Multiscale Analytical Method and Its Parametric Study for Lining Joint Leakage of Shield Tunnel

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Featured Application: This study could provide a shield lining joint leakage calculation and analysis model.

Abstract: Understanding the underlying processes of lining joint leakage is essential for predicting its waterproofing performance, improving the design, and assessing its operational health in shield tunnels. There is little literature reported on a leakage model that can reflect various influencing factors. This article introduced an analytical method for predicting joint leakage based on recently developed multi-scale contact mechanics: the Persson model. In addition, the critical leakage state and the self-sealing effect were defined, and an approach to calculate the critical leakage pressure, as well as self-sealing stress, were deduced. Then, taking the second Dapu Road Tunnel in Shanghai as a case study, the influence of various factors, including the gap and offset of joints, the roughness of sealing materials, the service time, and groundwater pressure on the lining joint leakage, was calculated. The applicability of the model was verified by comparing the calculated results with the experimental data and monitoring data in the literature. This research could contribute to understanding the development process of seepage in sealing engineering and provide a reference for waterproof design and the performance assessment of shield tunnels’ lining joints.

Keywords: shield tunnel; leakage model; critical leakage pressure; EPDM gasket; service time

1. Introduction

Leakage often occurs in operating tunnels due to the aging of sealing materials of tunnels’ lining joints [1–6]. Historically, leakages mainly start from joints of lining segments in tunnels supported by impervious concrete lining segments, since the whole tunnel lining consists of numerous longitudinal and circumferential joints, particularly, almost more than 90% occurs in circumferential joints [5,6]. Once leakage develops, surrounding soils of a tunnel can be eroded by leakages of water, which leads to tunnel deformation and further exaggerated leakages [7,8]. Consequently, continuous leakages have a significant potential impact on the operation of tunnels, which is especially adverse to the electrical equipment in it. Since leakages often happen at points of lining segments joints and have significant potential damage, the sealing and waterproofing capacity between joints of lining segments has attracted the extensive attention of researchers [6,9,10].

In the past decades, some scholars have focused on the sealing performance of shield joints [11–17], having experimentally investigated the waterproof and mechanical properties of shield joints. Gong and
Ding [18] presented a method to predict the water-leakage pressure of segmental joints in shield tunnels using a finite element solver. Meanwhile, a series of researches [5,6,10,19,20] were conducted on tunnel leakage and its induced hazards. All of those studies, to some extent, brought insights into the mechanisms that control the sealing performance of materials between joints, and presented hazards due to leakages through in-situ monitoring and numerical simulation. However, an analytical approach to describe the water-leakage failure process and reflect the main influencing factors of gasketed joint leakage is rarely reported.

In order to understand the underlying process of shield joint leakage and the influential law of factors on it, a recently developed multi-scale contact mechanical model (the Persson model) was introduced to predict the leakage of shield lining joints. The model can reflect the joint gap (i.e., contact stress) and the offset (i.e., the length of the leak path), the service time (i.e., rheological properties of sealing materials), the roughness of sealing materials, and groundwater pressure in its parameters. Then, the model was developed to derive the calculation process of the self-sealing stress and critical leakage pressure of the sealing interface. Then, the mathematical model was applied to study the case of the second Dapu Road Tunnel in Shanghai. Finally, the affecting degrees of factors were evaluated and arranged, and the application conditions, advantages and disadvantages of this computed model were also elaborated.

2. Leakage Model of Shield Joints Based on the Persson Model

A mathematical model to describe the leakage of shield joints must contain parameters that at least can reflect the influencing factors, including the joint gap, the joint offset, the contact surface roughness, and the service time. The method explored here is adequate. This section initially describes the influencing factors of shield joints and then introduces the process of calculating the average interfacial separation using the Persson model. It then defines the critical leakage state and the self-sealing effect, as well as deduces the solution of critical leakage pressure and the self-sealing stress. Finally, the size of the percolation channel is calculated through the above process, and further the leakage is obtained by Navier-Stokes equations (N-S equations).

2.1. Influencing Factors of Shield Joints

2.1.1. Configuration of Shield Joints

The lining of a shield tunnel is composed of prefabricated reinforced concrete segments linked by high-strength bolts. Its joints seal is achieved by ethylene-propylene-diene monomer (EPDM) gaskets around the segments. An EPDM gasket is the primary component of the waterproof structure of shield joints. Under assembly pressure, a rubber gasket deforms greatly and provides a great elastic restoring force, so as to be squeezed to fill the uneven contact surface and block the seepage channel of groundwater. The lining segments and the joint configurations are shown in Figure 1.

2.1.2. Sealing Principle and Influencing Factors of Shield Joint Leakage

EPDM gaskets are affixed to grooves on lining segments by a waterproof sealant (Figure 2), so leakages may occur only in-between the area where a pair of gaskets contact each other, on the premise that the sealant-affixed areas are impermeable. Under assembly forces, the EPDM gaskets are compressed and undergo large deformations. Since it has properties of rubber with the ability of resilience, in a pair of gaskets, both of them tend to recover, which generates an elastic restoring force that presses the opposite gasket and generates contact stress, leading to close contact with each other. Consequently, the surfaces of gaskets that are rough on the microscale are squeezed and become even and smooth, which limits the development of potential leaking channels and achieves the goal of sealing. The contact pressure is inevitably affected by assembly errors during the construction. According to the GB50446—2017 “Code for construction and acceptance of shield tunnelling method”, there is usually an allowable assembly error of less than 6 mm for subway tunnels [21].
Additionally, for an underground sealing project, the roughness of contact surfaces and groundwater (from the change of geology condition, all kinds of loads above the tunnel and ongoing surrounding construction), will change the contact stress and contact area of the sealing interface and further affect the joint gap and offset between lining segments caused by a poor assemblage or tunnel deformation. The joint gap and offset between lining segments caused by a poor assemblage or tunnel deformation (from the change of geology condition, all kinds of loads above the tunnel and ongoing surrounding construction), will change the contact stress and contact area of the sealing interface and further affect the sealing performance. The relaxation or aging of EPDM gaskets over the service time will cause some asperities on the sealing interface to show up again and further form new percolation channels. Additionally, for an underground sealing project, the roughness of contact surfaces and groundwater pressure will also influence leakage.

