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Review

Waterproof Performance of Sealing Gasket in Shield Tunnel: A Review

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Abstract: Rubber gaskets are commonly adopted as the waterproof component in shield tunnels for their outstanding sealing performance. The contact pressure between surfaces generated by the assembly stress ensures that the gaskets resist certain water pressure without leaking. However, with the continuous occurrence of leakage accidents, attention has been drawn to the topic of the waterproof performance of gasketed joint shield tunnels. In this article, prominent contributions to the waterproof performance of sealing gasket in shield tunnels are listed and sorted into four sections: (1) structural behavior of lining and joint; (2) material constitutive model and durability; (3) numerical simulation methods; (4) thermal-mechanical coupling analysis. First, examples of leakage are discussed and tests on gaskets are elucidated, which is followed by a summary of the progress on material mechanical properties and durability. Then, the development of the simulation methods is presented. Finally, the existing research on the thermal-mechanical coupling analysis is summarized. It is found that the contributions to gaskets' waterproof performance are fruitful, however, with stringent construction conditions, such as the material constitutive model and aging mechanism under special conditions, such as high temperature, numerical simulation, and laboratory test methods, which need to be further explored.

Keywords: shield tunnel; sealing gasket; sealing performance; thermal-mechanical coupling

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1. Introduction

With the development of the economy and the improvement of people's living standards, aboveground construction in urban areas is nearly saturated, which accelerates the vigorous development of tunnel construction. At the same time, the highway, railway, and subway tunnels, as the main arteries of transportation, are suffering from leaking accidents one after another due to natural or man-made factors, causing deleterious consequences and huge economic losses [1].

According to China's construction code, the design service life of energy and transportation shield tunnels is usually up to 100 years or even 120 years. Ensuring its safety and functionality during service life under harsh and variable influences [2,3] has become a severe challenge faced by the majority of engineering scientists. The existing construction and operation experiences of cross-river and sea-crossing tunnels present a situation of widespread leakage [4,5]. Table 1 lists the representative tunnel leakage accidents.

Table 1. Shield tunnel leakage accidents.

No.	Time	Accident	Caused by	Results
1	2018	Mud leak in Nanjing Yangtze River North Line Tunnel	The plug of the grouting hole falls off under high water pressure	Traffic stop
2	2018	Hangzhou Wangjiang Tunnel collapse	Frozen soil insulation layer breakdown by groundwater intrusion	Traffic stopped, several pipelines were damaged, and about 150 square meters of pavement collapsed
3	2018	Leakage in Tunnel of Foshan Rail Transit Line 2	Continuous failure caused by Shield tail seal failure	11 dead,1 missing, and 8 severely injured. The direct economic loss is about USD 8.358 million
4	2008	Large deformation in one of the Shanghai Metro Tunnel	large deformation of tunnel cross-section, joint leakage, and bolt breakage caused by the sudden pile load on the surface	Subway outage
5	2003	Leakage in Shanghai Metro Line 4	Insufficient freezing strength	The direct economic loss is about USD 23.55 million

The waterproof performance of shield tunnels follows the principle of "prevention first, rigid and flexible combined, multiple layers of defense, and comprehensive treatment". The key to it lies in the segment joints [6]. The reinforced concrete segment consists of the majority of the shield tunnel, which excels in permeability resistance, as shown in Figure 1a. It is worth mentioning, however, that the segments can be arranged both in alignment and staggered, in practice. Existing engineering examples show that the waterproof performance of tunnels is controlled by joints (Figure 1b). In the construction stage, the gaskets between the longitudinal joints and the circumferential joints are pressed by shielding jacks to form contact stress and resist the intrusion of external water pressure, as presented in Figure 1c. The mainstream strategy for shield tunnel joints in China is to glue EPDM gaskets onto the outer groove of the segment, which is proved reliable under targeted working conditions. However, with hazardous factors (earthquake, fire, etc.) imposed at a certain magnitude, the gaskets are likely to fail.

Waterproof failure is a typical continuous–discontinuous hydraulic expansion failing process [7]. Seepage of the gasket contact surface is a process in which the contact surface of the gasket keeps opening and water keeps penetrating under pressure. When the contact surface of the gasket is completely opened, a water seepage path is formed, resulting in the occurrence of joint leakage (Figure 1d). It can be seen, however, that sealing gaskets play a vital role in the segment joint waterproof process.

Based on the above engineering problems, this paper summarizes the research progress on waterproofing of sealing gaskets, to guide follow-up research and practical referencing for engineering design. Combined with the domestic and foreign scholars' research on the shield tunnel joint sealing performance and analysis methods related topics, in this article, the waterproof performance, material characteristics, numerical simulation, and thermal-mechanical coupling analysis of the shield tunnel joint sealing gasket are discussed.

2. Mechanical Behavior of Lining Structure and Joints

The waterproof performance of gaskets is related to many factors, which can be divided into material factors, structural factors, and external influences. Researchers have conducted in-depth studies on these influencing factors and carried out structural tests. Paul [8] took the lead in the study of the waterproof capacity of gaskets under different joint openings, which was based on the Chicago subway tunnel in the sandy soil, and laid the foundation of the steel-clamp-based joint gasket waterproof test. Table 2 summarizes the related contributions to the indoor waterproof performance test of shield tunnel joints.

Since then, with the large-scale development and utilization of urban underground space and metro tunnel construction, an increasing number of scholars have begun to pay close attention to tunnel waterproof problems. Corresponding tests are conducted to acquire the water pressure admissible value while the gasket joint is in an offset state. Representative cases in recent years include the Singapore metro tunnel [4], the Shanghai

Qingcaosha water tunnel [9], the Su'ai tunnel project [10], the Shanghai deep water storage tunnel [11], and the Changsha metro tunnel [12].

