Causes and hazards of perimeter rock cavities behind shield tunnels

Abstract: The purpose of this paper is to discuss the reasons for the generation of voids in the surrounding rock behind water transmission shield tunnels and the potential hazards they bring. Firstly, it analyzes in detail the possible causes of cavities from the aspects of geological conditions, construction technology, material properties, etc. On the basis of literature research, the causes and distribution patterns of the perimeter rock cavities behind the water transfer shield tunnels were explored with respect to the locations and sizes of the cavities behind the tube sheets. Secondly, it systematically elaborates the hazards of cavities on tunnels from the aspects of structural stability, use function, operation safety, etc. Finally, it proposes corresponding preventive measures and countermeasures for the problem of cavities. This paper aims to provide valuable reference for the design, construction and operation management of shield tunnels, which is of great theoretical significance and practical value for the safe construction and long-term operation of shield tunnels.

Keywords: shield tunnels; perimeter rock cavities; causes; hazards.

1. Introduction

Since the beginning of the twenty-first century, with the acceleration of urbanization, urban water supply systems are facing increasing pressure. China is encountering an urgent challenge: the extremely uneven distribution of water resources, which has led to water scarcity in some areas[1]. In order to effectively address this challenge, China has initiated and implemented a series of ambitious reservoir and water diversion projects. Among them, the Three Gorges Dam, as one of the world's largest water conservancy and power generation projects, has demonstrated China's strong determination and excellent capability in water resources management. Meanwhile, the Danjiangkou Dam, as a key component of the South-to-North Water Diversion Central Control Project, is of great importance. In addition, the Jinping-class hydropower dam, with its status as the world's tallest dam, once again proves China's outstanding achievements in the field of water conservancy technology. The South-to-North Water Diversion Project, the Dianzhong Diversion Project and the Tibet Water to Xinjiang Project are even more solid steps taken by China to optimize the allocation of water resources and achieve balanced regional development. These projects not only provide a strong guarantee for the effective utilization of water resources and sustainable development in China, but also fully demonstrate China's strong strength in water resources management and water conservancy project construction scheme. As an important part of urban water supply system, urban utility tunnels are widely used in urban water supply projects due to their unique construction advantages. According to the long-term operation of water diversion shield tunnels completed in China and the experience of railroad shield tunnel construction, a large number of problems have appeared in shield tunnels due to natural hydrogeology, preliminary design and construction, and later operation and management[2~4] . These problems have seriously affected the normal operation of tunnels and the safety of traveling in tunnels, among which, the emergence of cavities behind the tunnel lining tubes is a common problem. During the construction and operation of shield tunnels, the problem of cavities in the surrounding rock behind the tunnel lining has become more and more prominent, posing a serious threat to the structural safety and long-term stability of the tunnel. Studies[5, 6] have shown that the existence of cavities behind the tunnel lining affects the interaction between the structure and the ground, reduces the resistance of the surrounding rock and changes the amount and spatial distribution of the loads borne by the shield lining, leading to uneven structural stress and stress concentration, which further causes deformation of the tunnel structure, cracking, concrete falling and water seepage from the tubes and sheets, and so on. Therefore, an in-depth study of the causes and hazards of the peripheral rock cavities behind the water shield tunnel is of great significance to ensure the safe operation of the tunnel.

2. Reasons for the creation of voids in the surrounding rock behind water transfer shield tunnels

2.1 Geological and environmental factors:

As many tunnels are located in geologically complex areas, substances that are easily dissolved or corroded may be present in the surrounding rock or backfill behind the lining. Under specific environmental conditions, these substances are gradually dissolved or corroded, resulting in the formation of small cavities behind the lining[7]. Moreover, groundwater has a long-term erosive effect on tunnel lining structures, which mainly includes dissolution, freezing and thawing, and submerged corrosion. As the groundwater may contain a variety of dissolved substances, they will be chemical reaction with some components in the lining concrete, resulting in the gradual softening of the concrete, spalling, and then the formation of voids. At the same time, groundwater in the temperature change will occur freeze-thaw cycle, this cyclic action will produce damage to the concrete, exacerbating the formation of voids. Under the joint action of ground load and groundwater pressure, the tunnel lining structure may be subjected to uneven stress distribution, resulting in some parts of the stress concentration phenomenon. These stress concentration areas are prone to damage and cavity formation. In addition, the fluctuation of groundwater level may also produce cyclic pressure changes on the tunnel lining structure, aggravating the damage of the lining structure and the formation of cavities. In addition, in the process of groundwater flow, if the velocity of water flow is large, it will produce a scouring effect on the lining structure. This scouring action will continue to erode the lining structure, making it gradually thin or form cracks. With the aggravation of erosion, the lining structure will gradually lose the bearing capacity, and eventually total destruction.

