Analysis of Leakage Mechanism of Shield Tunnel Segment

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Abstract: With the rapid development of China's economic growth and increasing population, the construction of rail transportation infrastructure has entered a rapid development stage. However, due to the unique construction characteristics and complex storage environment of tunnel boring machines, tunnel diseases often occur. Among them, tunnel water leakage is the most common disease， which can not only directly cause damage to subway electrical systems and train stoppages, but also exacerbate the occurrence of other types of tunnel diseases, posing a serious threat to the safety of tunnel operations. Studying the leakage mechanism of tunnel water leakage is helpful for in-depth understanding of the formation reasons of water leakage, and then proposing more effective prevention and treatment methods. According to existing research achievements, we summarized and abstracted the leakage mechanism of tunnel water leakage caused by shield tunneling. The research mainly focused on three aspects: geological reasons, leakage mechanism analysis of shield tunnel lining during operation, and leakage mechanism analysis of shield tunnel lining during construction. The aim of the study was to provide useful reference for the development of tunnel waterproof materials, improving the performance and quality of tunnel waterproof materials, and thus better ensuring the safety and sustainable development of tunnels.

Keywords: Shield tunnel; Water leakage; Mechanism analysis.

1. Introduction

In most cities across China, metro systems are constructed in strata located below the groundwater table. In saturated soft soil formations, metro tunnels are subjected to various influences such as shield tunneling techniques, cyclic loads induced by metro operations, and heterogeneous soil distribution. These factors can lead to water leakage problems under the action of hydraulic pressure, which has become one of the most prevalent and critical issues affecting the operation of metro tunnels.

In response to the issue of water leakage in shield tunnels, scholars both in China and abroad have conducted a series of studies. Liu et al.[1] carried out inspections of segmental lining defects in four shield tunnels, including those of Shanghai Metro Line 1. The results indicated that water leakage, structural damage, and structural deformation are the most prevalent types of tunnel defects, among which the probability of water leakage is 2 to 5 times higher than that of structural damage. Dong et al.[2] conducted a statistical analysis on 112.7 km of shield tunnels across seven lines, including Beijing Metro Line 5. Their findings revealed that water leakage, voids behind the lining, slurry inflow, and segment cracking are the main types of defects, with water leakage accounting for as much as 64.95% of the total. Liu [3] examined the occurrence patterns of seven common defects in 41 typical sections across 12 metro lines in Beijing, including segment dislocation, water leakage, segment cracking, track bed cracking, track bed voids, tunnel ovalization, and concrete deterioration. The analysis showed that water leakage, dislocation, and track bed cracking are widely present in Beijing's shield tunnels, with water leakage identified as the predominant issue, accounting for approximately 70% of all observed defects. Ye et al.[4] found through data monitoring and visual inspection that the main defects in Shanghai's operational metro tunnels include water leakage, longitudinal settlement, and circumferential convergence deformation. Mair[5] reported that tunnel water leakage is most frequently observed at joints and manholes—locations with relatively poor waterproofing performance. Overall, water leakage in shield tunnels exhibits a high incidence rate and often serves as a direct or indirect cause of other tunnel defects.

With the continuous increase in the service life of shield tunnels, an increasing number of water leakage defects are expected to emerge over time. In addition, as China's transportation infrastructure approaches a more mature stage, the pace and scale of new tunnel construction are anticipated to slow down. It can thus be predicted that tunnel engineering will gradually shift from a phase of intensive construction to one focused on operation and maintenance. Consequently, the issue of water leakage in shield tunnels will become an increasingly critical concern requiring greater attention.