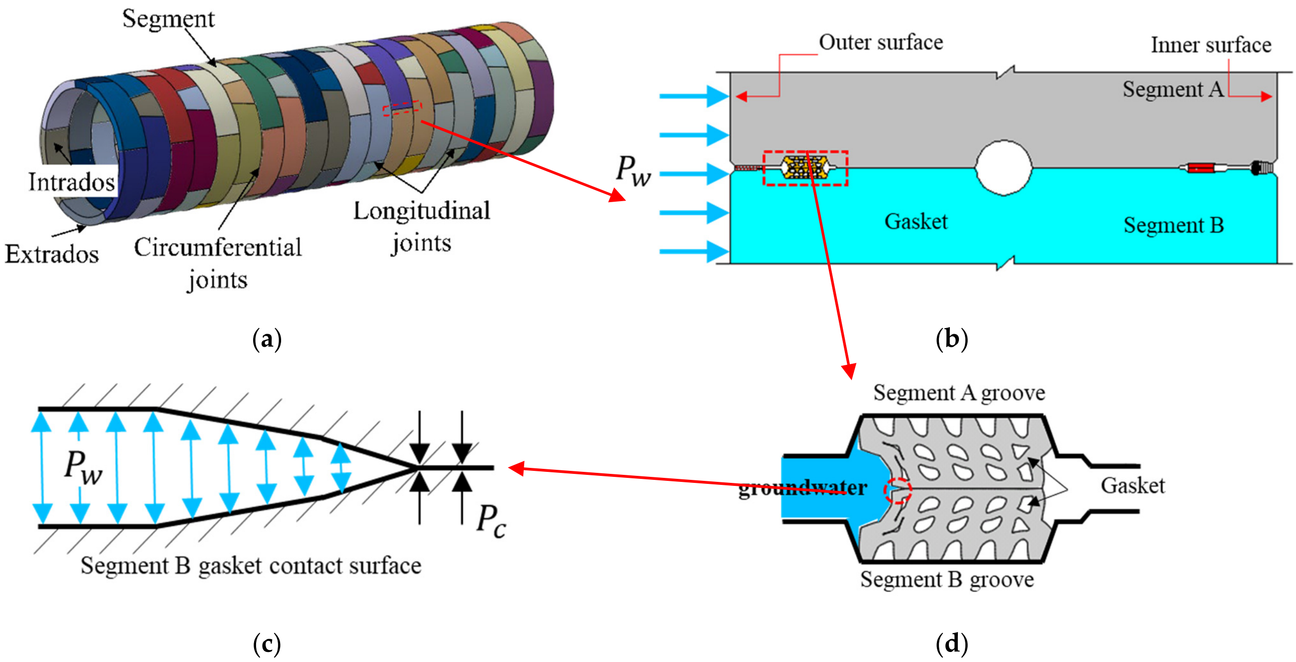

Figure 1. Joint waterproof sealing diagram of shield tunnel: (**a**) lining structure, (**b**) joints [13] (Reprinting with permission from Gong et al., 2019), (**c**) water pressure expansion process, (**d**) joint gaskets [7] (Reprinting with permission from Gong et al., 2018).

2.1. Waterproof Performance Deterioration of Tunnel

With the deepening understanding of the leaking mechanism, scholars devote themselves to the research of tunnel waterproof performance deterioration. In terms of laboratory test technologies and deterioration simulations, Lei et al. [14] carried out investigations and numerical simulations on gasket sealant behavior under high hydrostatic water pressure and a relationship between joint deformation; waterproof performance was obtained and a waterproof performance assessing method was proposed. Liu et al. [15,16] carried out joint waterproof performance tests for full-scale segments and reduced-scale specimens after fire damage. From this, the temperature distributions and the gasket deterioration pattern under high temperatures were acquired. Li et al. [17] and Dong et al. [18] studied the influences of the mechanism of joint opening and offset of subway tunnels on the waterproof performance of gaskets, and corresponding indoor tests were carried out. Aiming at the test characterization of waterproof capacity or seepage water pressure of tunnel joints, the behavior of seepage water under sand leakage conditions is not mentioned by the aforementioned contributions. Zhou et al. [19] established a Coupled Eulerian-Lagrange-based model and the whole leakage process at the segmental joints, considering large deformation and seepage flow in the contact surface, was simulated, and the validity of the hydro-mechanical model was verified. Zheng et al. [20,21] designed a test apparatus to simulate the soil and water losses under the condition of a large joint opening, and an analysis based on the sandy soil of the Tianjin Metro Tunnel was carried out. Given the working conditions of Southern California and Southern China with high seismic intensity, Shalabi et al. [22,23] and Xie et al. [24] conducted joint waterproof performance tests under reciprocating loading conditions, hence, the waterproof capability under vibration was obtained. Zhang et al. [25] investigated the influence mechanism of joint rotation on waterproof capacity; methods were proposed to mitigate the joint leaking situations. Zhang et al. [26,27] developed a waterproof performance testing technology for full-scale segment joints, and impacts of constructing loads on the deformation of gaskets were tested.

With the development of computer sciences and designing protocols, novel technologies and structure forms are introduced for the detection and prevention of the waterproof performance deterioration of joints. Based on a convolutional neural network and EfficientNet, Zhou et al. [28] proposed a defect detecting model, which can be implemented to detect localized leakage in tunnels and monitor the working conditions throughout the design service life (Figure 2). The waterproof performance of a novel structure type with double-layer sealing gaskets at intervals outside the bolt was tested by Xie et al. [29], and the results indicated that the novel structure can substantially enhance the waterproof capacity.

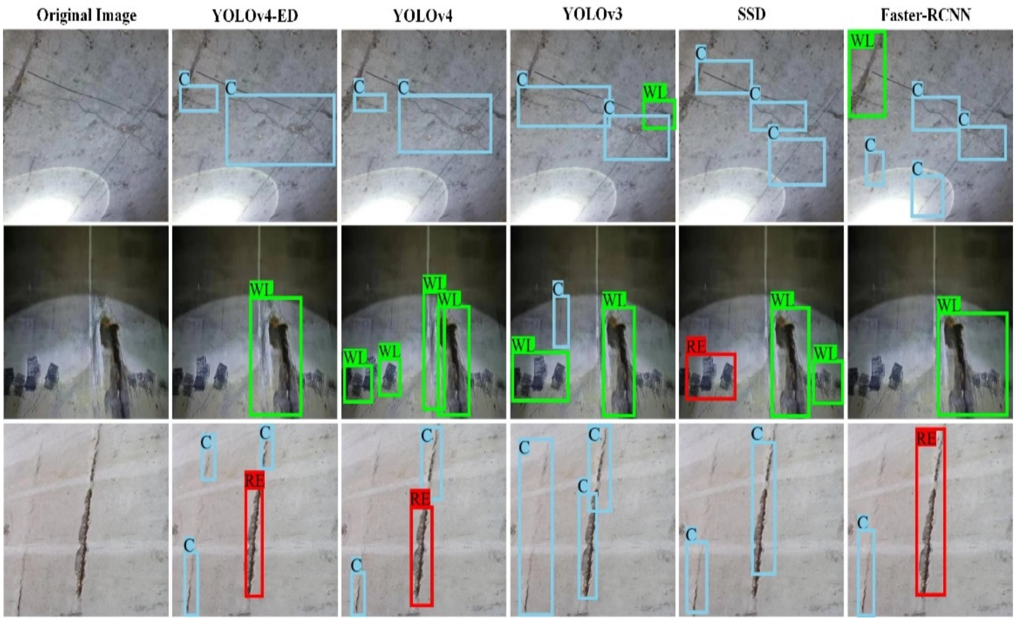

Figure 2. Detection results of different models (Reprinting with permission from Zhou et al., 2022).

