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Review Article

State-of-the-Art Review on Failure Mechanism and Waterproofing Performance of Linings for Shield Tunnels

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The introduction and development of shield tunnels have led to the innovation of precast segmental linings, which has significant advantages in improving the construction speed compared with in-situ cast concrete linings. However, damage of the linings and water leakage at the lining joints highlight defects in the design and construction of the linings. In this regard, it is necessary to investigate the failure mechanism of linings for shield tunnels and evaluate the waterproofing performance and repercussions of lining joints. The relevant research results published in recent years are reviewed in this paper, focusing on the failure mechanisms of linings and the waterproofing performance of lining joints. Progressive failure and instability of linings are introduced. Progressive failure has three stages: initial elastic stage, local damage stage, and overall failure stage. The performance-based design of joint waterproofing is described in seven steps. Further opportunities for the investigation of this topic are discussed.

1. Introduction

In recent decades, the construction and operation of public transport have gradually changed from single level to multilevel, from single dimensional to multidimensional, and from manual to intelligent. A typical example of the issues modern and intelligent rail transit tries to solve is the demand to alleviate the growing traffic pressure [1–4]. Moreover, the development of better construction techniques and innovations in materials used allows for the construction of subways in almost all kinds of soil environments, such as soft soil and with water pressure [5, 6].

Tunnel, one of the main forms of subway operation, is a three-dimensional traffic building buried in the stratum. Tunnel boring machines (TBMs), as the main tunneling tool for tunnel and utility construction in urban underground spaces [7], are widely used because of their high automation, fast construction speed, and low influence on ground disturbance [8, 9]. The tunnel lining is assembled into different shapes (circular, rectangular, and mixed shapes), which are determined by the shape of the TBM to withstand the loads imposed by the interior and exterior tunnel [10, 11]. Traditionally, tunnel linings are composed of several precast concrete segments, which are connected by rigid bolts [12], and the segments are usually reinforced with steel bars to bear both exterior and interior loads [10, 13]. The application of precast concrete segments (PCS) has increased significantly owing to its high quality, low cost of installation, and low cost of raw materials [14]. Compared with in-situ cast concrete segments (CCSs), PCS can be better actively controlled during the construction process, concrete pouring, and curing. In addition, for soft and hard soils, PCS can play a role in resisting external loads as soon as possible. Therefore, the use of PCS, especially in tunnel engineering in earthquake-prone areas, is becoming increasingly popular [15, 16].

The bearing capacity and sealing performance of tunnel linings have been widely studied to ensure the safety and durability of tunnel engineering. Most previous studies focused on in situ monitoring and theoretical analysis of tunnel linings subjected to various actions [4, 16–28]. Generally, the load actions that must be considered in the design and construction of linings include undisturbed land stress, water pressure, pavement traffic load, subgrade reaction, grouting load, and service load [29]. During a long-term operation process, segment linings are inevitably attacked by uneven subsoils, traffic loading, and groundwater leakage [26, 30–32], which finally results in extrusion deformation and leakage corrosion [3, 25, 27, 33–35].

The problems mentioned above may lead to serious or even disastrous consequences, such as weak load resistance and instability of local segments caused by extrusion deformation, and leakage and corrosion at lining joints caused by unsealing. However, there are a few experimental and numerical studies on the mechanical properties and waterproofing design for linings of shield tunnels [36]. Therefore, it is particularly important and necessary to systematically understand and master the failure mechanisms of tunnel linings and the waterproofing performance of lining joints. Corresponding failure control mechanisms and performance-based waterproofing design can be proposed only by clarifying the failure process and leakage principle of the linings.

2. Failure Mechanism of Linings

2.1. Assessment of Time-Variant Loading. Generally, linings for a shield tunnel are mainly designed using analytical and simplified numerical models [3, 5, 37, 38], which do not consider the adverse effects of nonlinear actions [39] and longitudinal bending moments [40] in actual engineering. To eliminate the limitations of the aforementioned method in the analysis of the interactions between the tunnel shell and the surrounding soil, updated design guides were proposed in reference [41], which consider and discuss the load linings that are subjected to.

Short-term loads caused by the tail gap pressure were monitored [42], and long-term loads acting around the linings, such as earth and water pressures, were also monitored [17, 43]. To further understand the variation regulations of loads with time in real time, a process-oriented model was proposed [44, 45], which can produce a more reasonable analysis of groundwater flow and slurry hardening during the construction of the linings. A typical load distribution around the tunnel linings and the temporal and spatiotemporal evolution of earth and water pressures are shown in Figures 1 and 2, respectively.