2. Characteristics of Water Leakage in Shield Tunnels

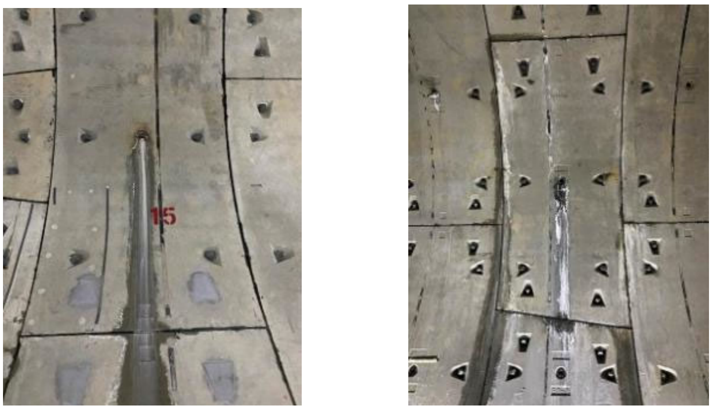
According to the varying seepage rates associated with water leakage defects in shield tunnels, the types of leakage are generally categorized into four classes: damp marks, seepage, dripping, and sand leakage[6]. The definitions of each type of leakage are summarized in Table 1 below.

Table 1. Types and definitions of leakage in shield tunnel

Type	Definition
Wet stained	The inner surface of the tunnel segment shows a wet spot with obvious color change
Water seepage	Water seeps into the segment, causing the inner surface of the segment to become wet
Drip	When the water reaches a certain level, it drips from above
Loam sand	The water is mixed with the soil particles and sediment behind the tube Leakage site outflow

The common locations of water leakage in shield tunnels primarily include leakage at grouting holes, segmental joints, and longitudinal joints. These typical leakage positions are illustrated in Fig. 1 below.

(a) Leakage in the longitudinal seam



(b)Leakage of grouting holes (c) Leakage in the ring joint

Figure 1. Water leakage position diagram of shield tunnel

By collecting and analyzing literature data related to water leakage defects in shield tunnels[3][7][8], statistical results were obtained regarding the types and locations of water leakage. These results are presented in Fig. 2 and 3 below.

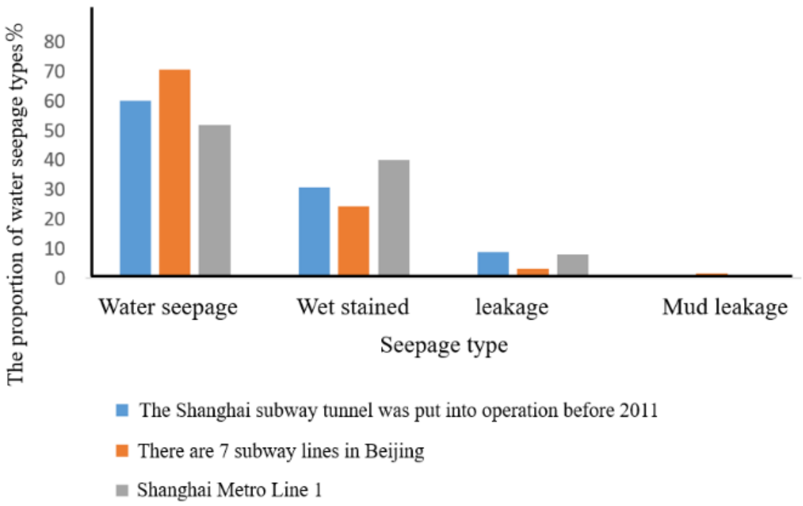


Figure 2. Survey results of seepage types of shield tunnel

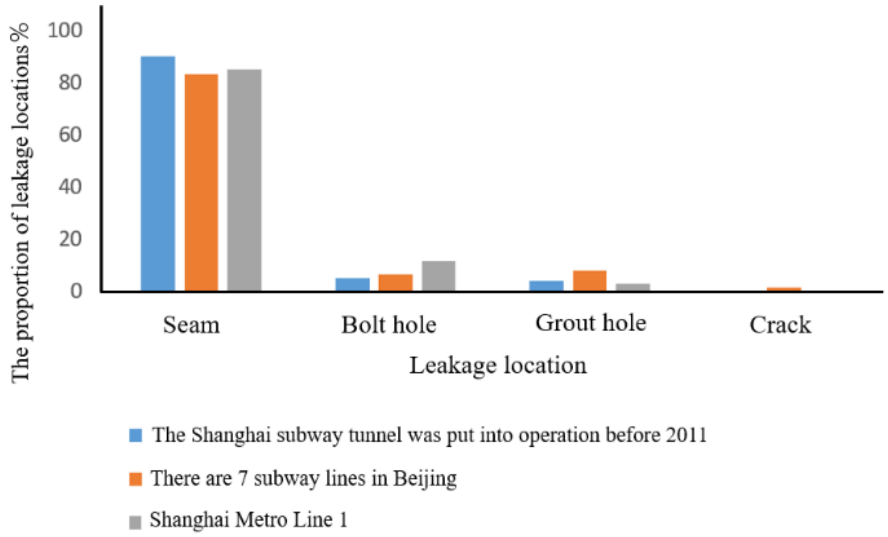


Figure 3. Survey results of leakage disease locations in different subway shield tunnels