Per the literature review, existing research on waterproof performance deterioration captured numerous undermining factors, e.g., high hydrostatic water pressure, high temperature caused by fire, sandy leakage, seismic load, and deformation of the segmental rings. New testing technologies were introduced, and novel structures and waterproof performance evaluation methods were introduced to address the challenges.

2.2. Double-Layer Gasket Configuration and Corresponding Test Technology

Tests and simulations have been conducted for large-diameter shield tunnels with the double-layer gasket configuration. Aforementioned methods are used to determine the functionality under high water pressure. Waterproofing of tunnel joint gaskets depends on the contact condition of the gasket–gasket contact surface and the gasket–segment contact surface, namely, the rubber-rubber contact and the rubber-concrete contact. It is difficult to ensure the smoothness of the in-use segment with reinforced concrete casting and, therefore, it is also hard to determine the contact behavior between the gasket and rubber. Hence, in the tests, the grooves cannot be accurately simulated by a precisely fabricated steel clamp, which makes the results unreliable. Given this, the author participated in the research and development of a novel joint waterproof testing apparatus based on the Nanjing Weisan Road Tunnel [30], and a full-scale concrete segment experiment was performed.

The contributions above on the waterproof testing of tunnel joints are mainly focused on urban railway tunnels and highway tunnels, with a single-layer gasket and the steel clamp specimen. In practice, gaskets are glued in concrete grooves, and the surfaces are rougher than that of steel clamps, so the test accuracy based on steel clamps needs to be further investigated [31]. The most significant difference between the large-diameter deep drainage tunnel and the traditional traffic tunnel is the bi-directional leakage characteristics caused by different drainage and function modes (empty pipe and full pipe).

With the construction of deep drainage tunnels, attention has been drawn to the joint waterproofing of the deep drainage tunnels. Zhang et al. [11] conducted the test of gasket selection according to the Suzhou River test section of the Shanghai Deep Drainage Tunnel. Based on the data collected from the Donghaochong test section of the Guangzhou Deep Drainage Tunnel and the Suzhou River test section of the Shanghai Deep Drainage Tunnel, Gong et al. [32] demonstrated the necessity of adopting a double-layer gasket configuration for joints. However, the above indoor tests of deepwater drainage tunnels adopt the experimental idea of separate testing of inner and outer sealing gaskets or by simply using steel clamps to simulate the contact behavior of sealing gaskets in the segment grooves. Therefore, the test results can not reflect the bi-directional leakage characteristics of the double-layer gaskets in deep drainage shield tunnels under different operating scenarios with high external pressure and variable internal pressure.

Throughout the current studies, the purpose was concentrated on the design and selection of the joint single/double-layer gaskets for urban subway tunnels, urban deep municipal tunnels, and cross-river or cross-sea traffic tunnels, considering the influence of different load conditions (static, earthquake, fire, soil erosion) on the waterproof capacity. To have a scientific and in-depth understanding of the actual leakage failure behavior of the double-layer gaskets in deep drainage shield tunnels under complex internal and external high water pressure, it is urgent to carry out corresponding targeted research and waterproofing performance testing of the double-layer gaskets.

3. Rubber Material Characteristics

The waterproof performance of shield tunnel gaskets is mainly realized by the contact stress between the gasket surfaces [32]. The commonly used materials can be divided into two categories: elastic material, such as ethylene propylene diene monomer (EPDM), chloroprene rubber (CR), etc., and water-swelling rubber material, such as water swelling rubber (WSR). The in-use materials are different, while the overall performance during service is similar. Yang et al. made a detailed review of the material properties, material selection, and chemical mechanism of aging of gasket rubber materials [33]. Test data of water swelling polymer (WSP) and water-swelling rubber polymer (WSRP), under different serving environments, were given by Wang et al. [34], and the performance of the tested materials is compared [35].

Table 2. Summary of joint waterproof performance indoor tests of representative shield tunnel.

Project	Material [1]	Specimen	Purpose	Reference
Chicago Subway Tunnels	NP	Steel clamp	Effects of joint opening	[8]
Singapore Subway Tunnel	EPDM	Steel clamp	Effects of joint opening/offset	[36]
Shanghai Qingcaosha water tunnel	EPDM	Steel clamp	Influence of joint opening/offset/rotation	[9]
Los Angeles Subway Extension	EPDM, NP	Concrete specimen	Influence of seismic load on waterproofing performance	[22]
Beijing Subway Tunnel	COMPOUND	Steel clamp	Effects of high temperatures in fire conditions	[15,16]
Los Angeles Subway Extension	EPDM, NP	Steel clamp	Effects of the opening at the bottom of the sealing gasket	[23]
Nanjing Weisan Road Tunnel	EPDM	Concrete specimen	Summary of test technology	[30]
A Subway Tunnel	EPDM	Steel clamp	Effects of joint opening/offset	[18]
Su'ai Tunnel	EPDM	Steel clamp	Design selection under earthquake	[10]
Nanjing Subway Tunnel	EPDM	Steel clamp	Double-layer waterproof	[17]
Changsha Subway Tunnel	EPDM	Steel clamp	Effects of joint opening/offset	[12]
A Subway Tunnel	EPDM	Steel clamp	Effects of soil erosion	[20,21]
Shanghai deep water storage tunnel	EPDM	Steel clamp	Double-layer waterproof	[11]
Su'ai Tunnel	EPDM	Steel clamp	Comparison of static and dynamic water resistance	[24]

[1] EPDM: ethylene propylene diene monomer; NP: neoprene; COMPOUND: EPDM and water-swelling rubber compound.

3.1. Constitutive Model and Aging Mechanism

The rubber material of gaskets is hyper-elastic, which means that its mechanical constitutive model cannot be described by the typical stress–strain curve. In continuum mechanics, for materials such as hyper-elastic rubber, the phenomenological theory can be used to determine the constitutive model of materials by obtaining the relationship between strain energy density and strain tensor invariants. Commonly used constitutive models include the Arruda–Boyce model, Mooney–Rivlin model (Equation (1)), neo-Hookean model, etc.

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \quad (1)$$

where W is the strain energy density, C_{10} and C_{01} are constants, and I_1 and I_2 are the strain invariants.