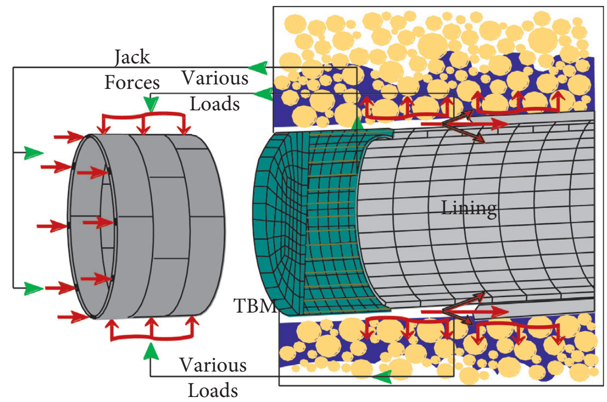

Figure 1: Various loads acting on the linings during construction (including grouting and earth and water pressures).

2.2. Analysis of Cracking and Deformation. From among possible damages, cracking of the lining is regarded as one of the most serious problems in tunnels, as it leads to a reduction in the durability and structural performance of the overall tunnel [47]. There are several summaries in the literature on the cracking and damage of segmental linings in the construction stage [19, 48–50]. Longitudinal cracks, a common cracking pattern in tunnel segment linings, are mainly caused by various construction loads [51]. Typical cracking patterns in tunnel construction are shown in Figure 3 and mainly include cracks formed by external force intrusion into a curved tunnel with a small radius, the reaction force between jacks and adjacent segments in a tunnel with a large radius [52], and unsymmetrical pressure during mortar injection [53].

Furthermore, the deformation convergence and the state of the internal force of the linings are discussed in reference [35]. The deformation characteristics of existing linings under the actions of a foundation pit were analyzed using a hybrid model [54]. With the help of a three-dimensional nonlinear theory, a finite element model (FEM) of the hybrid shield was established, and the influence of different water pressures on the deformation performance of linings and joints was discussed [55]. Meanwhile, lateral deformation caused by lining failure has been extensively reported based on observations at construction sites [56].

2.3. Investigation of Mechanical Properties and Failure Mechanism. Once cracking and deformation occur in a tunnel lining, serious and uncontrolled consequences may be induced. It is necessary to study the mechanical properties and failure mechanisms of segmental linings. A hydraulic simulation method was proposed for analyzing the mechanical properties of tunnel linings [57]. Subsequently, the mechanical properties of precast individual segment linings are discussed, and the failure mechanism is analyzed [58]. The damage and failure mechanisms of lining joints caused by an uneven settlement of the foundations have been researched [59]. The results showed that the stress of a bolt on the section was directly proportional to the settlement depth, and an obvious dislocation phenomenon was captured at the connector of the linings. The bolts in the reverse and top positions of the segmental linings were damaged before the bolts in other positions, which can be described as a gradual failure process.

More recently, experimental research and numerical analysis of the mechanical properties of reinforced concrete linings have been performed [14, 60]. Loading tests of multiring assembled linings were carried out successively [61–63]. Compared with similar failure tests characterized by an instability failure mode, establishing predictions for lining failure based on the change rate of the tunnel diameter and ultimate displacement was proposed [61]. Failure of the

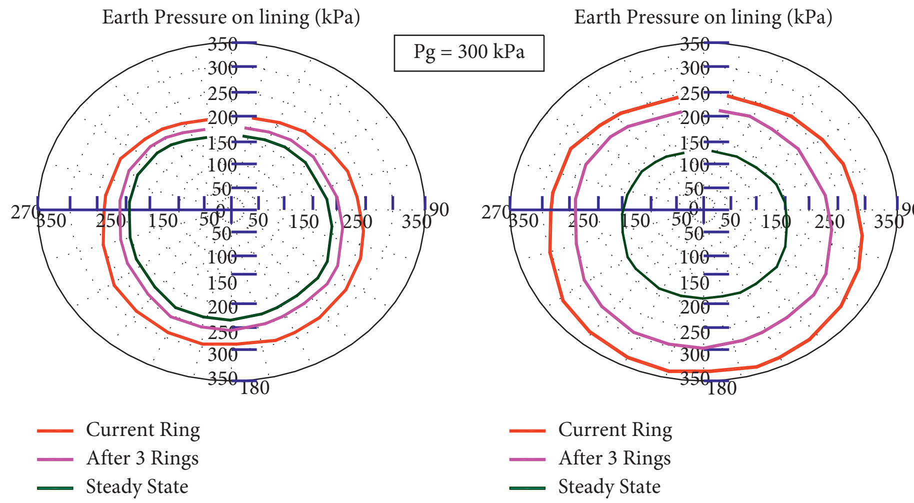

Figure 2: Spatiotemporal evolution (including earth and groundwater pressures) (reannotated based on literature [46]).