Based on the analysis of survey results concerning water leakage types in shield tunnels, it can be concluded that among the four identified categories of leakage defects, seepage is the most prevalent, accounting for approximately 50% to 80% of all leakage cases. This is followed by damp marks, while dripping is relatively less common. Although sand leakage occurs less frequently, it poses a significant threat to tunnel safety. Due to the large volume of leakage associated with this defect type, it can easily carry soil particles and mud from behind the segment lining, resulting in substantial soil loss in the surrounding environment. In severe cases, this may lead to the formation of voids behind the segment lining, causing stress concentration in the lining structure. Therefore, effective countermeasures must be implemented to prevent the occurrence of mud/sand leakage defects.

Based on the statistical analysis of leakage locations in various metro shield tunnels, it can be concluded that the most common leakage sites are the segment joints, accounting for approximately 80% to 90% of all leakage cases. Among these, annular joint leakage is the most prevalent. Leakage at bolt holes and grouting holes occurs relatively infrequently, and leakage through bolt holes is often indirectly caused by water ingress at the joints. Leakage through segment cracks is the least common. Therefore, waterproofing at segment joints should be regarded as the primary focus in the waterproof design of shield tunnels.

3. Analysis of Leakage Mechanism of Shield Tunnel Segments

3.1. Geological aspect

Gao[9] believes that the primary geological and environmental factors contributing to water leakage in shield tunnels include geological conditions and groundwater pressure.

3.1.1. Geological condition

The impact of geological conditions on water leakage in shield tunnel segment linings mainly includes the following three aspects: stratigraphic conditions, geological structural conditions, and variations in groundwater.

(1) Stratigraphic Conditions: When the strata through which the shield tunnel passes are complex, such as soft soils like silt, sand, and silty soils, the tunnel is more susceptible to erosion and seepage from groundwater. As the service life increases, the waterproof materials tend to age more rapidly, weakening their performance and thereby increasing the risk of water leakage through the tunnel segments[10]. The physical properties of weak strata determine their poor resistance to leakage; once groundwater seeps in, it is difficult to completely expel it. Additionally, impurities such as sand particles and silt in the weak strata can affect the water quality, increasing the risk of corrosion and damage to the tunnel segments.

(2) Geological Structural Conditions: When the shield tunnel passes through areas with unfavorable geological structures, it may be affected by factors such as sinkholes, underground rivers, faults, and weak surrounding rock, leading to water leakage through the tunnel segments. Therefore, before constructing the shield tunnel, a detailed geological survey must be conducted, and appropriate measures should be taken to prevent water leakage through the segments[11].

(3) Changes in Groundwater Level: Studies have shown[12] that prolonged water leakage can cause a decline in the tunnel's groundwater level. As the water level continues to drop, the effective stress of the soil increases significantly, particularly in the soil above the water table. This change leads to a continuous increase in the tunnel's diameter variation, which is difficult to stabilize in a short period. The tunnel structure may exhibit significant elliptical deformation in the transverse direction, as shown in Fig. 4, with deformation amounts reaching 15 to 25 mm.