As noted above, the better sealing performance is achieved by squeezing EPDM gaskets to make the contact surface more compact. However, many factors could cause the poorer performance of joint sealing, such as deformation of the tunnel structure and relaxation or aging of EPDM gaskets. The joint gap and offset between lining segments caused by a poor assemblage or tunnel deformation (from the change of geology condition, all kinds of loads above the tunnel and ongoing surrounding construction), will change the contact stress and contact area of the sealing interface and further affect the sealing performance. The relaxation or aging of EPDM gaskets over the service time will cause some asperities on the sealing interface to show up again and further form new percolation channels. Additionally, for an underground sealing project, the roughness of contact surfaces and groundwater pressure will also influence leakage.

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The geometry and stress distribution of the sealing interface are determined by the roughness of the contact surface, and their expression under stress can be given by the Persson model [22–26].
2.2. Persson Model

The Persson model is a multi-scale contact model that describes the contact mechanics of contact interfaces. The force-deformation correlation of sealing interfaces can be clarified by using it; then, the topography of contact interfacing asperities that characterize the percolation channel is obtained.

2.2.1. Magnification and Actual Contact Area

As shown in Figure 3, on a magnification, for two surfaces that are close contact with each other, the actual contact occurs only at some randomly distributed asperities, while the observed contact length \( L \) is large. Those uncontacted regions provide a possibility for the formation of leak channels. The magnification is then defined as the ratio of the observed contact length \( L \) to the length of the asperity wavelength \( \lambda \), as shown by Equation (1):

\[
\zeta = \frac{L}{\lambda}
\]  

(1)

The definition of magnification shows that, if it is the smallest, \( \zeta = 1 \), the two surfaces appear to be fully attached and as it increases, fine asperities will emerge, as well as the more non-contact region. Further, on magnification \( \zeta \), if the actual contact area is \( A(\zeta) \) and the observed contact region is \( A_0 \) when \( \zeta = 1 \), the relative contact area fraction is defined by:

\[
P(\zeta) = \frac{A(\zeta)}{A_0}
\]  

(2)

Then, there are \( \zeta \geq 1 \), \( P(1) = 1 \).

Figure 3. The contact surface under the different observation scales. When the magnification is the smallest (\( \zeta = 1 \)), two contact surfaces seem to be closely attached. As the magnification increases, some micro-holes gradually appear at the contact interface. Contact only exists between asperities.

2.2.2. The Equivalent Value of the Modulus

According to the contact mechanics, for the frictionless contact between two rough elastic surfaces, the contact stresses (stresses on the contact area and adjacent area) are only related to the interfacial topography between them before loading [27,28]. Moreover, contact mechanics between two rough elastic surfaces can be simplified to contact between one perfectly smooth elastic surface and one rough, rigid surface (shown in Figure 4).

As shown in Figure 4, the upper part of the figure is a rough, rigid body and the lower portion is a perfectly smooth elastic surface. When not subjected to compressive stress, the average interfacial separation of the contact interface is \( u_0 \). When the squeezing pressure is \( p \), it becomes \( \bar{u} \). The equivalent elastic modulus \( E^* \) of contacted surfaces can be calculated from Equation (3) [29,30]:

\[
\frac{(1-v_1^2)}{E^*} + \frac{(1-v_2^2)}{E_2} = \frac{(1-v_1^2)}{E_1} + \frac{(1-v_2^2)}{E_2}
\]  

(3)
where $E_1$ and $E_2$ are the elastic moduli of the two contact faces, respectively, and $\nu_1$ and $\nu_2$ are the respective Poisson's ratios.

![Figure 4](image-url) Simplified the contact surface model; the upper part of the figure is a rough, rigid body, and the lower portion is a perfectly smooth elastic surface. Under pressure, the rigid, rough surface will squeeze into the elastomer, resulting in a decrease in the average separation height of the contact interface.

After simplification, the contact mechanics will be achieved via two steps, the characterization of roughness (topography) of the rough-rigid surface then the calculation of deformation of the perfectly smooth elastic surface. See the detailed procedure in Persson's paper [23,31].

2.2.3. Characterization of Roughness

For a randomly rough surface, the surface topography is determined by the height autocorrelation function of asperities and is characterized by the surface roughness power spectrum $C(q)$ which is the Fourier transformation of the autocorrelation function [23]:

$$C(q) = \frac{1}{(2\pi)^2} \int \langle h(x)h(0) \rangle e^{-iqx} dx$$  \hspace{1cm} (4)

where $h(x)h(0)$ represents an autocorrelation function of the surface profiles. $q$ is the wavevector, and its modulus value $q = |q|$ is an integer multiple of $2\pi/L$.

It is assumed that the substrate surface roughness is the self-affine fractal for $q_0 < q < q_1$, and $C(q)$ can be obtained as [23]:

$$C(q) = \frac{H}{\pi} \left( \frac{q}{q_0} \right)^{2(H+1)}$$  \hspace{1cm} (5)

where $H$ is the roughness exponent and related to the fractal dimension $D_f$: $H = 3 - D_f$. $q_0$ represents the minimum surface fluctuation frequency, and the mean of the square of the contact surface height profile, $\langle h^2 \rangle = \langle h_{rms}^2 \rangle$. All of them can be obtained through the AFM (atomic force microscope) tests [32].

