efforts not only saves time but also provides a more comprehensive, detailed, and accurate understanding of geological information[7].

The engineering geological plan for the Tunnel site is developed by organizing and mapping the adjustment points. Geological information, including stratigraphic boundaries, formation occurrences, tectonic limits, surface depressions, and spring points, has been collected.

4.2 Engineering Geophysical Exploration

On the basis of the engineering geological plan, two primary geophysical profiles are established along the 20-meter sides of the tunnel axis to further investigate the rock mass structure at the tunnel site, as well as the mudstone and sandstone horizons of the water-barrier layer. In conjunction with the working principle, the magnetotelluric method (V8) has been selected for geophysical exploration[8].

The results of the geophysical interpretation (figure 1) on both the left and right sides of the tunnel axis indicate that the resistivity properties of the rock mass within five times the diameter of the first half of the tunnel differ significantly from those of the overlying rock. The height of the inferred water barrier layer on the left side varies from that on the right side. Additionally, the surface of the inferred water barrier layer is spherical. Further verification confirms that the front section of the tunnel is located within the synclinal core, and there is a water barrier layer above the tunnel plane.

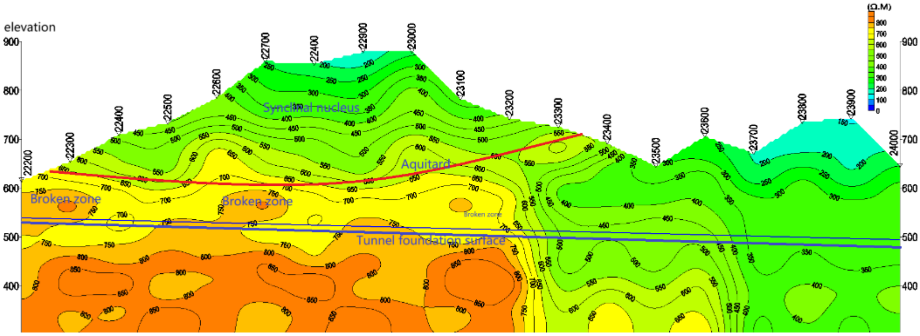

Fig. 1. Interpretation diagram of tunnel axis using magnetotelluric method

4.3 Geological Drilling

Geological drilling is the most traditional and fundamental method of exploration, while core drilling serves as the most direct verification of geological mapping and geophysical exploration results. With ongoing advancements in science and technology, geological drilling has evolved into a multi-purpose technique, enabling comprehensive logging, water pressure testing, and cross-hole CT detection to be conducted within the borehole.

Based on the progress of the geological study of the tunnel, four deep boreholes were arranged in the high-resistance dense area of the tunnel's front section, with a spacing of 80 meters between them. The geological investigations clearly revealed the presence of karst cavities, fracture zones, and waterproof layers, thereby fully validating the results of the geophysical exploration and ground adjustments. Comprehensive logging, including a pressure water test (detailed below), was conducted in the boreholes to measure the physical and mechanical properties at key locations. Additionally, computed tomography (CT) detection was performed to identify the runoff sections of karst water and underground rivers.

4.4 Pressure Water Test

The engineering geology and hydrogeological conditions of the tunnel are thoroughly analyzed. A water pressure test is conducted in the fracture zone of the tunnel roof and within a range of five times the diameter of the borehole, utilizing a drill pipe as the working pipe. The permeability of the rock mass in the test section is calculated using Formula 1, in accordance with the Test Rules for Drilling and Pressing Water in Hydropower and Hydraulic Engineering[9]. Additionally, the permeability characteristics of the rock mass in the test section are compared under various pressure conditions. Formula 2 is employed to determine the permeability of the rock mass in the test section at a pressure stage of 1.00 MPa.

$$q = Q_{\max} / \left(L \times P_{\max} \right) \tag{1}$$

$$q = Q_3 / \left(L \times P_3 \right) \tag{2}$$

According to the project's requirements, four sections within the depth range of 220 to 255 meters were selected to conduct pressurized water tests. The results of these tests are presented in Table 1.

Table 1. Pressure water test results table

Trial number	Trial depth (m)	lithology	Curve type	Waterpermeability (Lu)
1	220.0～225.0	Limestone mixed with mudstone	C	4.2
2	230.0～235.0		D	3.1
3	240.0～245.0	mudstone	E	1.3
4	250.0～255.0	limestone	C	5.4

The results indicate that the mudstone at the top of the tunnel exhibits strong integrity and low water permeability, making it a relative water barrier layer and a crucial component influencing the groundwater environment.

4.5 Tracer Test

The underground structure and configuration between the inlet and outlet of the underground river remain unclear due to the numerous drainage tunnels located in the upper reaches of the underground river system (recharge area). To address this issue, a tracer test is conducted to identify the interconnected distribution of rivers and karst pipelines within the system. This test will also facilitate the calculation of groundwater flow rate and direction, as well as the determination of the boundaries of the underground river system.

