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Research Status of Advanced Prediction for Water and Mud Inrush in Karst Tunnels

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Abstract: In the construction of tunnel engineering, adverse geological disasters such as water and mud inrush are frequently encountered, which tend to cause severe consequences including construction delay, casualties and economic losses. Therefore, it is crucial to conduct advanced prediction of water and mud inrush disasters. This paper summarizes the failure mechanism of water and mud inrush in tunnels and analyzes its influencing factors. Commonly used advanced prediction technologies and methods for tunnel water and mud inrush are introduced in detail, including the TSP geological prediction method, ground penetrating radar (GPR), infrared water detection, terrestrial sonar method, and transient electromagnetic method. According to the applicability and accuracy of these advanced prediction technologies, their specific applicable engineering conditions are summarized. Based on the latest theories and methods for water and mud inrush testing, cutting-edge achievements in water and mud inrush prediction are presented. New detection methods such as CT technology, nuclear magnetic resonance (NMR), and multi-homogeneous source array resistivity detection are elaborated in detail.

Keywords: Tunnel Engineering, Water and Mud Inrush, Advanced Prediction.

1. Introduction

Since the beginning of the 21st century, human science and technology have reached a new peak. With the explosive growth of the world population, human beings are facing increasingly severe challenges. Problems such as crowded living space and traffic congestion have become more serious, and the demand for transportation infrastructure is also increasing rapidly. To address these issues, engineering construction in China has shifted toward the development of underground space and the construction of urban subways. The development and utilization of underground space is an important measure to alleviate the shortage of urban transportation resources and is crucial to China’s sustainable development strategy.

China has the largest number of tunnels and underground engineering projects in the world, with the fastest development speed and the most complex geological and structural conditions [1]. As an important transportation infrastructure, tunnels can effectively relieve traffic congestion and improve transportation efficiency and safety. China has a vast territory and complex terrain with numerous natural topographical obstacles such as mountains and hills. Tunnels can cross these obstacles to connect different cities and promote economic development and exchanges.

At present, tunnel construction projects in China mainly include mountain highway tunnels, urban subway tunnels, tunnels for military and civil air defense projects, as well as national strategic tunnels such as those for the South-to-Northorth Water Diversion Project and the West-to-East Gas Transmission Project. Among them, railway and highway tunnels are the most extensively constructed and encounter the most complex engineering environments. By the end of 2023, there were 18,573 railway tunnels in operation with a total length of approximately 23,500 km; the total operating length of high-speed railways exceeded 45,000 km, with 4,561 high-speed railway tunnels completed, including 115 extra-long tunnels longer than 10 km and 13 extra-long railway tunnels longer than 20 km with a total length of about 312 km [2].

As more than two-thirds of China’s land area is mountainous, karst is well developed and soluble rock strata account for one-third of the total national land area. Karst is particularly developed in southwestern regions such as Yunnan, Guizhou and Sichuan, posing great challenges to tunnel construction. In recent years, with the implementation of the Western Development Strategy and the advancement of the Belt and Road Initiative, tunnel construction in China has gradually shifted to western mountainous and karst areas with extremely complex topographic and geological conditions, showing a development trend characterized by large buried depth, long tunnel lines, high in-situ stress, strong karst development, high water pressure, complex structures and frequent disasters [3]. Karst has become the major geological hazard in the safe construction of major underground engineering projects in China, and karst water and mud inrush has gradually become a bottleneck restricting the construction of major underground engineering projects in China [4].