Due to its simple mathematical form and high simulation accuracy, the Mooney–Rivlin model is often implemented in gasket performance [37]. A constitutive model of hyper-elastic rubber considering thermal-viscoelastic coupling (Equation(2)) and a rheological model based on non-Newtonian fluid (Equation(3)) were established based on different states of the rubber [38]. In terms of the thermal-mechanical aging model, Li [39] has been devoted to exploring the thermal-mechanical aging process of rubber and its relationship with property changes since the 1990s. Based on the Arrhenius formula (Equation (4)) and the Dakin prediction equation (Equation(5)), a P-T-t aging model was proposed, considering the influence of temperature and time on performance deterioration (Equation(6)).

$$\Psi = -\frac{G_s}{2}\frac{T}{T_0}\lambda_m\left[1 + b\left(\frac{T - T_0}{T_0}\right)\right]\ln\left\{1 - \frac{I_1 - 3}{\lambda_m[1 + b(T - T_0)/T_0]}\right\} + d\left(T - T_0 - T\ln\frac{T}{T_0}\right) \quad (2)$$

where G_s is the isothermal infinitesimal shear modulus, λ_m is the isothermal average maximum elongation, d is the material constant, and b is the temperature correlation factor of the maximum elongation.

$$\sigma_{12} = Y + \frac{A\dot{\gamma}}{B\gamma^{1-n}} \quad (3)$$

where Y and B are constant, and γ stands for the shear distance of the non-Newtonian liquid.

$$K = A_0 e^{-\frac{E}{RT}} \quad (4)$$

where K is the chemical reaction rate, A_0 is the pre-exponential factor, E is the activation energy, R is the molar gas constant, and T is the thermodynamic temperature.

$$f_t(P) = kt \quad (5)$$

where $f_t(P)$ is the reaction rate function, *k* is the coefficient, and *t* is the reaction time.

$$\log\left[-\log\frac{y}{B}\right] = B_0 + B_1/T + B_2 \times \log t \quad (6)$$

where y = f(P), $B_0 = \log(A_0/2.303)$, $B_1 = -E/2.303R$, B_2 is a constant.

Based on thermodynamics, the mathematical relationship among the prevailing predicting models: the kinetic curve method, linear relation method, variable reduction method, and response function method, were analyzed, and the advantages of the proposed three-element aging mathematical model (Equation (6)) in rubber service life prediction were proved. Shi et al. [40] calculated the activation energy of the thermal-oxygen aging reaction process of phenyl ether silicone rubber by taking the critical value of rubber as the key index and establishing the relationship between the temperature and rubber aging prediction. Wang et al. [41] proposed a time-temperature-strain/stress superposition principle (TTSSP), which is useful for the long-term relaxation and creep prediction of EPDM rubber.

The rubber components in tunnels are facing complex situations with high temperature, offset, mechanical factors, etc. Prominent works have been done given the serviceability of the rubber components under different aging conditions by conducting laboratory tests. Liu et al. [42] carried out compressive stress-hydrothermal aging (CS-HA) tests and the residual performance under different pre-compression forces was obtained, hence, the corresponding institutive model was proposed. Based on undersea shield tunnels, mechanical and microchemical tests (TGA, SEM, FTIR) were conducted on accelerated aged EPDM specimens by Wang et al. [43], and the degradation process of EPDM rubber in seawater was obtained.

3.2. Structural Characteristics and Durability

In the indoor segment joint full-scale test, it was found that with high rubber hardness, the closure stress will exceed the shear strength of the concrete groove and cause shear failure at the joint closure stage, which leads to concrete burst in segments [44,45]. Targeting the engineering problems mentioned above, recent studies have been focusing on optimizing the cross-section of the gasket to control its closure stress. Liu et al. [46] discussed the influences of the Balloon Effect on the compressional performance of the internal closed cavity; the results indicated that due to the presence of pressure in the internal holes, the buckling process of gasket hole wall lags was obvious, and the closure stress increased by over 10%. Lei et al. [47] investigated the effect of the internal hole layout and constitutive model, and corresponding simulation results showed great influences of coefficient C_{10} and the internal hole layout on the average contact stress. In addition to in-depth research on the mechanical properties of joint gaskets at room temperature, some scholars [15,37,48] showed interest in the material property damage of joint gaskets in high-temperature scenarios.

On the other hand, regarding the durability of tunnel joint gaskets during the service period, Sun [49] pointed out the significant effect of the durability of segment joint waterproof materials on the long-term safety and functionality of tunnels. Taking the Shanghai Chongming Yangtze River tunnel as the engineering case, Wu et al. [50] carried out the artificially accelerated aging test of EPDM gaskets and predicted the contact stress of joint gaskets after simulating 100-year aging. Zhong et al. [51] studied the long-term performance of EPDM gaskets under constant compression for the Qiantang River tunnel. Further, Shi et al. [52] proposed a hyper-elastic time-varying constitutive model of EPDM material suitable for the water environment by conducting tensile tests of EPDM dumbbell-type specimens based on the theory of large deformation of elastomer [53] and its extended theory [54]. Gong et al. [55] carried out a full-scale parametric study on the design parameters of the gasket and its influences on the waterproof performance, and the fluid pressure penetration (FPP) module of the FE commercial package ABAQUS/Explicit was implemented to simulate the seepage process of segmental joint leakage. In addition to that, Yang et al. [33] summarized the material characteristics of joint gaskets in shield tunnels.

Scholars have conducted productive studies on the mechanical properties and durability prediction of joint gasket materials, and preliminarily explored the degradation of material properties of gaskets. Existing material characteristic research focused on the constitutive model, time-dependent characteristics, structure response, and gasket layouts while a comprehensive solution is yet to be proposed. The layout study is closely related to the constitutive model, which is highly variable with aging. To begin with, a comprehensive investigation and a universal longevity prediction method should be established.

4. Waterproof State Simulation Methods Development

Numerical simulation methods of the shield tunnel joint waterproof process are twofold [56]: a simplified simulation based on average contact stress and a fine simulation based on the meso-opening process of the contact surface.

4.1. Simplified Method

In terms of the simplified numerical simulation method, the key point is to collect the average contact stress under specific joint deformation conditions, such as the waterproofing threshold due to the material nonlinearity of gaskets, large geometric deformation, and complex contact relations. Zhao et al. [57] proposed the concept of taking average contact stress as a reference for waterproofing ability. Gong et al. [58] proposed empirical formulas for contact stress and waterproofing capacity of seven typical gaskets based on experimental results and numerical analysis data. Sun [59] analyzed the stress deformation of gaskets considering water pressure and studied the corresponding contact stress distribution and waterproof failure mode. Due to the nonlinear nature, large deformation, and complex contact of gaskets, the research of numerical simulation analysis is focused on accurately reproducing the compression deformation process of gaskets in grooves [33,60]. The latest research extends to how to simulate the leaking failure process of joint gaskets: Based on the concept of average contact stress, Gong et al. [13] compared the contact stress on different contact surfaces under the joint opening, offset, and rotation modes to predict the location of leakage. Li Pin et al. [61] proposed the concept of effective contact stress and refined the failure mechanism of different contact surfaces. In essence, the above methods are simplified models that equate the lateral water pressure to uniform pressure and do not consider the mesoscopic opening process of water pressure invading the gasket contact surface. In the preliminary design stage, the simplified numerical simulation method can better predict the deformation performance and contact stress of gaskets.