2.2 Raw material factors:

Tunnel lining concrete is mixed from a variety of raw materials such as aggregate, cement, sand, etc., the quality of which has a great impact on the long-term stability of the tunnel. If the quality of raw materials is uneven, coupled with measurement errors, inadequate mixing and other factors, the concrete mix is prone to stratification and segregation, water secretion, dryness, slaking and other phenomena. All these problems may lead to voids behind the lining. In addition, the concrete itself has shrinkage characteristics, and if it is not handled properly during the initial support, it is easy to make the sprayed concrete and the rock surface can not be closely adhered to each other, resulting in gaps, and then forming voids.

2.3 Construction Factors:

In tunnel construction, if the drilling and excavation processes are not operated properly, voids will be formed in the tunnel. In addition, over-excavation backfill concrete backfill is not dense will also make the tunnel left with voids. If the lining demolding time is too early, and the maintenance conditions and time are not suitable, it will prevent the strength of the concrete from being fully utilized, with poor bearing and deformation resistance, and will easily cause cracks in the concrete, which may result in the formation of voids.

3. Distribution pattern of peripheral rock cavities behind water transfer shield tunnels

3.1 Positional patterns of voids:

Yu Dongyang[8] field investigation of 29 high-speed rail tunnel, behind the lining cavity mostly exists in the arch, arch waist and side wall position, the tunnel produces a cavity accompanied by crack expansion, the longitudinal length of the cavity is mostly distributed in 1 ~ 3 m, accounting for 87.3% of the total number of research samples. According to Zhang Danfeng's research[9] on 13 railway and highway tunnels, the arch of the tunnel is the key part of the caving, the number of caving arches and two arches accounts for 85% of the total, and the longitudinal length of the caving is mainly concentrated in 1~4 m. Zhou Shaowen[10] investigated 64 highway tunnels and found that the cavities behind the lining were mainly distributed in the arch, with radial depths of the cavities in the range of 15~40 cm, and longitudinal lengths of the cavities were mostly in the range of 1~3 m. The longitudinal length of the cavities was between 1~3 m. The majority of the cavities were in the range of 1~3 m.

Commonly in the location of the presence of voids accompanied by the phenomenon of grouting is not dense, lining wall cavity defects in many operational tunnels are more common[11], the distribution of voids may appear in the tunnel arch, arch shoulder, arch waist, side walls and other locations. The main reason for these locations to cause cavities is that the tube sheet and the surrounding rock did not form a close contact, at this point, the force state is severely weakened compared to the original close-fitting state.

3.2 Dimensional regularity of voids:

The cavity geometry study includes the cavity height, the longitudinal length of the cavity, and the cavity circumferential angle. Typical cavity geometric features can be roughly categorized into rectangular, triangular, circular arc and so on. Wang Wei et al[12] found that the size of voids on the Chengdu-Chongqing Line mostly obeyed the normal distribution, with the depth mainly within 20~30cm and the width mostly within 1~2.0m. Ren Ren[13] found that according to the detection of a passenger tunnel, the cavities behind the arch are mainly 8~24 cm, and the longitudinal length is mainly 3~6 m. Lai et al[14] carried out a geo-radar detection on the Xiaotigou Tunnel, and the lengths of the hollows within the measurement line are generally 1.5 m, and the frequency of the hollows with a length of 2~6 m is the highest. Ye Yichao[15] and others found that the frequency of hollows at the vault was higher according to the statistics of Fanjiagou Tunnel hollows, and the length of hollows was 1~4 m. The range of hollows was 8°~33°. Through the research and statistics of hollowing behind the lining, it is generally believed that there is the following pattern, the radial size of hollowing is mainly concentrated in 0.2~0.5 m, the longitudinal length is 1~5 m, and the depth distribution is 0.1~0.5 m. The depth of hollowing is 0.1~0.5 m, and the length of hollowing is 1~5 m.

4. Hazards of perimeter rock cavities behind water transfer shield

tunnels

The voids will cause a loss of equilibrium between the original lining and the soil, making the ground reaction force available from the soil reduced, and the stress concentration on the outside of the pipe sheet under the influence of the voids will occur, affecting the stability and durability of the structure.

4.1 Impaired structural stability:

Cavities in the surrounding rock behind water transfer shield tunnels can directly lead to impaired stability of the tunnel structure[16]. Cavities deteriorate the interaction between the lining structure and the surrounding rock, leading to localized stress concentrations. This stress concentration phenomenon not only causes cracks or cracking in the lining structure, but also may lead to problems such as structural bias and surface subsidence[17]. Especially under the influence of multiple factors such as traffic and groundwater in the tunnel, the existence of voids may further aggravate the destabilization of the surrounding rock, thus triggering the collapse of the tunnel. In addition, the existence of peripheral rock cavities can cause a series of associated diseases. Water can easily accumulate inside the cavity, forming a leakage water source, which will lead to the leakage of the lining structure in the long term. At the same time, the cavity may also accumulate harmful gases, which may pose a threat to the environment and the health of the workers in the tunnel. In addition, the cavity may also become a channel for the intrusion of erosion media, leading to the occurrence of concrete spalling, steel corrosion and other diseases. The frequent occurrence of these associated diseases will further aggravate the damage to the tunnel structure, affecting the normal use and operational safety of the tunnel.