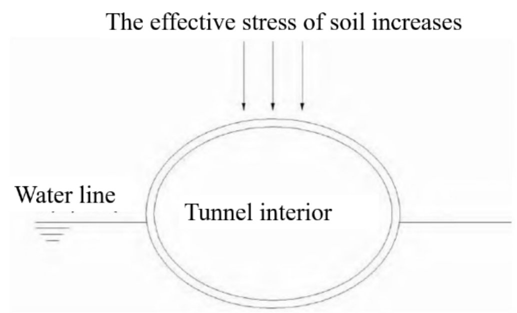


Figure 4. Transverse ellipticity deformation diagram of structure

As the elliptical deformation of the tunnel intensifies, the internal forces within the tunnel will gradually change. At the vertical diameter, the segments will experience tension, with the bending moment at the tunnel's crown increasing while the axial force decreases. At the horizontal diameter, the segments will experience compression, with both axial force and bending moment continuously increasing. This results in a reduction of the contact stress on the sealing gasket located at the outer arc of the segment, thereby creating a potential pathway for leakage.

3.1.2. Groundwater pressure

Groundwater pressure is also a crucial factor contributing to water leakage in shield tunnel segments[13]. Groundwater pressure refers to the upward force exerted by groundwater on the ground surface or objects, and its magnitude depends on factors such as the groundwater level, the volume of water, and the geological conditions beneath the tunnel segments. When the groundwater pressure becomes excessively high, it may lead to water leakage through cracks in the tunnel segments. Therefore, during the construction of shield tunnels, the influence of groundwater pressure must be thoroughly considered, and appropriate measures should be implemented to prevent water leakage.

3.2. Analysis of leakage mechanism of shield tunnel segment during operation

The analysis of the water leakage mechanism during the operational period of shield tunnel segments mainly includes the following factors: segment cracks, differential settlement of the segments, and bolt failure.

3.2.1. Segment crack

The main causes of cracks in shield tunnel segments during their operational period can be classified into internal and external factors. Internal factors: Over time, the reinforcement inside the segment interacts with substances such as water in the surrounding environment, causing corrosion. This corrosion leads to the expansion of the concrete, which gradually deteriorates and results in the formation of cracks. External factors: The distribution of surrounding soil and rock, uneven settlement, or a sudden increase in external loads can create stress concentration areas in the segment, which leads to the formation of microcracks. Under the influence of moisture and other factors in the surrounding soil, these microcracks can gradually develop into larger cracks. Additionally, under the long-term influence of surrounding soil and rock, the segment may experience significant internal structural forces, leading to fatigue damage and the eventual cracking or misalignment of the segment. Furthermore, if the bolts used to connect and secure the segments fall off or fail, it can also cause local stress concentration, leading to cracks in the segment[14].

3.2.2. Segment settlement difference

Differential settlement of tunnel segments during the operational period refers to the uneven settlement of the tunnel segments caused by external uneven loads or the varying geotechnical structures of the surrounding soil and rock. This differential settlement is typically due to geological factors surrounding the tunnel, such as the boundary between different geological environments, soil heterogeneity, and uneven stress distribution on the tunnel segments. During the operational period, the tunnel segments are highly susceptible to external forces, such as uneven or sudden changes in water pressure and soil pressure. These factors create significant stress differences across different parts of the tunnel, leading to uneven settlement of the segments[15].

3.2.3. Bolt failure

Bolts are crucial components that connect the longitudinal and circumferential segments of a shield tunnel, ensuring the structural rigidity of the tunnel. The waterproof gasket and bolts between the segments are tightly connected, ensuring good sealing performance between the segments. In addition to issues related to the factory quality of bolts and construction irregularities, bolt failure during the operational period of the tunnel can occur due to the following reasons: Under the influence of the tunnel's surrounding soil and rock, the waterproof gasket and bolts may corrode, gradually losing their performance, and thus no longer effectively seal or connect the segments. Furthermore, if external forces are excessive or unevenly distributed, it can lead to significant internal forces or stress concentration at the bolt connections, ultimately resulting in bolt failure[16].

3.3. Analysis of leakage mechanism of shield tunnel segment during construction period

(1) When the tunnel segments are subjected to compression and collision, it may result in surface damage such as scratches, cracks, or deformations. These imperfections can serve as pathways for water leakage. Additionally, issues such as edge chipping or missing corners in the segments can also affect their joining quality and sealing performance, leading to the occurrence of water leakage problems[17].