4.2. Fine Simulation Method

To further investigate the impacts of progressive water pressure intrusion on the waterproof performance of joint gaskets, Yuan et al. [62] introduced the fluid-structure coupling algorithm based on the Euler–Lagrange grid method to perform a fine simulation of the joint seepage process. Zhou et al. [63] further extended the algorithm to the seepage process simulation of t-shaped joints. However, the above calculation method assumes that the fluid has no pressure, and there is a certain deviation from the actual situation. Gong et al. solved the problem while still unable to account for the progressive open leakage process of two-layer gasket waterproofing structures under different water pressure directions [7].

To investigate the tunnel structure and joint deformation under partial joint leakage, a lot of work has been accomplished in recent years. Shin et al. [64] and Zhang et al. [65] established two-dimensional/three-dimensional finite element models based on the formation-structure method and analyzed the evolution of seepage formation and structural deformation under the condition of localized joint seepage. However, the above models adopt the idea of weakening joint stiffness from the Homogeneous Ring method, and the simulation results are not verified by collected data. To tackle this dilemma, Wu et al. [66] proposed a self-defined joint leakage unit, however, the joint opening process in the seepage process is not considered.

The main difficulty of the fine simulation lies in the reappearance of the continuous – discontinuous process of water pressure expansion on the contact surface, and the key to it is overcoming the convergence problem caused by large deformation. Gong et al. [7] adopted the idea of numerical simulation of a large deformation process of static penetration test for a reference [67,68]. Based on the built-in “mesh-to-mesh Solution Mapping” technology of FE commercial package ABAQUS/Explicit, the Mesh Regeneration Method, illustrated in Figure 3, was proposed, and the accurate simulation of the dynamic process of water pressure expansion on the contact surface was realized. A Continuous-Discontinuous Fine Finite Element method for calculating the joint waterproofing capacity of the shield tunnel under normal temperature was established.

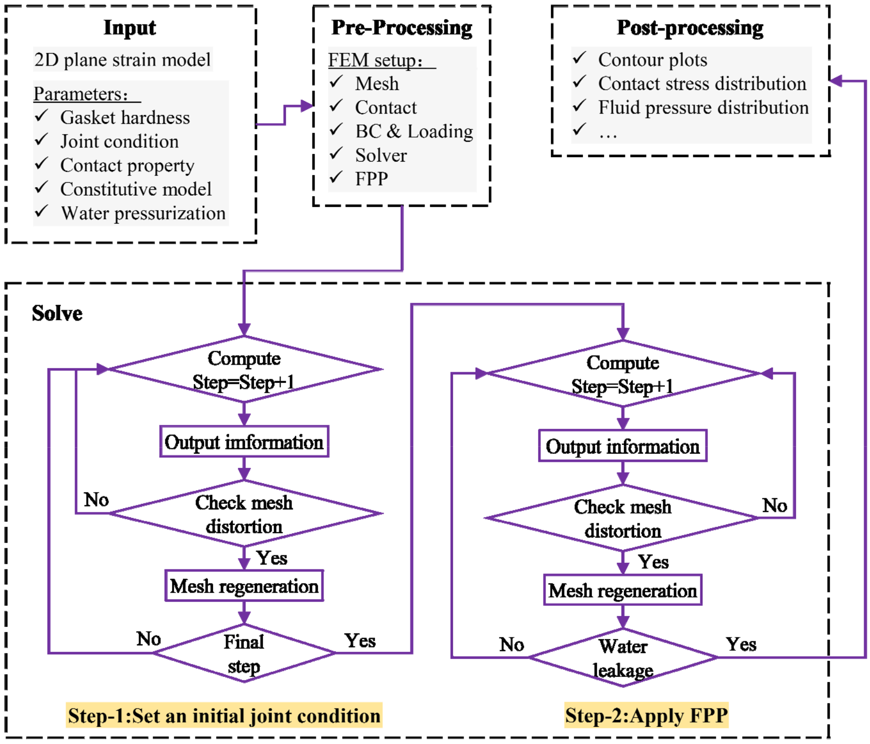

Figure 3. Flowchart of the Mesh Regeneration method [7] (Reprinting with permission from Gong et al., 2018).

The existing fine numerical simulation method of waterproof performance of joint gaskets for shield tunnels and the large numerical simulation model considering the interaction between stratum and tunnel structure did not consider the double-layer gasket configuration, and the adopted model only considers the application of external water pressure, which does not apply to deep drainage shield tunnels.

Therefore, it is necessary to focus on the upcoming requirements of joint bi-directional waterproof sealing of deep drainage shield tunnels under complex internal and external water pressure conditions, and carry out research on the seepage formation mechanism of segment joints and the waterproof failure mechanism of double-layer gaskets.

5. Thermal-Mechanical Coupling Analysis Model

In terms of the thermal-mechanical coupling analysis model, the existing research focuses on mathematical models and corresponding calculation methods for the shield tunnel lining under high temperatures caused by fire.

Zhu et al. [1] made an in-depth and detailed analysis and reviewed the research progress in the theoretical analysis model for segment joints and lining structures under high fire temperatures. Representative research achievements in recent years include Savov et al. [69], who established a layered Beam-Spring model that can characterize the bursting of lining concrete under fire; Yao et al. [70], who discussed the temperature field distribution of lining structure at high temperatures based on the Homogeneous Ring model. Luo et al. [71] used a thermal-mechanical coupling numerical model of tunnel lining structure to analyze the influence of different heating curves on stress. Further, Zhang et al. [72] developed a strong coupling numerical model of heat, water, and steam. Liu et al. [15] constructed a fine thermal-mechanical coupling model for lining structures, considering the cracking and crushing characteristics of concrete at high temperatures. In addition, some scholars have also modeled the mechanical behavior of the structure and waterproofing weak point-segment joints. Shen et al. [73] established the thermal-mechanical coupling finite element model for reinforced concrete and fiber-reinforced segment joints at high temperatures in fire. Liu et al. [15] used the joint thermal-mechanical coupling numerical model to predict the opening amount of joint gaskets and explore the waterproof performance at high temperatures.

In general, compared with the research on mechanical behavior models of shield tunnel lining structures and joints, there are few reports on the sealing capacity and response of lining structures at different joint positions under the effect of temperature.

6. Conclusions

Throughout this article, it can be seen that the research on the waterproof sealing performance of shield tunnel joints is a worthy and in-depth subject. Scholars have carried out a considerable amount of productive research, from full-scale and reduced-scale specimen waterproofing tests to numerical simulations and other aspects. However, the following problems remain to be further probed:

1. Current research mainly focuses on the sealing performance at normal temperature, and the deterioration evolution mechanism of sealing performance considering the variation of temperature is worth exploring.
2. The current aging mechanism of rubber is rather vague, and full-scale, long-term aging tests are not commonly conducted. Starting from the actual working conditions, the relationship between the gasket material aging and the waterproof ability deterioration of the shield tunnel can be obtained through the full-scale test, which will aid engineering practice.
3. The continuous–discontinuous numerical method of gasket waterproof capability is limited to the normal temperature scenarios while failing to cover extreme working conditions, such as fire, etc., which needs to be modified to consider the temperature effect.
4. Research on the thermal-mechanical coupling mechanical performance analysis model of shield tunnel lining structure and the joint is more in-depth and systematic, while the research on the thermal-mechanical coupling sealing performance analysis model is relatively rare.