The tracer test (figure 2) is widely utilized in hydrogeological investigations. Sodium fluorescein, Rhodamine B, and ammonium molybdate are among the most commonly used tracers today. This method offers high accuracy in tracer element detection, is well-established, and is both environmentally friendly and cost-effective. For the demonstration test in this project, ammonium molybdate was selected.

The ammonium molybdate released at the skylight (WD01) in the upper part of the tunnel exhibited a significant curve at the underground river outlet (DJ01). Twelve to fifteen hours after the release of ammonium molybdate, the receiving point displayed a noticeable peak value. The distance from the skylight to the underground river outlet is approximately 1.5 km, and the water runoff velocity in the underground river pipeline in this section ranges from 100 to 125 m/h.

Based on the results of geological mapping, engineering geophysical exploration, and tracing tests, a groundwater drainage model for the tunnel site has been established.

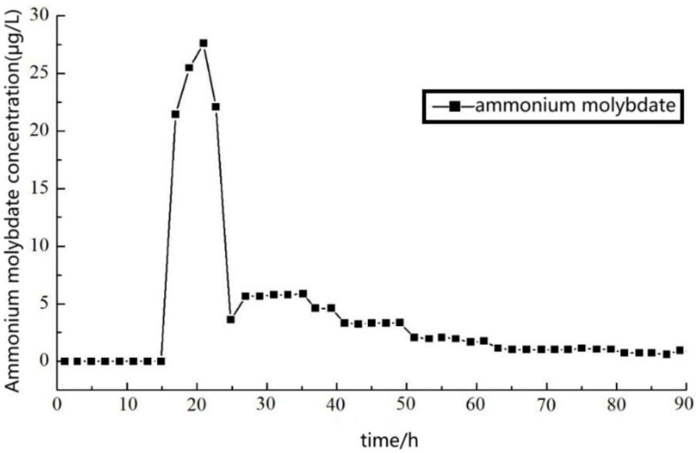

Fig. 2. Results of ammonium molybdate tracer at receiving point

4.6 Survey Conducted During the Construction Period

HSP acoustic reflection method is a forecasting technique that employs both time domain and frequency domain analysis to detect reflected wave signals. It utilizes the current geological conditions of the tunnel's face to predict the geological conditions ahead of the parallel tunnel construction. This method enables the detection of the scale, nature, and extent of potential faults, rock mass fracture zones, karst formations, and underground rivers in front of the tunnel face.

Combined with the results of surface geophysical imaging and the HSP acoustic reflection method, advanced horizontal drilling was conducted on the upper, left, and right sides of the palm surface within the fracture zone or water-rich section. The tunnel was probed using horizontal drilling in the suspected water-rich area before excavation. The length of the horizontal drill pipe is 20 meters.

5 Analysis of Survey Results and Highlights

Through detailed geological mapping of the surface, various geological features such as surface caves, underground river inlets, spring dew points, and stratigraphic boundaries are identified. By analyzing the differences in wave velocity between borehole data and laboratory rock tests, geophysical data are interpreted to accurately delineate internal water barrier layers and their thicknesses[10]. The use of tracers enhances the prediction of underground river pathways and allows for a precise understanding of the permeability characteristics at different depths, in conjunction with borehole pressure test results. This comprehensive approach provides reliable investigation data essential for selecting underground water sources and assessing the foundation surface of the tunnel.

As part of the verification and enhancement of the investigation during the design phase, the construction stage investigation adds an additional layer of protection for the safe excavation of the tunnel. By comparing the geological data from the excavation face during construction with the geological profile established during the design phase, the preliminary work on the Tunnel ensures accuracy in the stratigraphic survey of the rock formations and the identification of the water-barrier layer. Utilizing the HSP acoustic reflection method and advanced horizontal drilling techniques allows for a more intuitive detection of any fractured zones ahead of the tunnel and the presence of water accumulation in the upper layers. This approach addresses the limitations of point and plane investigations conducted earlier, accurately determining the geological conditions of the unexcavated section in front of the face and providing essential data to support the dynamic design of the tunnel.

6 Conclusion

The Tunnel has been safely constructed and has been open to traffic for two years, during which no water leakage or other issues have been reported in the tunnel across two natural hydrological years. The implementation of comprehensive survey technology in the karst tunnel has proven successful.

In steep, densely vegetated terrain, the use of airborne radar is more accurate and efficient than traditional manual geological mapping, making it a valuable method to promote in mountainous regions.

Design surveys and construction surveys collaborate and validate one another, enabling the acquisition of detailed engineering geological information. This process verifies the crushing zone and the upper stagnant zone, providing essential data for the dynamic design of the tunnel.

The critical and challenging aspect of tunnel investigation in karst regions is the identification of karst formations, karst water, and associated water barrier layers. The use of comprehensive survey technology can provide precise and efficient basic data for tunnel design.

Acknowledgment

This work was supported by China Geological Survey Project [NO. DD20230133]

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