(2) During the shield tunneling process, if the alignment and positioning of the shield machine are not properly adjusted, it may result in misalignment or step differences between the segments, thereby affecting the joining quality and sealing performance of the segments, which can lead to water leakage problems[18]. Additionally, if the tail seal fails and causes grout leakage, it can have significant consequences. The tail seal is a critical component in shield tunnel construction, and its failure allows slurry and groundwater to enter the tunnel from the tail seal area during excavation, which leads to water leakage in the tunnel[19].

(3) The pull bolts between the segments, if not tightened promptly after assembly, can also cause water leakage in shield tunnel segments. This is because the function of the pull bolts is to apply tension. If not tightened in time, the tension in the bolts gradually decreases, leading to an increase in the gap between the segments and resulting in water leakage[20]. Additionally, during the vertical curve advancement or alignment correction, the application of asbestos wedges may also lead to water leakage in the tunnel segments. This occurs because the direction and speed of the shield machine's movement change during vertical curve advancement or alignment correction, which can cause deformation of the segments. If asbestos wedges are applied at the deformed areas, it may cause expansion of the circumferential joints, leading to a relaxed state between the segments and exacerbating the water leakage issue[21].

(4) During the segment construction process, poor sealing quality at weak points such as hand holes, grouting holes, and other areas, lack of waterproof sealing gaskets in bolt holes, improper grouting, and poor handling of joints between the I-beam ring and the longitudinal connections during jointing can all lead to water leakage in the tunnel segments[22].

(5) Poor grouting quality behind the segment wall, leading to incomplete filling, can result in uneven stress distribution, excessive local deformation, and failure of the first

waterproof layer, causing water leakage. In such cases, grouting treatment is required to ensure the integrity and load-bearing capacity of the concrete structure behind the segment wall, while also repairing or replacing the damaged first waterproof layer to prevent further leakage[23].

4. Research Deficiencies and Prospects

Water leakage in tunnel segments is a common issue, and although many studies have been conducted on this problem, there are still some deficiencies, including the following aspects:

(1) Lack of systematization in research: Many studies simply analyze the causes of water leakage in tunnel segments without providing a systematic investigation of the entire leakage process. As a result, key issues such as the generation mechanisms, development processes, and influencing factors of water leakage in tunnel segments have yet to be fully explored.

(2) Limited research methods: The commonly used methods for studying water leakage in tunnel segments include laboratory simulation, field monitoring, and numerical simulation. However, these methods have their limitations and are often insufficient to comprehensively and accurately reveal the phenomena and mechanisms of water leakage. Therefore, there is a need to develop more advanced and reliable research methods to improve the accuracy and reliability of the studies.

(3) Lack of unified evaluation standards: The evaluation standards for water leakage in tunnel segments have not been standardized, making it difficult to compare and unify conclusions from different studies. Therefore, there is a need to establish a unified and scientific evaluation standard to enhance the comparability and reliability of research results.

To address the aforementioned shortcomings, future research can be directed towards the following three areas:

(1) Enhance scientific rigor and reliability: Research methods and techniques need to be more scientific and reliable, with more accurate data analysis and processing to improve the accuracy and practical applicability of the research results.

(2) Explore from multiple perspectives: The issue of water leakage in shield tunnel segments involves various aspects. Future research can explore this problem from multiple angles, such as materials, structure, and construction, to improve the prevention and treatment effectiveness of water leakage in shield tunnel segments.

(3) Promote new technologies: With the continuous advancement of technology, many new techniques and tools are emerging. It is important to actively promote and apply these innovations to improve the efficiency of addressing water leakage issues in tunnel segments.

References

[1] Liu Dejun, Zhong Fei, Huang Hongwei, et al. Present Status and Development Trend of Diagnosis and Treatment of Tunnel Lining Diseases [J]. China Journal of Highway and Transport, 2021, 34(11): 178–199.

[2] Dong Fei, Fang Qian, Zhang Dingli, et al. China Civil Engineering Journal [J]. China Civil Engineering Journal, 2017, 50(06): 104 - 113.

[3] Liu Yajiang. Study on Structural Safety of Shield Tunnel and Vehicle DynamicBehavior under Disease Condition in Beijing Subway [D]. BEIJING JIAOTONG UNIVERSITY, 2019.