2.2.4. Average Interfacial Separation

The size of the leakage channel, which represents the sealing performance, is directly reflected by the average interfacial separation. When being pressed, the average interfacial separation will decrease, and so does the non-contact region, which further reduces the chance of penetration of the leak channel. The sealing gaskets are made of EPDM rubber, so it can be considered that the sealing material undergoes only elastic deformation when being pressed.

The relationship of the average interfacial separation $\bar{u}$ and squeezing pressure on them can be correlated via the elastic potential energy and can be calculated as Equation (6). The detailed derivation procedure can be obtained in Persson's papers [23,25,31].
where \( P_p(q) \) represents the relative area fraction of the contact surface under the compressive stress \( p \) and at the magnification \( \zeta = q/q_0 \), \( C(q) \) is the surface roughness power spectrum, and \( \gamma \) is the reduction coefficient of elastic potential energy generated per unit area of contact region relative to the complete contact.

### 2.3. Critical State of Leakage

Percolation theory given that when the area of the non-contact region on the seal interface is larger than a certain value, it would be interconnected to form a passage that penetrated the seal interface. The moment the first passage formed is defined as the critical leakage state.

#### 2.3.1. Critical Percolation Channel

As the magnification increases, unconnected areas become more and larger. Therefore, on a certain scale, many non-contact regions (micro-pores and short fractures) are connected for the first time to form a hole penetrating the contact interface. The hole is defined as a critical percolation channel, and the scale is called critical magnification \( (\zeta_c) \). Leakage is thought to occur only through the critical percolation channel, because the cross-section of the percolation channel and the pressure gradient are the largest at the moment. Critical percolation channels are shown in Figure 5; the gray area indicates the surface that has been contacted, and the green area is the unconnected surface that is observed during the increase of the magnification from \( \zeta_c - \Delta \zeta \) to \( \zeta_c \). As the magnification approaches the critical observation scale, the non-contact region penetrates the two sides of the contact surface for the first time (circle marks in Figure 5).

![Figure 5](image-url)

**Figure 5.** Gray areas represent the contact region, white areas are the non-contact region, and green areas are the observed new non-contact region during the increase of the magnification from \( \zeta_c - \Delta \zeta \) to \( \zeta_c \), which leads to the first connection of the sealing interface. Lines with arrows represent critical percolation channels, and its average diameter is \( u_c \).

Then the average height of the critical percolation channel \( u_c \) can be expressed by the average interfacial separation and the contact area \([31]\).

\[
u_c = w(\zeta) + w(\zeta_c) \frac{A(\zeta_c)}{A'(...)}
\]
The relative contact area at this point is given by the percolation theory; thus, the relative contact area $P(\zeta_c) = A(\zeta)/A_0 \approx 1 - P_c$, where $P_c$ is the so-called site percolation threshold. The literature suggests taking $P_c \approx 0.6$ so that $A(\zeta)/A_0 \approx 0.4$ will determine the critical magnification $\zeta = \zeta_c$ [33].

2.3.2. Critical Leakage Pressure and Self-Sealing Effect

In addition to the formation of a leakage channel, energy that overcomes the viscous resistance of fluid and drives its flow is also needed to activate a leakage, though any sealing interface is permeable as long as the magnification is large enough. There is no leakage occurring in some sealing projects; the reason is that the interfacial fluid in the percolation channel will form a plug, which prevents further penetration. We call this phenomenon the self-sealing effect. All complete sealing projects are achieved through their self-sealing effects. The optimal sealing performance of joints depends on the self-sealing stress of the critical percolation channel. This may explain why the greater the squeezing pressure, the better the sealing performance, because, in this case, the size of the critical percolation channel is narrower and, further, provides stronger self-sealing stress. According to the Bernoulli equation [34], the energy consumption is:

$$
\frac{p_1}{\rho g} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + z_2 + h_w
$$

where $p_1$ and $p_2$ are the fluid pressure on both sides of the sealing interface, respectively, $v_1$ and $v_2$ are the velocities of both sides of the sealing interface, $z_1$ and $z_2$ are the heights of both sides of the sealing interface, and $h_w$ is the energy loss.

When a medium (non-contact region) is filled with fluid but no leakage occurs (i.e., the fluid is finally stationary), as shown in Figure 6, the upstream pressure at the right cross section is $P_w$ and the pressure potential energy is all consumed along the leak path, so the velocity and pressure become 0 at the left-side cross section. This moment is defined as the critical leakage state. The upstream pressure $P_w$ is equal to the critical leakage pressure ($P_{wc}$), and it is also equal to the self-sealing stress $P_{ss}$:

$$
P_{wc} = P_{ss} = \rho g \left( h_w + z_2 - z_1 - \frac{(1/2 v_{max})^2}{2g} \right)
$$

![Figure 6. Critical leakage state. Under critical leakage pressure $P_{wc}$, the fluid slowly seeps into the percolation channel, and the fluid kinetic energy is completely dissipated after the channel is just filled. The velocity of the water in the right side is the maximum ($v_{max}$), and it decreases gradually to 0 in the channel, permeating the left side due to the shear stress $\tau$.](image-url)
According to the equilibrium equation of the axial direction, the tangential stress can be obtained as follows:

\[ P_w \pi r^2 - \pi r^2 (P_w + \frac{\partial P}{\partial l} dl) - 2 \pi rl \tau - \pi r^2 \rho g dl \sin \theta = 0 \]  