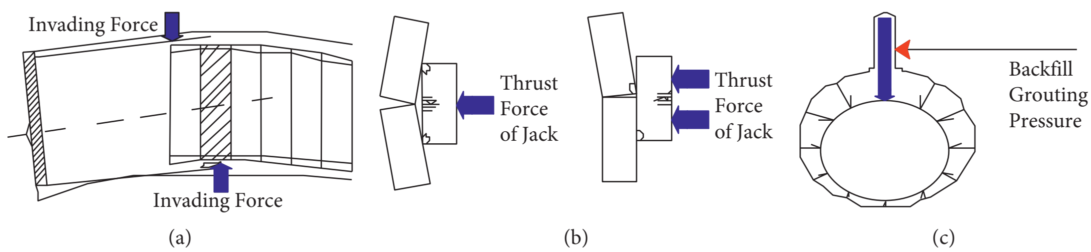

Figure 3: Typical cracking patterns in tunnel construction (reannotated based on reference [49]). (a) Invasion of shield tail. (b) Jack thrusting at deficient contacting segments. (c) Unsymmetrical pressure.

lining joints eventually led to a failure in the overall linings, but no significant damage occurred to the lining itself [62, 63]. A numerical simulation of the continuous failure process of the lining caused by local failure was performed. The results illustrate that the mechanical properties between adjacent linings can be predicted by means of existing failure criteria [64, 65].

2.4. Discussion of Progressive Failure and Instability. Although previous studies focused more on an analysis of loads, cracking and deformation, mechanical properties, and failure mechanisms, research on the progressive failure and stability of segmental linings has become increasingly popular in recent years. This research covers the experimental and theoretical analysis of the influence of sandy soil [66], soft surrounding rock [67], slope action [68], river glacier gravel [69], groundwater flow [70], water storage tunnel [71], uncorrelated flow [72], and different soil action [73] on the stability of tunnel linings. All these results contribute to further improvements in the linings in terms of preliminary design, rapid construction, operation, and maintenance.

In addition, a large number of scale tests were carried out [74] to reveal the progressive failure and instability process of linings from the aspects of assembly mode, lateral pressure, and cap block position. The progressive failure of linings consisted of three stages: initial elastic stage, local damage stage, and overall failure stage. The lining material was compacted, and the friction stress gradually increased between the equipment and the soil (points A to B). New cracks appeared one after another, and existing cracks continued to widen and elongate, implying that the microfailure of the linings was gradual rather than an instantaneous process (points B to C). Penetrating cracks were observed, and regional fractures occurred, resulting in the fracture of segmental linings along the overall section (points C to D). Subsequently, the segment linings began to rapidly lose stability until final failure occurred. The force-displacement curves of the segment linings at each characteristic point are shown in Figure 4.

3. Waterproofing Performance of Linings

3.1. Water Leakage Behavior of Lining Joints. In recent years, the advantages of precast linings, such as plain concrete (PC) and steel fiber-reinforced concrete (SFRC) linings, have been explored, which led to the promotion of its application in tunnel construction. Table 1 presents the literature on experimental studies of precast linings using different materials [14, 25, 26, 58, 75–82]. However, adverse factors in the underwater environment [83, 84], such as high-pressure water and weak seabed, lead to the weak performance of the lining (leakage water of the lining joint). Therefore, it is