Water and mud inrush, rock burst, large deformation, collapse, high geotemperature and harmful gases are the main types of engineering hazards during tunnel construction. Statistics on the proportion of various hazards in total accidents show that water and mud inrush and collapse are the two most common types in tunnel construction, with water and mud inrush accounting for approximately one-third of all accidents [5]. Due to the characteristics of high in-situ stress, high water pressure and large buried depth in tunnels, water and mud inrush, once it occurs, develops extremely fast and is very likely to cause casualties and equipment damage. For example, on September 10, 2002, an explosive mud inrush occurred suddenly at the Yuanliangshan Tunnel. The tunnel face burst open at 14:30, ejecting a large amount of hard plastic to plastic clay. Within 30 seconds, mud inflow filled the lower pilot tunnel with a volume of 4,200 m^3. The huge scale and rapid speed of mud inflow killed 9 construction workers [6]. On June 10, 2018, a water and mud inrush event occurred at the exit of the Chaoyang Tunnel on the Guiyang-Nanning High-Speed Railway. A large amount of muddy water gushed out for approximately one hour, with a total volume of about 1.6×10^6 m^3, directly causing 2 deaths, damaging about 50 mu of cultivated land and polluting about 20 residential houses [7]. Similar water and mud inrush disasters frequently occur in tunnel construction. According to statistical data, within only 10 years of the 21st century, geological disasters caused by tunnel water and mud inrush accounted for 77.3% of those in China's large-scale project construction [8].

During tunnel construction in karst areas, unpredictable geological hazards such as water and mud inrush can lead to severe consequences, even tunnel abandonment or route relocation, resulting in huge economic losses and waste of resources. To ensure the construction safety of karst tunnels, accurate and timely advanced prediction of the development of karst fissure water and adverse geological bodies is a key issue urgently to be studied and solved in the design and construction of tunnels in karst areas [9].

2. Research Status of Failure Mechanism of Water and Mud Inrush

Research on the mechanism of water and mud inrush remains a challenging issue in tunnel construction. At present, scholars and experts worldwide have conducted in-depth investigations on the mechanism of water and mud inrush using theoretical analysis, numerical simulation, field tests and other methods, and have achieved a series of important results.

Ribicic [10] first proposed the concept of the thickness of the relative water-resisting layer. By considering the relationship between water pressure and the thickness of the water-resisting layer, he discussed the variation of stress distribution with mining methods and local geological conditions, and evaluated the risk of water inrush based on stress changes. C. Faria Santos and Z. T. Bieniawski [11] introduced the concept of the critical energy release point to interpret the long-term strength based on the modified Hoek-Brown rock mass strength criterion, and analyzed the bearing capacity of mine floor strata. Ma et al. [12] studied the effect of fine particle migration in fractured sandstone on water inrush under different porosity, particle size distribution and water flow pressure conditions. They found that fine particle migration significantly promotes the increase of permeability and porosity, revealing the meso-mechanism of water inrush induced by particle migration. Fu et al. [13] established a working face water inrush prevention model and a roof water inrush prevention model. Based on the limit equilibrium method, they derived a theoretical formula for the minimum safety thickness, and found that the minimum safety thickness increases with the increase of fault size, water pressure and tunnel diameter. When the fault size exceeds a critical value, its influence becomes negligible. Guo et al. [14] simulated the evolutionary process of water inrush using a new method based on DEM and fracture modeling. The results show that the water inrush resistance increases with the increase of the thickness of the water-resisting rock mass, and the failure mode of the tunnel gradually changes from overall collapse of the vault to local collapse, forming a relatively stable collapse arch.