(10)

and then, we can simplify Equation (10) to get the following equation:

\[ - \frac{\partial P_w}{\partial l} - \frac{2 \tau}{r} - \rho g \sin \theta = 0 \]  

(11)

Additionally:

\[ \sin \theta = \frac{\partial z}{\partial l} \]  

(12)

Then the tangential stress can be equal to:

\[ \tau = -r^2 \left( \frac{\partial P_w}{\partial l} + \rho g \frac{\partial h}{\partial l} \right) \]  

(13)

It can be written as:

\[ \tau = - r \frac{d(P_w + \rho gz)}{dl} \]  

(14)

According to the law of Newton internal friction, the tangential stress can be calculated by

\[ \tau = \mu \frac{dv_x}{dr} \]  

(15)

Substitute Equation (15) into Equation (14) to obtain:

\[ \frac{dv_x}{dl} = \frac{d(P_w + \rho gz)}{dl} \frac{r}{2\mu} dr \]  

(16)

The fluid velocity can be obtained by integrating Equation (16):

\[ v_x = \frac{r^2}{4\mu} \frac{d(P_w + \rho gz)}{dl} + C \]  

(17)

According to the boundary condition: when \( r = r_0 \), the velocity is equal to 0, then the following equation can be obtained:

\[ v_x = -\frac{r^2}{4\mu} \frac{d(P_w + \rho gz)}{dl} \]  

(18)

Therefore, the maximum velocity at the channel axis is equal to:

\[ v_{max} = -\frac{r_0^2}{4\mu} \frac{d(P_w + \rho gz)}{dl} \]  

(19)

The average fluid velocity in the whole percolation channel can be expressed as:

\[ v = \frac{1}{4} v_{max} = -\frac{r_0^2}{16\mu} \frac{P_w + \rho gz}{l} \]  

(20)

The head loss during transportation satisfies the following relationship:

\[ h_w = \lambda \frac{l}{u_c} \frac{v^2}{2g} \]  

(21)

where:
$\lambda$ is the dynamic friction coefficient of the fluid, $\lambda = 64/Re$, and $Re$ is the Reynolds number of fluids. $l$ is the length of the critical percolation channel; $u_c$ is the equivalent diameter of the critical percolation channel; and $v$ is the average fluid velocity of water in the process of filing the percolation channel.

For shield tunnels, considering the change in position head, the critical leakage pressure of the tunnel joints can be expressed as:

$$P_w = \rho g \left( h_w - L \sin \theta - \frac{(1/2 v_{\text{max}})^2}{2g} \right)$$  \hspace{1cm} (22)

where $L$ is approximately equal to the length of the sealing interface, and $\theta$ is the relative position of the leak point in the tunnel.

### 2.4. Calculation of Shield Lining Joint Leakage

The calculation method of the percolation channel in the previous section is introduced, and then, the leakage can be calculated using the N-S equations and Bruggeman effective medium theory [35].

If the interfacial separation $u(x)$ is continuous with the change of $x$, the flow at the point $x = (x, y)$ can be obtained according to the N-S equations

$$\mathbf{J} = -\sigma \nabla p$$  \hspace{1cm} (23)

$$\sigma = \frac{u^3 (x)}{12 \mu}$$  \hspace{1cm} (24)

where $\sigma$ represents the conductivity of the point, $\mu$ is the hydrodynamic viscosity coefficient, and $\nabla p$ is the pressure field distribution.

The sealed leaking fluid can be regarded as a laminar flow, which can be equivalent to a uniform leakage flow with the same seepage rate at each point. Then the fluid volume passing through any point in unit time is equal to

$$\mathbf{J} = -\sigma_{\text{eff}} \nabla p$$  \hspace{1cm} (25)

where $\sigma_{\text{eff}}$ is the effective flow rate; it can be obtained by the following equation:

$$\sigma_{\text{eff}} = \frac{u_c^3 (x)}{12 \mu}$$  \hspace{1cm} (26)

The most commonly used sealing materials of joints between lining segments are EPDM gaskets, as shown in Figure 7, an EPDM sealing interface with geometrical dimensions of $L_y \times L_x (L_y > L_x)$; the leaking starting point of the leaking medium is $x < 0$, and the leaking endpoint is $x > L_x$. The volume of fluid leaking per unit time is

$$Q = L_y I_x = \frac{L_y}{L_x} \sigma_{\text{eff}} P_w$$  \hspace{1cm} (27)
was analyzed computationally in this section. The influencing factors of the lining joint leakage, Additionally, the gasket is designed to provide an effective seal under the groundwater pressure of 0.8 MPa when the offset is up to 15 mm or the gap opening is up to 8 mm. The EPDM joint leakage model diagram. $F_N$ represents assembly stress, which can be calculated according to the rubber strain (assume the rubber is linear elasticity). $L_x$ is the width of the contact surface of the gasket, and $L_y$ is the length of the circumferential joints per meter of the tunnel.

3. Case Study and Parametric Analysis

Using the model presented above, the lining joint leakage of the second Dapu Road Tunnel [36] was analyzed computationally in this section. The influencing factors of the lining joint leakage, including the joint gap, the joint offset, the surface roughness of the EPDM gasket, the service time, and the groundwater pressure, were analyzed, founded on the calculation results. Furthermore, the applicability, advantages, and disadvantages of this mathematical model were elaborated.

The influencing factors of shield lining joint leakage can be reflected in the model directly or indirectly through transformation. The changing joint gap can be reflected by the contact stress provided by the changing gasket deformation. The joint offset is reflected through the length of the percolation channel, which is approximately the length of the sealing interface $L_x$. Roughness is reflected by the root-mean-square roughness of the contact surface height profile $h_{\text{rms}}$. Service time can be reflected by the decrease of contact stress over time. Groundwater is reflected directly by the $P_w$ in Equation (27).