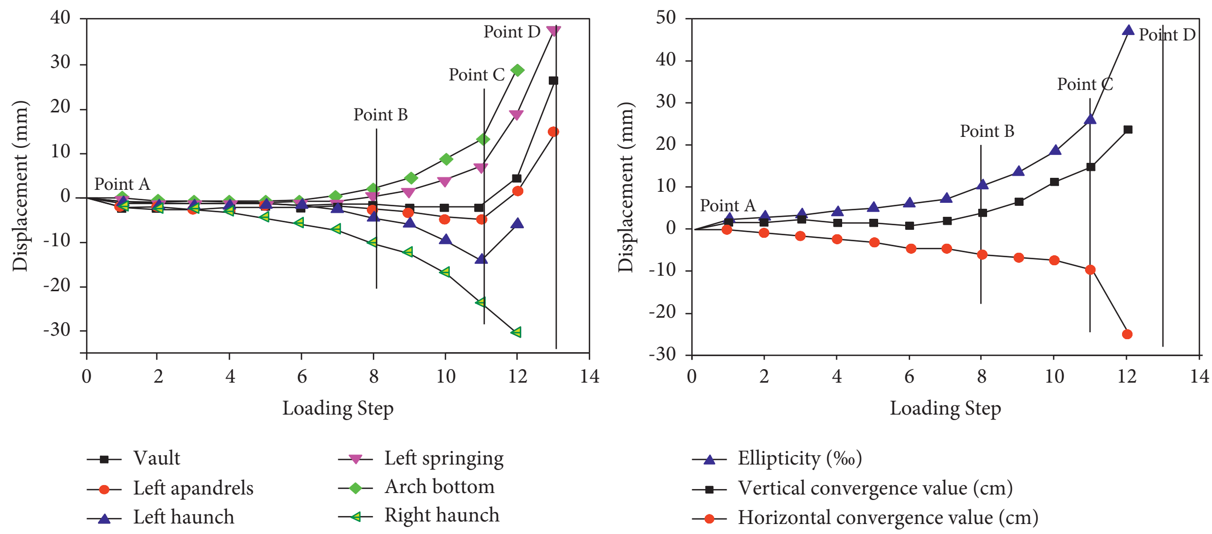

FIGURE 4: Force-displacement curves at each characteristic point [63].

TABLE 1: Summary of relevant literature on precast linings.

Objective	Material	Objective	Material
Bearing capacity [75]	PC and SFRC	Structural behavior [76]	RC and SFRC
Structural behavior [58]	RC and SFRC	Settlement behavior [14]	RC and SFRC
Structural response [77]	SFRC	Structural behavior [78]	RC and SFRC
Mechanical behavior [79]	FRHPC	Bearing capacity [80]	UHPFRC
Ductile behavior [81]	SFRC	Structural behavior [82]	RC and HFRC

where PC represents the plain concrete, RC represents the reinforced concrete, SFRC represents the steel fiber-reinforced concrete, FRHPC represents the fiber-reinforced high-performance concrete, UHPFRC represents the ultrahigh-fiber-reinforced concrete, and HFRC represents the hybrid-fiber-reinforced concrete.

necessary to master the leakage behavior of the lining joint to understand the failure mechanism and performance-based design of joint waterproofing.

It is well known that the waterproofing performance of precast linings mainly depends on the joint. A countermeasure for the failure of a joint is to install a rubber gasket. Joint leakage usually occurs at the contact surface between the rubber gasket and the groove, or between the two rubber gaskets [36, 85]. Compared with the first, the latter has a smaller contact stress value, resulting in easier water leakage between the two rubber gaskets [7]. Figures 5 and 6 illustrate the leakage point and water leakage process of the lining joint, respectively. Under the continuous action of water pressure, the two contact surfaces experienced initial separation (Figure 6(a)), contact failure (Figure 6(b)), and complete separation (Figure 6(c)), and finally formed a complete leakage path.

3.2. Failure Mechanism of Joint Waterproofing. A series of national specifications were issued [84–88], and experimental studies were carried out [6, 7, 16, 25–28, 31, 36, 89–92], aiming to further understand the behavior and mechanism of joint waterproofing of linings.

Typical joint waterproofing failure patterns are shown in Figure 7 and are mainly grouped into four failure patterns [7, 91]. In the joint opening pattern (Figure 7(a)), the waterproofing capacity of the groove interface was significantly better than that between the two gaskets, resulting in leakage often occurring between the contact surfaces of the two gaskets. In the joint offset pattern (Figure 7(b)), the joint waterproofing failure was mainly caused by displacement dislocation between the gasket and the groove. In the positive and negative rotation patterns (Figures 7(c) and 7(d)), the rate of leakage reduction was positively correlated with the rate of joint rotation. Meanwhile, within the controllable range of joint rotation, the waterproofing capacity of the interface between the gasket and the groove is due to the waterproofing capacity between the two gaskets.