4.2 Difficulty in rescuing accidents and social impact and economic losses:

Accidents such as landslides caused by cavities are often accompanied by gushing sand and mud, making rescue and relief work much more difficult. If the communication between the tunnel and the ground is not connected, the rescue work may be even more delayed, further aggravating the impact of the accident. In addition, the rescue process also needs to face a variety of complex geological environments and construction conditions, such as rich groundwater and complex strata, making the rescue work more difficult and dangerous. The hazards of peripheral rock cavities behind water transfer shield tunnels are not limited to the tunnels themselves, but may also have a wide range of social and economic impacts. On the one hand, accidents such as tunnel collapse caused by voids will directly affect the normal operation of urban transportation and water supply systems, bringing inconvenience to people's production and life; on the other hand, the treatment and repair of accidents need to invest a lot of manpower, material and financial resources, which will bring huge economic losses to the country and people.

To summarize, the hazards of peripheral rock cavities behind water transfer shield tunnels are multifaceted and serious. In order to guarantee the safe and stable operation of the tunnel and the safety of people's lives and properties, it is necessary to strengthen the detection and treatment of the surrounding rock cavities, and to find and eliminate the potential safety hazards in time. At the same time, it is also necessary to strengthen the quality management and supervision and inspection during tunnel construction and operation to ensure the quality and safety of tunnel construction.

5. Preventive measures and countermeasures

5.1 protective measure:

Before tunnel construction, carry out detailed geological investigation and assessment work to clarify the geological conditions, hydrogeological characteristics and possible geological risks of the area in which the tunnel is located. Using advanced technologies such as geological radar detection, acoustic wave detection and groundwater level monitoring, detailed cavity detection is carried out in the tunnel construction area to ensure that potential cavities are fully recognized before construction.

In the design stage, geological conditions are fully considered, and the tunnel lining structure and waterproofing system are reasonably designed to ensure that the tunnel is closely integrated with the surrounding rock.

During the construction process, the excavation method combining mechanical and artificial is adopted to reduce the disturbance to the surrounding rock and avoid the occurrence of over-excavation and under-excavation. For the area with water seepage on the rock surface, pre-buried drainage blind pipe before spraying concrete, and do a good job of centralized drainage measures to prevent the influence of water dispersion on the surrounding rock surface on the bonding of sprayed concrete and surrounding rock.

During tunnel construction and operation, establish a perfect monitoring and inspection system to monitor the changes of tunnel lining structure and surrounding rock in real time. For areas where voids may occur, equipment such as geo-radar is utilized for regular testing, so that potential safety hazards can be detected and dealt with in a timely manner.

5.2 Response:

As soon as a cavity is detected behind the tunnel, a detailed inspection and assessment is carried out using equipment such as geo-radar to determine the location, size and shape of the cavity and other key parameters. According to the detection results of the cavity, develop a corresponding treatment program. For smaller voids, the filling material infusion method is used for repair. By injecting filling materials such as cement and mortar, the cavity is filled and the integrity and stability of the tunnel structure is restored. For larger cavities, blasting reinforcement method or drilling and grouting method can be used for repair. Blasting reinforcement method destroys the loose soil layer or rock layer around the cavity by blasting, and then injects filling materials for reinforcement; drilling grouting method is to drill holes around the cavity and inject slurry into the cavity to fill and reinforce it.

While dealing with the cavity, the tunnel lining structure is reinforced and supported. Support measures such as steel frames and anchors can be used to enhance the stability and bearing capacity of the tunnel structure. For the lining structure that has cracked or cracked, timely repair measures are taken to prevent further expansion and deterioration of the cracks.

After the completion of the cavity treatment, continue to monitor and maintain the tunnel to ensure the long-term stability and safe use of the tunnel. Establish a perfect monitoring system to monitor the changes in the tunnel structure in real time, so that potential safety hazards can be detected and dealt with in a timely manner. Strengthen the maintenance and management work of the tunnel, and carry out regular cleaning, inspection and repair of the tunnel to ensure its normal operation and safe use.

6. Conclusion

To summarize, the prevention and countermeasures of peripheral rock cavities behind water conveyance shield tunnels need to comprehensively consider geological conditions, design and construction, material selection, monitoring and testing, and other aspects. By strengthening geological investigation and assessment, optimizing design and construction, selecting high-quality materials, establishing a perfect monitoring and testing system[18], and taking timely measures to deal with the situation, the safety hazards caused by the peripheral rock cavities behind the water transmission shield tunnels can be effectively prevented and dealt with.

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Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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