3.1. Case Introduction and Calculation Parameters

The second Dapu Road Tunnel is a highway tunnel across the Huangpu River of Shanghai. It runs nearly parallel to the original one. The tunnel was opened in February 2010; the outer diameter of the tunnel is 11 m, the inner diameter is 10.04 m, the segment thickness is 0.48 m, and the width is 1.5 m. The tunnels constructed adopted an EPDM gasket, which has a section shape, as shown in Figure 7. Additionally, the gasket is designed to provide an effective seal under the groundwater pressure of 0.8 MPa when the offset is up to 15 mm or the gap opening is up to 8 mm.

The EPDM gasket is approximately considered as a linear elastic material, with an elastic modulus ($E$) of 10 MPa and Poisson’s ratio ($v$) of 0.5. The calculation parameters take the EPDM surface fractal dimension $D_f = 2.2$, the root mean square height of the EPDM gasket surface $h_{\text{rms}} = 25 \text{ nm}$ [37], and the dynamic viscosity coefficient of groundwater $\mu = 10^{-3} \text{N}\cdot\text{s}/\text{m}^2$. The length of sealing interface $L_x = 22 \text{ mm}$, and the length of the EPDM gasket per meter shield tunnel $L_y = 6 \text{ m}$. For the leakage calculation, the important roughness is the part for $q_L < q < q^*$ where $q^*$ is the wavenumber where the contact area percolates when increasing the magnification, which approximately occurs when $A(q) = 0.4$. Therefore, the minimum surface fluctuation frequency $q_0 = q_{Lx}$, and the maximum surface fluctuation frequency $q_1 = 7.8 \times 10^9$. 

Figure 7. The EPDM joint leakage model diagram. $F_N$ represents assembly stress, which can be calculated according to the rubber strain (assume the rubber is linear elasticity). $L_x$ is the width of the contact surface of the gasket, and $L_y$ is the length of the circumferential joints per meter of the tunnel.
According to the German STUVA, the tunnel already leaks 0.024 L/m²/day when no seepage marks are observed in the tunnel lining [38]. Some of the leakages evaporate without being found, so even if the tunnel is not stored for leaking by the water storage method, the leakage amount is large. The tunnel waterproof level is 2—that is, when it is mainly dry, there is already a leakage of 0.1 L/m²/day. Therefore, this paper takes 0.1 L/m²/day as the waterproof performance evaluation standard.

3.2. Calculation and Analysis of Critical State

3.2.1. Critical Magnification and Critical Percolation Channel Height

The magnification in which the critical percolation channel appears is called the critical magnification. When the critical magnification increases, the height of the critical percolation channel decreases, and the sealing performance is enhanced. The squeezing pressure determines the waterproof ability by affecting the critical magnification and the height of the critical percolation channel. The larger the squeezing pressure, the larger the critical observation scale, the smaller the critical percolation channel’s height, and the stronger the waterproof performance.

As shown in Figure 8, at the initial stage when the nominal contact stress increases, the height of the critical leakage channel decreases rapidly. This is because, when the contact stress is very small, asperity on the contact surface does not deform sufficiently, and there are a large number of connected non-contact regions that can be found at the sealing interface, with no need to increase the observation scale; as a result, the height of the critical percolation channel mainly depends on the deformation of the larger asperity. As the nominal contact stress continues to increase, the decreasing trend of the critical leakage channel height becomes gentle, while the critical magnification increases rapidly. This is caused by that, with the increase in contact stress, the larger asperity of the contact surface is flattened, and the actual contact regions are mostly found among smaller asperities; this means that the critical percolation channel only could be found by increasing the observation scale.

![Figure 8](image_url)  
Figure 8. The variation curves of the critical percolation channel height \( u_c \) and critical magnification \( \zeta_c \) with increasing nominal contact stress; the critical magnification of the sealing interface under a nominal contact stress of 2 MPa is calculated as 627250.

3.2.2. Critical Leakage Pressure and Self-Sealing Stress

The critical leakage pressure is equal to the self-sealing stress, which is supplied by the viscous resistance of the percolation channel to the liquid. If it is assumed that the liquid pressure will not
cause deformation of the seal interface; the sealing surface may be considered an absolute seal when the liquid pressure is below the critical leakage pressure. The critical leakage pressure (also equal to the self-sealing stress) of the horizontal percolation channel (no elevation head change) is calculated here and depicted in Figure 9.

As shown in Figure 9, when the nominal contact stress is on the brink of 0, the self-sealing effect is observed. The beginning of the black curve is almost vertical; after the obvious self-sealing effect, the critical percolation pressure increases exponentially, with increasing contact stress. The trend of the black curve and color curves is consistent, but the prediction is more substantial than the test of the literature [39]. This may be because the ideal conditions for the calculation hypothesis are challenging to achieve in the trial. For example, the calculation does not consider the joints of gaskets, and the specimen may have defects.

![Figure 9](image-url)  
**Figure 9.** EPDM sealing performance, curves with different symbols are test results, and the black curve is the calculation of the critical leak pressure in this paper. The dotted line shows that the contact stress and critical leakage pressure are equal.

The authentic leakage process is much more complicated when the liquid pressure is large enough; it will split the seal interface to form a leakage channel, so, in theory, the real critical leakage pressure is much smaller than the calculation results.