3.3. Performance-Based Design of Joint Waterproofing. After mastering the leakage behavior and waterproofing failure mechanism of the lining joints, a performance-based design concept for joint waterproofing was proposed [7, 16]. The specific design process is illustrated in Figure 8. Corresponding experimental and numerical studies have verified the impact of different influencing factors on the waterproofing performance, such as gasket hardness, joint opening and rotation angle, and friction coefficient. The described design effectively simplifies the waterproofing performance evaluation of the lining joints during preliminary design and operation.

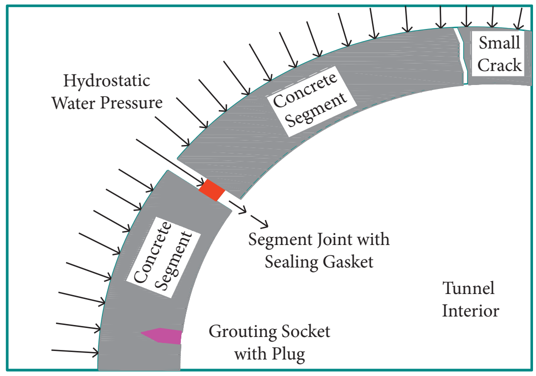

Figure 5: Illustration of leakage point (reannotated based on references [84, 86]).

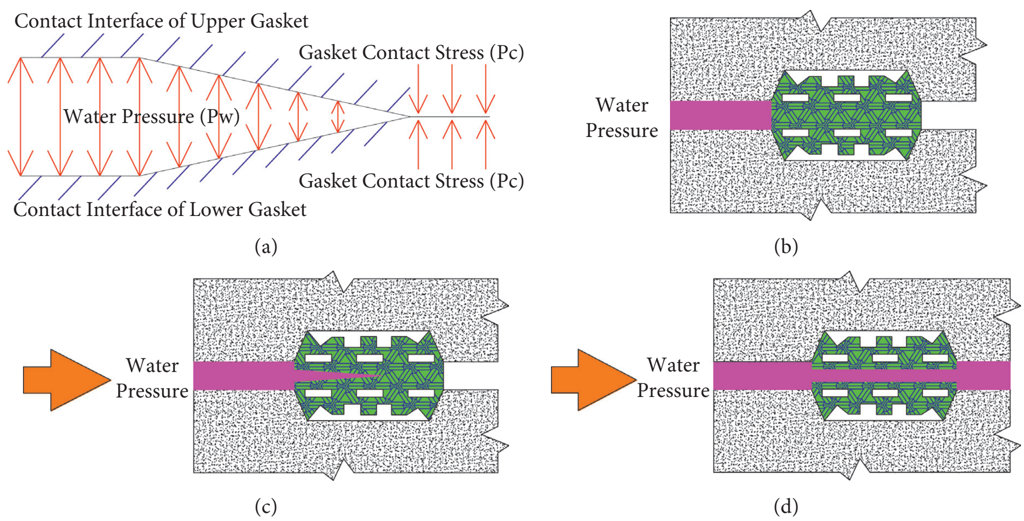

Figure 6: Water leakage process of lining joint. (a) Various loads on the gasket. (b) Initial penetration. (c) Further penetration. (d) Final leakage.

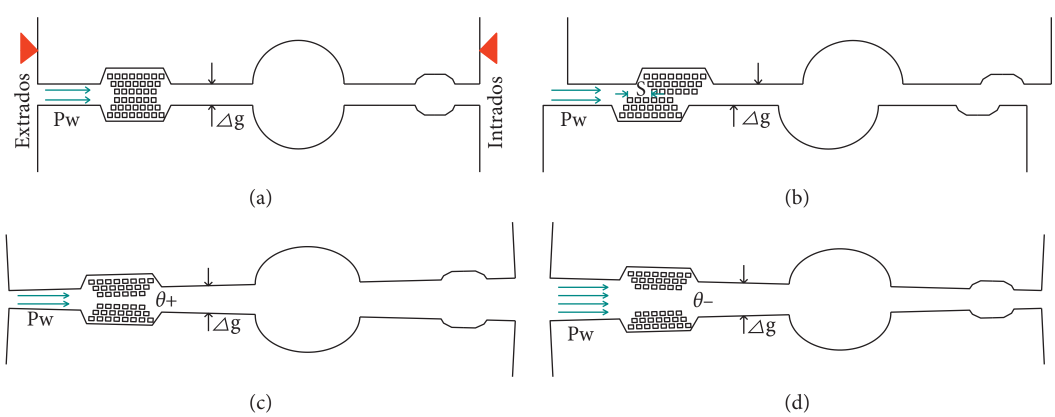

Figure 7: Failure patterns of joint waterproofing. (a) Opening of joint. (b) Offset of joint. (c) Positive joint rotation. (d) Negative joint rotation.