The waterproof performance of shield tunnel gaskets is affected by materials, structures, and external factors. With the growing number of shield tunnels with large burial depth, high water pressure, and long design life, more attention will be paid to the waterproof performance of the gaskets. The design and inspection of joint gaskets in engineering practice will benefit from research on material durability, structural characteristics, external hazards, and simulation methods.

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References

1. Zhu, H.H.; Zhou, L.; Shen, Y.; Yan, Z.G. Review of experiments and mechanical models of shield lining structure exposed to high temperature. *China J. Highw. Transp.* **2017**, *30*, 15–23, 48. (In Chinese) [CrossRef]
2. He, C.; Liu, S.J.; Zhang, Y.C.; Feng, K. Service Security of Underwater Tunnel Lining Structures and Corresponding Guarantee Countermeasures. *Eng. Sci.* **2017**, *19*, 44–51. (In Chinese) [CrossRef]
3. Du, Y.L.; Sun, B.C.; Wu, Z.S.; Qian, Y.J.; Gao, Y. Strategies for Establishing and Perfecting Long-Life Security Strategy of Transportation Infrastructure. *Eng. Sci.* **2017**, *19*, 1–5. (In Chinese) [CrossRef]

4. Howard, A.J. Report on the damaging effects of water on tunnels during their working life. *Tunn. Undergr. Space Technol.* **1991**, *6*, 11–76.
5. Dammyr, O.; Nilsen, B.; Thuro, K.; Grondal, J. Possible Concepts for Waterproofing of Norwegian TBM Railway Tunnels. *Rock Mech. Rock Eng.* **2014**, *47*, 985–1002. [CrossRef]
6. Wu, H.Y.; Dong, M.; Han, T.C.; Xu, R.Q.; Gong, X.N. Riview and prospects of new materials in urban underground development. *Eng. Sci.* **2017**, *19*, 116–123. (In Chinese)
7. Gong, C.J.; Ding, W.Q. A computational framework to predict the water-leakage pressure of segmental joints in underwater shield tunnels using an advanced finite element method. *Int. J. Numer. Anal. Methods Geomech.* **2018**, *42*, 1957–1975. [CrossRef]
8. Paul, S. *Sealability Tests of Gaskets between Precast Concrete Tunnel Lining Segments*; Unpublished Report; Department of Civil Engineering, University of Illinois at Urbana-Champaign: Urbana, IL, USA, 1978.
9. Liu, J.G. Waterproof Mechanism and Application of Shield Segment Gasket. Master's Thesis, Tongji University, Shanghai, China, 2010. (In Chinese).
10. Xie, H.M.; Du, Y.L.; He, C.; Feng, K.; Liu, S.J.; Zhang, J. Waterproof performance of segment joints of large section subsea shield tunnel under strong earthquake. *China J. Highw. Transp.* **2017**, *30*, 201–209. (In Chinese) [CrossRef]
11. Zhang, Z.X.; Sun, J.; Zhu, Y.F.; Huang, X.; Yuan, W.H. Experimental study on waterproof performanceof oint seal for deeply-buried storage and drainage tunnel. *J. Zhejiang Univ.* **2018**, *52*, 431–439. (In Chinese)
12. Shi, C.H.; Cao, C.Y.; Lei, M.F.; Yang, W.C. Sealant Performance Test and Stress-Seepage Coupling Model for Tunnel Segment Joints. *Arab. J. Sci. Eng.* **2019**, *44*, 4201–4212. [CrossRef]
13. Gong, C.J.; Ding, W.Q.; Soga, K.; Mosalam, K.M. Failure mechanism of joint waterproofing in precast segmental tunnel linings. *Tunn. Undergr. Space Technol.* **2019**, *84*, 334–352. [CrossRef]
14. Lei, M.F.; Zhu, B.B.; Gong, C.J.; Ding, W.Q.; Liu, L.H. Sealing performance of a precast tunnel gasketed joint under high hydrostatic pressures: Site investigation and detailed numerical modeling. *Tunn. Undergr. Space Technol.* **2021**, *115*, 104082. [CrossRef]
15. Liu, T.; Yuan, D.J.; Wang, A.H.; Wang, H.; Pan, D. Experimental study on watertight performance of prototype shield tunnel segment joint affected by fire. *China Civ. Eng. J.* **2016**, *49*, 116–122. (In Chinese) [CrossRef]
16. Liu, T.; Yuan, D.J.; Zhang, H. Experimental study on waterproof performance deterioration regulation of shield segment joint rubber in environment of high temperature fire. *China Civ. Eng. J.* **2015**, *48*, 244–249. (In Chinese)
17. Li, X.; Zhou, S.H.; Di, H.G.; Wang, P.X. Evaluation and experimental study on the sealant behaviour of double gaskets for shield tunnel lining. *Tunn. Undergr. Space Technol.* **2018**, *75*, 81–89. [CrossRef]
18. Dong, L.W.; Jiang, Y.S.; Yang, Z.Y.; Cheng, J.G.; Liu, C.Q.; Zhang, J.J. Experimental study and water-resistant mechanism of gaskets in joints of tunnel segments. *Chin. J. Geotech. Eng.* **2017**, *39*, 469–474. (In Chinese)
19. Zhou, W.F.; Liao, S.M.; Men, Y.Q. A fluid-solid coupled modeling on water seepage through gasketed joint of segmented tunnels. *Tunn. Undergr. Space Technol.* **2021**, *114*, 104008. [CrossRef]
20. Zheng, G.; Dai, X.; ZHang, X.S. Experimental study an numerical simulation of leaking process of sand and water in underground engineering. *Chin. J. Rock Mech. Eng.* **2014**, *33*, 2458–2471. (In Chinese) [CrossRef]
21. Zheng, G.; Yao, J.; Dai, X.; YAng, X.Y.; Sun, J.Y. Experimental study on sand inflow under different opening widths of shield tunnel segments. *Chin. J. Geotech. Eng.* **2018**, *40*, 969–977. (In Chinese)
22. Shalabi, F.I.; Cording, E.J.; Paul, S.L. Concrete segment tunnel lining sealant performance under earthquake loading. *Tunn. Undergr. Space Technol.* **2012**, *31*, 51–60. [CrossRef]
23. Shalabi, F.I.; Cording, E.J.; Paul, S.L. Sealant behavior of gasketed segmental tunnel lining—Conceptual model. *Geomech. Tunn.* **2016**, *9*, 345–355. [CrossRef]
24. Xie, H.M.; He, C.; Feng, K.; Liang, M.F.; Li, C.; Maged, A.-S. Unidirectional Vibration Waterproof Test of Ring Joint of Shield Tunnel under the Action of Earthquake. *J. Southwest Jiaotong Univ.* **2020**, *55*, 713–718. (In Chinese)
25. Zhang, D.M.; Liu, J.; Huang, Z.K.; Yang, G.H.; Jiang, Y.; Jia, K. Waterproof performance of tunnel segmental joints under different deformation conditions. *Tunn. Undergr. Space Technol.* **2022**, *123*, 104437. [CrossRef]
26. Zhang, W.J.; Zhang, G.L.; Li, H.L.; Gao, W.Y.; Guo, W.S.; Gao, P. Waterproof performance of sealing gaskets impact of construction loads on segment joints in shield tunnel. *China J. Highw. Transp.* **2020**, *33*, 130–141. (In Chinese) [CrossRef]
27. Zhang, G.L.; Zhang, W.J.; Li, H.L.; Cao, W.Z.; Wang, B.D.; Guo, W.S.; Gao, P. Waterproofing behavior of sealing gaskets for circumferential joints in shield tunnels: A full-scale experimental investigation. *Tunn. Undergr. Space Technol.* **2021**, *108*, 103682. [CrossRef]
28. Zhou, Z.; Zhang, J.; Gong, C. Automatic detection method of tunnel lining multi-defects via an enhanced You Only Look Once network. *Comput. Aided Civ. Infrastruct. Eng.* **2022**, *37*, 762–780. [CrossRef]
29. Xie, H.M.; Wang, S.M.; He, C.; Ma, T.Y.; Peng, X.Y.; Li, P. Performance of a new waterproof system with double sealing gaskets outside bolt hole of segment. *Tunn. Undergr. Space Technol.* **2022**, *119*, 104206. [CrossRef]
30. Ding, W.Q.; Gong, C.J.; Mosalam, K.M.; Soga, K. Development and application of the integrated sealant test apparatus for sealing gaskets in tunnel segmental joints. *Tunn. Undergr. Space Technol.* **2017**, *63*, 54–68. [CrossRef]
31. Wang, S.M.; Xie, H.M. Review and prospect of waterproofing of segment joints of shield tunnel with high hydraulic pressure. *Hazard Control Tunn. Undergr. Eng.* **2020**, *2*, 66–75.
32. Gong, C.J.; Ding, W.Q.; Mosalam, K.M.; Gunay, S.; Soga, K. Comparison of the structural behavior of reinforced concrete and steel fiber reinforced concrete tunnel segmental joints. *Tunn. Undergr. Space Technol.* **2017**, *68*, 38–57. [CrossRef]