[4] Ye Yaodong, Zhu Hehua, Wang Rulu. Analysis on the Current Status of Metro Operating Tunnel Damage in Soft Ground and lts Causes [J]. Chinese Journal of Underground Space and Engineering, 2007(01): 157-160+166.

[5] Mair R J. Tunnelling and geotechnics: new horizons[J]. Géotechnique, 2008, 58(9): 695-736.

[6] Chen Sensen, Wang Jun, Liu Wen, et al. Comprehensive Treatment Technology of Water Leakage in Shield Tunnel [J]. Railway Construction Technology, 2019, No.319(12):101-106.

[7] Shao Hua, Wang Rong. Analysis of the Influence Factors and lts Characteristics of Metro Shield Tunnel Defects in Shanghai [J]. Modern Tunnelling Technology, 2018, 55(S2): 922-929.

[8] Wang Rulu, Xiao Tonggang, Zhu Yan. Water leakage control and deformation control of shield tunnel in Shanghai Metro [C]. Proceedings of the 15th Academic Exchange Meeting of Waterproofing and Drainage Professional Committee of Tunnel and Underground Engineering Branch of China Civil Engineering Society, 2011:8.

[9] Gao Shu. Leakage Cause Analysis and Treatment Technology for River-crossing Subway Shield Tunnel Segments [J]. China Building Waterproofing, 2015(06): 32-36.

[10] Gong Xiaonan, Guo Panpan. Prevention and Mitigation Methods for Water Leakage in Tunnels and Underground Structures [J]. China Journal of Highway and Transport, 2021, 34(07): 1-30.

[11] Zhang Ai, Xue Haitao, Zhang Sherong, et al. Influence of Construction Parameters on Tunnel Convergence Deformation [J]. Transport Research, 2017, 3(03): 55-61+68.

[12] Liu Yin, Jiang Mingming. Long-term influence of leakage at shield tunnel joint on its deformation and inner force [J]. Yangtze River, 2017, 48(21): 96-102.

[13] Wang Shimin, Xie Hongming. Review and prospect of waterproofing of segment joints of shield tunnel with high hydraulic pressure [J]. Hazard Control in Tunnelling and Underground Engineering, 2020, 2(02): 66-75.

[14] Sun Jun. Durability Design of Segment Lining Structure in Chongming Yangtze River Shield Tunnel [J]. Journal of Architecture and Civil Engineering, 2008(01): 1-9.

[15] Zhang Dingli. Deformation control technology of poor geological body and structural interface in undersea tunnel [J]. Chinese Journal of Rock Mechanics and Engineering, 2007, No.190(11): 2161-2169.

[16] Zhang Dongmei, Chen Congcen. Time-dependent Reliability Analysis of Shield Tunnel Structure under Corrosion Conditions of Segment Rebars and Bolts [J]. Modern Tunnelling Technology, 2021, 58(06): 111-120.

[17] Qiao Xiaolei, Dong Fei, Li Ao, et al. Structural Safety State Evaluation of Metro Large Diameter Shield Tunnel During Operation [J]. Railway Investigation and Surveying, 2023, 49(01): 119-125.

[18] Zang Shiwen. Key Technology of Shield Construction Quality Control [J]. Guangdong Architecture Civil Engineering, 2022, 29(03): 75-78.

[19] Li Wenguang. Study on leakage mechanism and construction control measures of mud shield tunnel [J]. Railway Standard Design, 2007(05): 70-73.

[20] Liu He. Study on water leakage risk management during the whole life cycle of shield tunnel project in soft soil layer [D].GUANGXI UNIVERSITY, 2018.

[21] Chen Yong, Zhu Jiwen. Mechanism of Seepage Emergence in Regional Tunnel of Shanghai Metro [J]. Chinese Journal of Underground Space and Engineering, 2001(01): 55-60+66-79.

[22] Lu Cong, Li Tao, Yuan Shengjie. Study on the leakage cause and treatment technology of underwater shield tunnel during operation period [J]. Engineering Construction, 2021, 53(10): 44-49.

[23] Li Xiangyu, Li Xinyuan, Li Mingyu, et al. The Cause and Distribution of Water Leakage in Metro Shield Tunnel [J]. Building Science, 2020, 36(S1): 233-238.