4. Future Works

Adverse factors in the construction process should be eliminated as much as possible, such as the pressure exerted by the jacks and unbalanced pressure between the interior and the exterior, which can effectively avoid the occurrence of initial cracks. The design of linings should focus on the weak positions rather than the overall structure, such as on lining joints, because it is often damaged at weak positions that lead to lining failure. Moreover, early warning

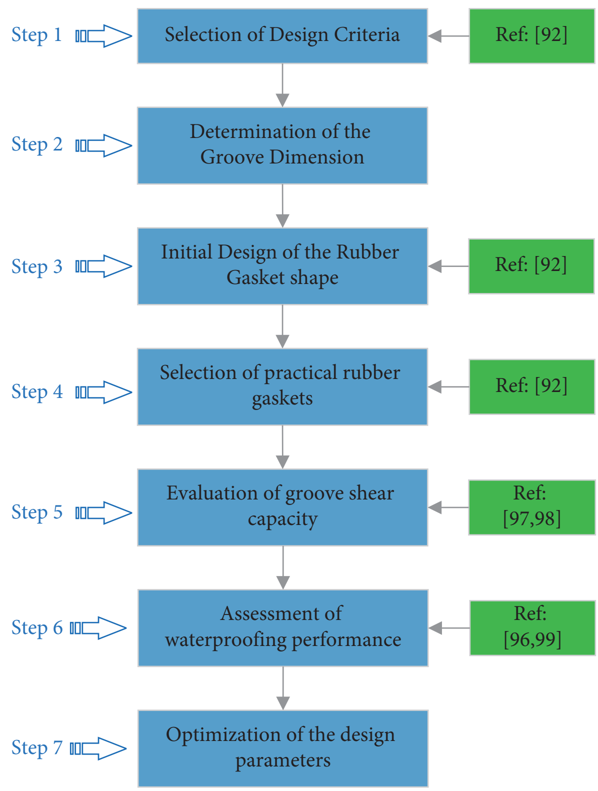

Figure 8: Specific performance-based design process for joint waterproofing.

mechanisms (EWMs) should be established [63, 93]. Once the critical value of local damage reaches point B, an early warning response (EWR) is initiated and the corresponding countermeasures are taken.

5. Conclusions

To investigate and master the failure control mechanism and performance-based design methods for linings of shield tunnels, this paper summarizes the results of the failure mechanism and waterproofing performance in the field of linings for shield tunnels. The main conclusions based on the findings of this review are as follows:

(1) Most cracks in tunnel construction are caused by external force intrusion into a curved tunnel with a small radius, by reaction force between the jacks and adjacent segments in a tunnel with a large radius, and by unsymmetrical pressure during mortar injection. Orderly construction operation and strict grouting process are essential for controlling the cracks of a tunnel.

(2) Failure of the overall linings is caused by a failure of the lining joint, and there is no obvious damage to the lining itself. The mechanical properties between adjacent linings can be predicted reasonably using the existing failure criteria. However, there are a few application cases of existing failure criteria in practical tunnel engineering. It is important to predict the mechanical response of existing lining through the proposed failure criteria.

(3) The typical waterproofing failure patterns of joints mainly include the joint opening pattern, the joint offset pattern, and patterns of positive rotation and negative rotation. At the same time, within the controllable range of joint rotation, the waterproofing capacity of the interface between the gasket and the groove mainly depends on the waterproofing capacity between the two gaskets. In order to meet the requirements of durability, it is necessary to research the mechanical properties of gaskets with new materials and new processes.

(4) In the actual tunnel engineering, the adverse factors in the construction process should be eliminated as far as possible, and the design of the weak part of the lining should be paid special attention to. In addition, comprehensive early warning mechanisms (EWMs) and solutions should be established. Once the critical value of local damage reaches the set value, EWR is initiated and the corresponding countermeasures are taken [94–96].

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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