33. Yang, C.; Shen, S.L.; Hou, D.W.; Liao, S.M.; Yuan, D.J. Material properties of the seal gasket for shield tunnels: A review. *Constr. Build. Mater.* **2018**, *191*, 877–890. [CrossRef]
34. Wang, Z.N.; Shen, S.L.; Zhou, A.N.; Lyu, H.M. Experimental data of water swelling characteristics of polymer materials for tunnel sealing gasket. *Data Brief* **2020**, *31*, 106021. [CrossRef] [PubMed]
35. Wang, Z.N.; Shen, S.L.; Zhou, A.N.; Lyu, H.M. Experimental investigation of water-swelling characteristics of polymer materials for tunnel sealing gasket. *Constr. Build. Mater.* **2020**, *256*, 119473. [CrossRef]
36. Schurch, M. Small but important–gaskets for tunnel segments. In Proceedings of the International Symposiumon on Underground Excavation and Tunnelling, Bangkok, Thailand, 2–4 February 2006.
37. Tan, W.Y. Research on the Property of Rubber Gaskets in Shield Tunnel Lining Joints after High Temperature. Master's Thesis, South China University of Technology, Guangzhou, China, 2015. (In Chinese).
38. Wei, Y.T.; Fang, Q.H.; Jin, Z.B.; Feng, X.J. Progress in constitutive models of filled rubber. *Polym. Bull.* **2014**, *5*, 15–21. (In Chinese) [CrossRef]
39. Li, Y.J. Study on deterioration of physical and mechanical properties of vulcanized rubber during thermal oxygen aging. *Spec. Rubber Prod.* **1997**, *18*, 44–53. (In Chinese) [CrossRef]
40. Shi, X.B.; Chen, X.Y.; Jiang, L.; Xue, H.H. Activation energy and life analysis of rubber based on accelerated thermal aging test. *Chin. N. Technol. Prod.* **2021**, *11*, 18–20. (In Chinese) [CrossRef]
41. Wang, Z.N.A.; Shen, S.L.; Zhou, A.N.; Lyu, H.M. Investigation of Time-Dependent Characteristics of EPDM Rubber Gasket Used for Shield Tunnels. *J. Mater. Civ. Eng.* **2021**, *33*, 04021251. [CrossRef]
42. Liu, Y.K.; Zhang, Q.S.; Liu, R.T.; Chen, M.J.; Zhang, C.Y.; Li, X.H.; Li, W.H.; Wang, H.B. Compressive stress-hydrothermal aging behavior and constitutive model of shield tunnel EPDM rubber material. *Constr. Build. Mater.* **2022**, *320*, 126298. [CrossRef]
43. Wang, Z.N.; Shen, S.L.; Zhou, A.N.; Xu, Y.S. Experimental Evaluation of Aging Characteristics of EPDM as a Sealant for Undersea Shield Tunnels. *J. Mater. Civ. Eng.* **2020**, *32*, 04020182. [CrossRef]
44. Jin, Y.L.; Ding, W.Q.; Yan, Z.G.; Soga, K.; Li, Z.L. Experimental investigation of the nonlinear behavior of segmental joints in a water-conveyance tunnel. *Tunn. Undergr. Space Technol.* **2017**, *68*, 153–166. [CrossRef]
45. Caratelli, A.; Meda, A.; Rinaldi, Z.; Giuliani-Leonardi, S.; Renault, F. On the behavior of radial joints in segmental tunnel linings. *Tunn. Undergr. Space Technol.* **2018**, *71*, 180–192. [CrossRef]
46. Liu, J.G.; Zhou, S.H. Analysis of the performance of the shield tunnel gasket compression considering the ballon effect. *J. Build. Mater.* **2013**, *16*, 993–997. (In Chinese)
47. Lei, Z.Y.; Liu, M. Sensitivity analysis of water-proof performance of elastic rubber gasket in shield tunnel. *J. Tongji Univ.* **2017**, *45*, 336–341. (In Chinese)
48. Yan, Z.G.; Zhu, H.H.; Ju, J.W.; Ding, W.Q. Full-scale fire tests of RC metro shield TBM tunnel linings. *Constr. Build. Mater.* **2012**, *36*, 484–494. [CrossRef]
49. Sun, J. Durability design of segment lining structure in Chongming Yangtze River shield tunnel. *J. Archit. Civ. Eng.* **2008**, *25*, 1–9. (In Chinese)
50. Wu, Z.Z.; Yang, L.D.; Ji, Q.Q.; Dai, S.; Mo, Y.T. Experimental Study on Stress Relaxation of Waterproof Gasket of River-Crossing Shield Tunnel. *J. Build. Mater.* **2009**, *12*, 539–543. (In Chinese)
51. Zhong, X.C.; Qin, J.S.; Zhu, W.; MIn, F.L. Durability Tests and Analysis on the Waterproof Material for Joint Seam of Shield Tunnel. *Chin. J. Undergr. Space Eng.* **2011**, *7*, 281–285. (In Chinese)
52. Shi, C.H.; Cao, C.Y.; Lei, M.F.; Peng, L.M.; Shen, J.J. Time-dependent performance and constitutive model of EPDM rubber gasket used for tunnel segment joints. *Tunn. Undergr. Space Technol.* **2015**, *50*, 490–498. [CrossRef]
53. Mooney, M. A theory of large elastic deformation. *J. Appl. Phys.* **1940**, *11*, 582–592. [CrossRef]
54. Rivlin, R.S. Large elastic deformations of isotropic materials IV. further developments of the general theory. *Philos. Trans. R. Soc. London Ser. A Math. Phys. Sci.* **1948**, *241*, 379–397.
55. Gong, C.J.; Ding, W.Q.; Xie, D.W. Parametric investigation on the sealant behavior of tunnel segmental joints under water pressurization. *Tunn. Undergr. Space Technol.* **2020**, *97*, 103231. [CrossRef]
56. Gong, C.J.; Ding, W.Q.; Mosalam, K.M. Performance-based design of joint waterproofing of segmental tunnel linings using hybrid computational/experimental procedures. *Tunn. Undergr. Space Technol.* **2020**, *96*, 103172. [CrossRef]
57. Zhao, M.; Ding, W.Q.; Peng, Y.C.; Shen, B.W.; Guo, X.H.; Yang, L.S. Experimental study on joint waterproofing reliability of shield tunnel with high water pressure. *Mod. Tunn. Technol.* **2013**, *50*, 87–93. (In Chinese) [CrossRef]
58. Gong, C.J.; Ding, W.Q.; Soga, K.; Mosalam, K.M.; Tuo, Y.F. Sealant behavior of gasketed segmental joints in shield tunnels: An experimental and numerical study. *Tunn. Undergr. Space Technol.* **2018**, *77*, 127–141. [CrossRef]
59. Sun, L.W. Shield Tunnel Structure Behavior under External Load. Doctoral Dissertation, Zhejiang University, Hangzhou, China, 2016.
60. Zhang, Q.J.; Mo, H.H.; Huang, C.R.; Chen, J.S. Study of Compression Performance and Cross-section Design of Rubber Gasket for Prefabricated Utility Tunnel. *Tunn. Constr.* **2018**, *38*, 399–405. (In Chinese)
61. Li, P.; Xie, H.M.; He, C.; Zhou, Z.Y.; Wang, S.M. Waterproof Performance Analysis of Water Sealing Gasket of Large Open Shield Tunnel Based on Effective Contact Stress. *Tunn. Constr.* **2019**, *39*, 1993–1999. (In Chinese)
62. Yuan, D.J.; Wu, J.; Shen, X.; Jin, D.L.; Li, X.G. Engineering safety of cross-river or cross-sea long-distance large-diameter shield tunneling under superhigh water pressure. *China J. Highw. Transp.* **2020**, *33*, 26–45. (In Chinese) [CrossRef]