### 3.3. Factors Influencing the Sealing Capacity of the EPDM Gasket

#### 3.3.1. The Joint Gap of Lining Segments

In the process of assembling the shield segments, the joint gap is common and has a great influence on the waterproof performance of the lining joints. The joint gap (shown in Figure 2) is inevitable between a pair of lining segments besides the designed value. Whether it is the error when assembling or the outcome from the deformation of the tunnel during operations, the joint gap will occur. This may alter the pressure on the opposite gasket, leading to less pressure on a pair of gaskets, thus, making their sealing capacity less efficient. For a designed shield tunnel, the waterproof ability of the joints
depends mainly on the contact stress provided by the assembly force. The smaller the clearance is, the closer the contact interface is and the stronger the sealing performance is.

The joint gap can be converted into compressive stress (i.e., nominal contact stress \( p \)) through gasket deformation and reflected in the model. As shown in Figure 10, the trend of the calculation curve is consistent with that of the analysis; when there is the smallest gap in the joints, the contact stress is the largest, and the leakage is the smallest. Under several different groundwater pressure conditions, when the gap is less than 10 mm, the relationship between the logarithm of the leak rate and the joint gap is approximately linear, while the leakage begins to increase rapidly after the gap is more than 10 mm. This is because that, as the joint gap increases, the contact stress decreases significantly, and more of the non-contact region of the contact interface is penetrated. As a result, the amount and diameter of the percolation channels increase, which further leads to a rapid increase in leakage. Take that the daily average leakage does not exceed 0.1 L/m² as the standard, and the maximum allowable joint gap in groundwater pressure of 0.4, 0.8, 1.2, 1.6 and 2 MPa is 10.4 mm, 8.48 mm, 6.69 mm, 5.02 mm, and 3.69 mm, respectively.

![Figure 10](image_url)

**Figure 10.** Effect of a joint gap and groundwater pressure on the leakage; the dashed line represents that the daily average leakage is 0.1 L/m², and the abscissa of the intersection points between it and curves with different symbols are the maximum allowable joint gaps under groundwater pressures of 0.4, 0.8, 1.2, 1.6 and 2 MPa.

### 3.3.2. The Joint Offset of Lining Segments

The joint gap is often accompanied by joint offset. The effect of offset on leakage has multiple aspects: On the one hand, the offset will reduce the leakage path, increase the hydraulic gradient, and further increase the leakage. On the other hand, the offset reduces the contact area, and the contact surface stress increases, further reducing the leakage.

As shown in Figure 11, the calculation curve of the joint offset is in good agreement with the qualitative analysis. When the joint gap is 11.24 mm, the leakage increases from 0.22 to 0.46 L/m²/day.
as the joint offset increases from 0 to 15 mm, and their relationship seems to be linear, which means
the leakage may be exacerbated by the growing joint offset. The reason is that the increase of joint
offset shortens the seepage path and increases the hydraulic gradient. However, when the joint gap
is less (9.73, 8.21, and 4.42), the curve concaves down. When the joint gap is 9.73 mm, the leak rate
ascended to a peak value of 0.160 L/m²/day at an offset of 11 mm and then descen des. As the joint
gap decreases, the peak value of the leakage appears earlier. When the joint gap is 8.21 and 4.42 mm,
respectively, the peak value is at an offset of 0. The two peak values of the leak rate are 0.095 and
0.048 L/m²/day, respectively. This is because when the joint gap is at a certain value, although the
increase of the joint offset will shorten the seepage path, it also causes the reduction of the contact
area and, thus, increases the contact stress and reduces the leakage. Furthermore, the limit of the joint
offset is related to the joint gap; the joint offset will not exceed the product of the joint gap and the
cotangent of the groove inclination (shown in Figure 2). In our case, when the joint gap is 11.24, 9.73,
8.21, and 4.42 mm, the corresponding maximum offset is 6.49, 5.62, 4.74, and 2.55 mm, respectively.
The reason why the leakage increases correspondingly mainly depends on the increasing gap, and the
effect of the offset change on the leakage is slight.

![Figure 11](image-url)

**Figure 11.** Effects of the joint offset and gap coupling on leakage; the curves from top to bottom are the
relationship between leakage and offset when the joint gap is 11.24 mm, 9.73 mm, 8.21 mm, and 4.42 mm
respectively. The four points of the dotted line are the maximum offsets when the groove slope is
30 degrees; they are 2.55 mm, 4.74 mm, 5.62 mm, and 6.49 mm, respectively.

### 3.3.3. Service Time

EPDM gaskets are subject to aging and creep during a long service, and the contact stress will
experience a gradual relaxation over time, which will further lead to an aggravation of the leak.
This paper uses the EPDM aging model provided by Shi CH et al. [40] to calculate the leakage evolution
of EPDM in service for 100 years.

\[
p(t) = p_0 \times 1.308 \exp(-0.004t^{0.4687})
\]  

(28)
The calculations agree well with the qualitative analysis. Figure 12a shows the leakage versus service time under conditions of different joint gaps within the service time of one year reported in [10]. Figure 12a indicates that the leakage increases with the aging of sealing materials and all five curves show the same trend illustrated by Figure 12b. The difference lies in the fact that larger gaps have more initial leakage volume (leakage at a service time of 0). The fitted curve of leakage of the second Dapu Road measured at a different time is in accordance with calculated lines. The measured leakage is almost distributed below the calculation of the joint gap of 8 mm (the maximum allowable joint gap of this tunnel design). This conclusion verifies the reliability of the model. The fitting curve of leakage monitoring of the second Dapu Road Tunnel shows a good agreement with the calculation slope.

![Graph of leakage monitoring]

**Figure 12.** Effects of the service time and joint gap coupling on leakage. In (a), the red line is the calculated leakage value for one year of service, in groundwater pressure of 0.8 MPa. The circle with half a shadow indicates the leakage monitoring data for one year of service of the second Dapu Road Tunnel in Shanghai. The dotted line is the fit to the measured data. The curves in (b) show the calculated leakage during 100 years for lining joints with gaps of 0, 2, 4, 6, and 8 mm.