Many Chinese scholars have also carried out detailed studies on adverse geological disasters such as water and mud inrush in tunnels. Weng [15] took the Yonglian Tunnel as the engineering background, and simulated the evolution laws of the stress field, displacement field and seepage field during tunnel excavation into the fault zone. The results show that poorer surrounding rock grade, higher groundwater level and better surrounding rock permeability are more likely to trigger water and mud inrush disasters. Li et al. [16] conducted statistical analysis on 221 cases of water and mud inrush disasters, and classified them into three categories: karst type, fault type and other genetic types. Four typical disaster-inducing modes of water and mud inrush were proposed: direct exposure mode, progressive failure mode, seepage instability mode and intermittent failure mode, which laid a foundation for the study of disaster-causing mechanisms of water and mud inrush. Wang et al. [17] studied tunnel excavation through laboratory model tests, and analyzed the variations of pore water pressure and earth pressure at the vault, spandrel and haunch before and after the disturbance of fault rock mass. The mechanism of fault water inrush was further analyzed using Comsol software from the perspective of permeability variation, providing a reference for the study of water and mud inrush mechanisms in tunnels. Huang et al.[18] developed a comprehensive test system for filling medium deposition and intermittent water and mud inrush in karst caves, and analyzed the catastrophic processes of intermittent water and mud inrush caused by dredging and rainfall. The results can provide a theoretical basis for the prevention and control of intermittent water and mud inrush disasters in karst tunnels. Yang et al.[19]investigated the shear instability mechanism of the water-inrush prevention rock mass at the tunnel face by theoretical analysis and numerical simulation. It is found that water and mud inrush in tunnels crossing fault fracture zones is essentially induced by the changes of stress field and seepage field of surrounding rock in fault fracture zones under construction disturbance.

3. Research Status of Advanced Prediction for Water and Mud Inrush

Once water and mud inrush disasters occur in tunnels and underground engineering, they will not only cause heavy economic losses to project construction, but also lead to project delays, environmental pollution, and even serious casualties. In 1988, sudden water inrush occurred during the construction of the Dayaoshan Tunnel, the largest double-track railway tunnel in China, submerging more than 200 meters of the tunnel and suspending construction for as long as one year. In May 1990, two more water and sand inrush incidents happened inside the tunnel, resulting in the suspension of the Beijing-Guangzhou Railway line, with enormous economic and social impacts [20]. In 2006, a severe water and mud inrush disaster occurred in the Malujing Tunnel of the Yiwan Railway, killing 11 people and injuring 3 others [21]. Therefore, it is of great significance to conduct research on advanced prediction of water and mud inrush in tunnels so as to reduce economic losses, avoid casualties and ensure social stability.

As the construction of tunnels and underground engineering started earlier abroad, many scholars have been conducting relevant research since the initial stage of tunnel construction. In China, research on advanced tunnel prediction began around the 1950s. With the development of tunnel construction in China, the Ministry of Science and Technology approved a special project under the National

Basic Research Program of China (973 Program) to address major water and mud inrush disasters in tunnels. Among them, the Geotechnical Research Center of Shandong University has long been engaged in advanced prediction of adverse geology and prevention of water and mud inrush disasters during tunnel construction, achieving abundant research results.

In the late 1950s, Japanese scholar Takahashi Hikoji first proposed a simple method for calculating water inflow during the construction of the Hokuriku Tunnel. In the late 1960s, Japanese scholars Ito Hiroshi, Sato Kuniaki and others carried out simulation experimental studies on water inflow prediction of subsea tunnels using indoor seepage tanks [22]; Soviet scholars V. I. ARVIN and S. N. NUMEROV proposed the complex velocity potential theory to calculate water inflow of strip seepage channels under water based on simulation test results [23]. Xue et al. [24] analyzed the mechanism of water and mud inrush in tensile faults, shear faults and compressional faults based on the cusp catastrophe model, established a potential function for water and mud inrush risk, and conducted prediction using the water inrush index obtained from the equilibrium equation of fault planes. Chen et al. [25] established the relationship between rock mass activity and MS signals during the evolution of water inrush disasters according to the MS characteristics of water inrush channels in different water inrush events, and predicted disaster occurrence based on MS signal variations. Lou et al. [26] developed a new method for detecting karst and groundwater using three-dimensional seismic waves based on seismic wave propagation dynamics theory, and established a simplified expression of rock mass stress response under seismic wave propagation and an evaluation formula for groundwater volume. This method can accurately reflect the variation of rock mass media and the existence of groundwater, improve the accuracy of advanced geological prediction in tunnels, and is of great significance for the advanced prediction of water and mud inrush.