63. Zhou, W.F.; Liao, S.M.; Men, Y.Q. Contact stress and waterproof capacity of T-joint in shield tunnel. *Chin. J. Geotech. Eng.* **2020**, *42*, 2264–2270. (In Chinese)
64. Shin, J.H.; Kim, S.H.; Shin, Y.S. Long-term mechanical and hydraulic interaction and leakage evaluation of segmented tunnels. *Soils Found.* **2012**, *52*, 38–48. [CrossRef]
65. Zhang, D.M.; Ma, L.X.; Zhang, J.; Hicher, P.Y.; Juang, C.H. Ground and tunnel responses induced by partial leakage in saturated clay with anisotropic permeability. *Eng. Geol.* **2015**, *189*, 104–115. [CrossRef]
66. Wu, H.N.; Shen, S.L.; Chen, R.P.; Zhou, A. Three-dimensional numerical modelling on localised leakage in segmental lining of shield tunnels. *Comput. Geotech.* **2020**, *122*, 103549. [CrossRef]
67. Tian, Y.H.; Cassidy, M.J.; Randolph, M.F.; Wang, D.; Gaudin, C. A simple implementation of RITSS and its application in large deformation analysis. *Comput. Geotech.* **2014**, *56*, 160–167. [CrossRef]
68. Wang, D.; Bienen, B.; Nazem, M.; Tian, Y.H.; Zheng, J.B.; Pucker, T.; Randolph, M.F. Large deformation finite element analyses in geotechnical engineering. *Comput. Geotech.* **2015**, *65*, 104–114. [CrossRef]
69. Savov, K.; Lackner, R.; Mang, H.A. Stability assessment of shallow tunnels subjected to fire load. *Fire Saf. J.* **2005**, *40*, 745–763. [CrossRef]
70. Yao, J.; Zhu, H.H.; Yan, Z.G.; Zeng, L.J. Experimental research on mechanical property of tunnel lining concrete after high temperature effect. *Chin. J. Undergr. Space Eng.* **2007**, *3*, 66–72, 82. (In Chinese)
71. Luo, J.L.; Xu, Z.S.; Guo, X.J.; Zhang, Y. Analysis of the failure mechanism of a new-type bamboo structure building due to heat and moisture. *J. Saf. Environ.* **2013**, *13*, 159–164. (In Chinese)
72. Zhang, Y.M.; Zeiml, M.; Maier, M.; Yuan, Y.; Lackner, R. Fast assessing spalling risk of tunnel linings under RABT fire: From a coupled thermo-hydro-chemo-mechanical model towards an estimation method. *Eng. Struct.* **2017**, *142*, 1–19. [CrossRef]
73. Shen, Y.; Yan, Z.G.; Zhu, H.H. Full-scale Experimental Research on the Development of the Initial Stage of Fire in a Large Cross-section Road Tunnel. *Chin. J. Undergr. Space Eng.* **2015**, *11*, 1080–1087. (In Chinese)