3.3.4. Roughness of Sealing Surface

The surface roughness has a great influence on the sealing ability. The rougher the contact surface of sealing materials, the more non-contact regions will be generated, which will lead to the degradation of the waterproofing performance. Under high-contact stress, the deformation of asperity can reduce the roughness, so the rougher sealing interface requires higher contact stress. Figure 13 shows that, under different joint gaps, relationships between the leakage and surface roughness (asperity root mean square height) may all satisfy exponential functions that concave up. Specifically, as the asperity height becomes greater, the leakage grows slowly at first (asperity height is less than 15 μm) and then ascends faster with an increasing slope. The reason why a larger joint gap has a more significant effect on leakage is that the flattening of asperity with a large height requires greater contact stress, as the joint gap increases, the non-contact areas around the rough body are connected to form a larger number and scale of leakage channels.
3.3.5. Groundwater Pressure

Groundwater pressure determines the hydraulic gradient and further affects the leakage. Large groundwater pressure can overcome the self-sealing stress of smaller percolation channels or split the seal interface to form a larger percolation channel, which is the reason why large groundwater pressure is more likely to cause leakage. Increasing the contact stress can reduce the size of the critical percolation channel and further improve the sealing performance of joints. This section analyzed the relationship among the contact stress (in Figure 14, replaced by a joint gap), groundwater pressure, and leakage. As shown in Figure 14, the leak rate increases linearly with the groundwater pressure, and the slopes of their curves increase exponentially with the increasing joint gap. This is because the underwater pressure directly provides the power for leakage, and its influence on the unit time leakage is linear, while the increase of the joint gap further leads to the increase of the number and diameters of leakage channels, and the leakage increases exponentially with the joint gap.

![Figure 13. Influence of the contact surface roughness on leakage. Curves of different colors indicate the relationship of leakage with the root-mean-square roughness contact surface height profile in the case of different joint gaps.](image)

![Figure 14. 3D diagram of the leakage, joint gap, and groundwater pressure. The leakage calculation takes the groundwater pressure from 0~2 MPa and joint gap from 0~12 mm.](image)
3.3.6. Sensitivity Analyses of Influencing Factors

In order to compare and analyze the influence of various factors on the shield lining joint leakage, the orthogonal array testing is designed here with four factors including the joint gap, the surface roughness, the service time, and groundwater pressure. The joint offset is not considered here, because its influence is meager. Each of those factors was calculated in five levels as Table 1. The value of each level is selected according to the possible value range of each factor in engineering practice.

| Joint Gap (mm) | Time (Year) | Roughness h (nm) | Groundwater Pressure (Mpa) | Leakage (L/m²/day) |
|----------------|-------------|------------------|----------------------------|--------------------|
| 1              | 1 (0)       | 1 (10)           | 1 (0.4)                    | 0.000123           |
| 2              | 1           | 2 (25)           | 2 (30)                     | 0.011012           |
| 3              | 1           | 3 (50)           | 3 (60)                     | 0.073867           |
| 4              | 1           | 4 (75)           | 4 (90)                     | 0.288195           |
| 5              | 1           | 5 (100)          | 5 (120)                    | 0.838985           |
| 6              | 2 (2.5)     | 1                | 2                          | 0.003468           |
| 7              | 2           | 2                | 3                          | 0.073565           |
| 8              | 2           | 3                | 4                          | 0.312645           |
| 9              | 2           | 4                | 5                          | 0.266312           |
| 10             | 2           | 5                | 1                          | 0.008295           |
| 11             | 3 (5)       | 1                | 3                          | 0.030485           |
| 12             | 3           | 2                | 4                          | 0.090373           |
| 13             | 3           | 3                | 5                          | 0.382805           |
| 14             | 3           | 4                | 1                          | 0.011040           |
| 15             | 3           | 5                | 2                          | 0.078869           |
| 16             | 4 (7.5)     | 1                | 4                          | 0.064213           |
| 17             | 4           | 2                | 5                          | 0.494333           |
| 18             | 4           | 3                | 1                          | 0.014627           |
| 19             | 4           | 4                | 2                          | 0.103503           |
| 20             | 4           | 5                | 3                          | 0.118154           |
| 21             | 5 (10)      | 1                | 5                          | 0.177043           |
| 22             | 5           | 2                | 1                          | 0.007473           |
| 23             | 5           | 3                | 2                          | 0.045529           |
| 24             | 5           | 4                | 3                          | 0.156215           |
| 25             | 5           | 5                | 4                          | 0.399236           |

A B C D

| Rj  | 0.123722 | 0.233642 | 0.423584 | 0.154520 |
|-----|----------|----------|----------|----------|
| Rank| 4        | 2        | 1        | 3        |

According to the range analysis, the influential degree of each factor on the leakage is in the order of surface roughness > service time > groundwater pressure > joint gap. Among them, instead of the joint gap and groundwater pressure, the surface roughness of the sealing material is the most important factor affecting the joint leakage of shield tunnels. A rougher contact surface can directly result in a less-real contact region, which makes it easier to form percolation channels. The service time and the joint gap can reduce the real contact region by changing the contact stress, which indirectly affects the formation of percolation channels. The groundwater pressure can determine the leakage in the observation scales. If the water pressure is large enough, the leakage will occur through finer percolation channels.