Tunnel disaster prediction and forecast are divided into two aspects: prediction and pre-warning. Prediction refers to identifying karst-developed areas and determining dangerous sections prone to water and mud inrush based on hydrogeological theories. Forecast refers to directly applying geological detection methods (horizontal drilling, geophysical prospecting, ground penetrating radar, etc.) to detect the distribution of karst caves ahead of the construction tunnel face in these areas, and directly giving forecasts through intuitive detection of adverse geological conditions by instruments. At present, commonly used geological prediction technologies at home and abroad include the TSP geological prediction method, ground penetrating radar (GPR), infrared water detection, terrestrial sonar method, transient electromagnetic method, etc. [9].

Yuan Zhenxiu et al. [27] applied infrared detection technology to study karst development in the Yuanliangshan Tunnel and found that infrared detection can judge whether there are water-bearing structures ahead of the tunnel face, thus providing guidance for preventing tunnel water inrush. Shi Fusheng [28] proposed temperature gradient measurement to forecast tunnel water inrush. When tunnel excavation approaches a water-rich stratum, the rock mass is gradually cooled by low-temperature water sources, and temperature changes can be monitored by infrared thermometers, providing a prerequisite for water inrush prediction. Chen Lei [29]found that the accuracy of TSP prediction decreases with increasing distance, while the forecast distance of GPR is relatively short and greatly affected by engineering experience. Therefore, a comprehensive geological prediction method combining TSP and GPR detection assisted by advanced horizontal borehole water detection was proposed to investigate adverse geological characteristics of water-rich fault fracture zones. Jin [30]conducted advanced prediction of water and mud inrush in debris flow strata based on the reflection principle of seismic waves combined with seismic tomography. The results show that there are significant differences between seismic wave energy in water and mud inrush-prone sections and that in surrounding media.

4. Research Status of Advanced Prediction Technologies for Water and Mud Inrush

At the initial stage of research, advanced geological prediction in China mainly adopted methods such as advanced geological pilot tunnels and horizontal advanced drilling. These prediction methods were simple and crude, causing significant interference to tunnel surrounding rock and being gradually eliminated. To develop methods with less interference to the project and simpler prediction processes, people began to use geophysical prospecting to detect adverse geological bodies, such as radar and sonar detection. Later, the Ministry of Railways conducted research and improvement on various geophysical prospecting methods, and proposed a comprehensive geophysical prospecting method dominated by the "seismic reflection negative apparent velocity method" and "terrestrial sonar method", supplemented by ground penetrating radar (GPR) and horizontal acoustic profile method. Subsequently, HSP was further improved and CT imaging technology was developed. With the research and development of researchers, technologies such as TSP (Tunnel Seismic Prediction), reflected seismic wave CT technology, TRT (Tunnel Reflection Tomography) technology, ground penetrating radar, and terrestrial sonar have been successively applied to the advanced prediction of water and mud inrush by engineering personnel. However, due to the complexity of the actual working environment and the limitations of technologies, the prediction accuracy of a single technology is not high. Therefore, it is necessary to conduct in-depth research on advanced geological methods and technologies to develop the optimal advanced geological prediction method. The 973 Program project led by the team of Academician Li Shucai from Shandong University has made important research progress on the "Disaster-causing Mechanism, Prediction, Early Warning and Control Theory of Major Water and Mud Inrush Disasters in Deep and Long Tunnels". It has achieved significant research results in aspects such as water and mud inrush disaster-causing structures and their geological identification methods, as well as advanced prediction methods of water and mud inrush, promoting the progress of water and mud inrush advanced prediction technology in China [31].

(1) Focus on the Theory and Method of Deep-Focusing Induced Polarization Advanced Prediction

This new method is based on tunnel advanced detection using multi-homogeneous source array resistivity. Li Shucai et al. [32] adopted multi-homogeneous sources arranged in a ring for power supply, which suppresses the interference signals behind the tunnel face and improves the detection sensitivity of distant abnormal bodies ahead of the tunnel face. By gradually moving the power supply electrodes towards the rear of the tunnel face, the electrode spacing is continuously increased, thereby realizing the detection and perception of water body information ahead at different distances.

(2) Full-Space Three-Dimensional Transient Electromagnetic Advanced Prediction Method

Li Xiu et al. [33] used transient electromagnetic data to perform rapid resistivity imaging by the equivalent conductive plane method, and took the imaging results as the electrical model for three-dimensional nuclear magnetic resonance (NMR) inversion for joint interpretation. Model data show that this method can accurately reflect underground three-dimensional water-bearing structures.

(3) Cross-Hole Resistivity CT Fine Detection Method

Li Shucai et al. [34] improved and developed the cross-hole resistivity CT fine detection method and proposed a combined observation mode. This mode can integrate the detection advantages of various conventional observation modes and increase the amount of data collection, thereby improving the ability to identify abnormal bodies. At the same time, through numerical simulation tests, the influence of hole spacing and electrode spacing on the detection effect was studied, and the effective hole spacing range and reasonable electrode spacing parameters under the combined observation mode were obtained.

(4) Multi-Source Geophysical Information Constrained Joint Inversion Method for Tunnel Water and Mud Inrush Disaster Sources

Li et al. [35] proposed a new comprehensive geological prediction method for water-bearing tunnel structures based on constrained inversion and comprehensive interpretation. According to the needs of advanced detection of water-bearing structures, four optimized prediction methods were selected: seismic reflection method, transient electromagnetic method, three-dimensional resistivity method, and ground penetrating radar method. On this basis, a three-dimensional resistivity constrained inversion method based on asymmetry and spatial structure constraints was proposed. Finally, by combining constrained inversion with comprehensive interpretation, a new set of comprehensive geological prediction technology system was established.

5. Conclusion

This paper summarizes the research on the prediction and forecast of water and mud inrush, an adverse geological disaster in karst tunnels, briefly introduces severe tunnel water and mud inrush disasters at home and abroad, and puts forward the importance of conducting water and mud inrush prediction and forecast.

The failure mechanism of water and mud inrush is introduced. Many scholars have found that the thickness of the water-resisting layer is related to the water inrush resistance of tunnel surrounding rock: the thicker the water-resisting layer, the stronger the water inrush resistance, and a stable arch structure is more likely to form after tunnel damage. The team led by Academician Li Shucai from Shandong University classified the water and mud inrush disaster-causing structures into three types: karst type, fault type and other genetic types, and also proposed four typical disaster-inducing modes of tunnel water and mud inrush: direct exposure mode, progressive failure mode, seepage instability mode and intermittent failure mode.

The technical means adopted by researchers in water and mud inrush prediction are introduced. At the initial stage of tunnel construction, most prediction methods adopted hydrogeological methods to identify karst-developed areas and determine dangerous sections prone to water and mud inrush. Later, with the development of technology, technical personnel began to use advanced geophysical prospecting methods such as TSP (Tunnel Seismic Prediction) geological prediction method, ground penetrating radar (GPR) detection method, infrared water detection method, terrestrial sonar method and transient electromagnetic method to directly detect adverse sections and conduct advanced prediction. At the same time, the new theories and methods of water and mud inrush advanced prediction from the 973 Program project led by Academician Li Shucai's team are introduced. By combining multiple prediction means, new prediction theories are proposed: 1. Theory and method of deep-focusing induced polarization advanced prediction; 2. Full-space three-dimensional transient electromagnetic advanced prediction method; 3. Cross-hole resistivity CT fine detection method; 4. Multi-source geophysical information constrained joint inversion method for tunnel water and mud inrush disaster sources. With the development of technology and the innovation of theories, more advanced geophysical prospecting means and prediction theories will be available for the advanced prediction of tunnel water and mud inrush in the future, and the accuracy will also be greatly improved.

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