4. Discussion

The model presented in this paper can help understand the leakage development process from a micro-scale. It provides a prediction method of leakage using physics and mathematics, which helps to clearly understand the underlying mechanisms of leakage. For the shield engineering cases mentioned
above, it can reflect the influential law of factors, including the joint gap, the joint offset, roughness of the contact surface, and service time, of the EPDM gasket on leakage. It can be known that the calculated results of each influencing factor are consistent with its qualitative analysis; the slope of the self-sealing stress is similar to that in the literature, and the seepage evolution during one year is in good agreement with the observed leakage of the second Dapu Road Tunnel. These indicate that the model is suitable for analyzing the leakage of shield lining joints. However, due to the complexity of the actual engineering situation, it is hard to calculate it accurately by mathematical methods only. As a result, there are some defects in this research, especially the differences between the hypothesis and the actual situation, which are explained as follows:

1. The measurement error of the contact surface height profile of the EPDM gasket is large, which has a great influence on the accuracy of the calculation results.
2. Consider that the groove is filled with a fully compressed gasket and it is bonded by the sealant, the model assumes that the leakage mainly occurs at the contact interface of the gaskets and ignores the effects of water pressure (lateral pressure) on the gasket contact pressure.
3. When the groundwater pressure is large enough, the contact region will be split into several leakage channels, which is not reflected in the model. As a result, the calculation results may be relatively smaller than that in practice.
4. The model cannot consider the effects of water—swelling sealing materials.
5. The calculation results of self-sealing stress and leakage need more observed results and experiments for further verification.

5. Conclusions

In order to understand the underlying process of shield joint leakage and the influential law of factors on it, this research describes an analytical method for shield lining joint leakage calculation, which is built on the Persson contact mechanics and percolation theory. Various influencing factors, including the joint gap, the joint offset, the roughness of the contact surface, the service time, and groundwater pressure on the shield joint leakage, can be reflected by the parameters in the model. Based on this method, the critical leakage state and the self-sealing effect were defined, and their calculations are derived using the law of Newton’s inner friction. Then, taking the Dapu Road Tunnel in Shanghai (China) as a case study, the calculation results of self-sealing stress was compared with results in the literature, and the influential law of factors on shield joint leakage was analyzed, and the calculation results were verified through the leakage data observed at the tunnel. The following conclusions were drawn:

1. Any sealing interface is permeable; they are mainly sealed by the interfacial fluid, which can form a plug, preventing further penetration. We called this phenomenon the self-sealing effect. The greater the squeezing pressure, the narrower the size of the critical percolation channel, which further provides stronger self-sealing stress.
2. The joint gap is often accompanied by joint offset. For the case where the joint offset is independent of the joint gap, the offset with considerable contact stress will enhance the joint waterproof performance, while, for the gap-dependent offset, the offset will increase the leakage. The leakage mainly depends on the increasing gap, and the effect of the offset change on leakage is slight.
3. The leakage increases with the aging of the sealing material. The aging model of Shi CH is utilized to calculate the leakage trend for one year, and the results show good agreement with the monitoring value of the second Dapu Road Tunnel.
4. The orthogonal array testing is designed with four factors including the joint gap, the surface roughness, the service time, and groundwater pressure in five levels. The range analysis showed that the roughness of the contact surface is the most influential, followed then by the service time, groundwater pressure and the joint gap.
The applicability of this model was verified by comparing the calculation results with experimental results in the literature. However, due to the differences between the hypothesis and the actual situation of engineering, this model aims to help more clearly understand the underlying processes of shield lining joint leakage and the influential laws of various factors rather than accurately predict it.

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**Glossary**

Definitions are given here in the following sequence: Bold quantities denote vectors or tensors.

- ζ: magnification, $\zeta = L/\lambda = q/q_0$
- $L$: length of the nominal contact surface
- $\lambda$: length of asperity wavelength
- $A(\zeta)$: actual contact area
- $A_0$: nominal contact area (i.e., observed contact region is $A_0$ when $\zeta = 1$)
- $P(\zeta)$: relative contact area fraction: $P(\zeta) = A(\zeta)/A_0$
- $E^*$: equivalent elastic modulus (MPa)
- $E_1, E_2, v_1, v_2$: Young’s elastic module and respective Poisson’s ratios of the two contact faces
- $C(q)$: surface roughness power spectrum
- $\langle h^2 \rangle$: mean of the square of the contact surface height profile ($\mu$m)
- $h_{rms}$: The root-mean-square roughness of the contact surface height profile ($\mu$m)
- $\langle h(x)h(0) \rangle$: autocorrelation function of the surface height profiles ($\mu$m)
- $q$: Wavevector of asperity, $q_0, q_1$ represent the minimum and maximum surface fluctuation frequency, respectively
- $D_f$: The fractal dimension of self-affine fractal surfaces, $D_f = 3 - H$, where $H$ is Hurst exponent
- $p(\overline{\Pi})$: the pressure distribution at sealing interface with the average interfacial separation $\overline{\Pi}$
- $U_{el}(\overline{\Pi})$: the elastic potential energy (J)
- $P_p(q)$: relative area fraction of the contact surface with the compressive stress $p$ and magnification $\zeta = q/q_0$
- $\zeta_c$: critical observation scale
- $u_c$: the average height of the critical percolation channel ($\mu$m)
- $W(q,p)$: elastic energy
- $u(\zeta)$: the average interfacial separation
- $p_1, p_2, v_1, v_2$: the fluid pressure and the velocity on both sides of the sealing interface
- $z_1, z_2$: Head height on both sides of the seal interface
- $h_w$: the energy loss
- $P_w$: Groundwater pressure (MPa)
- $P_c$: critical leakage pressure (MPa)
- $P_{ss}$: self-sealing stress (MPa)
- $P_{c}$: site percolation threshold
- $r$: the radius of the percolation path, $r = \overline{\Pi}(\zeta)/2$
- $v_{max}$: the maximum flow rate of liquid in percolation path (m/s)
- $\lambda$: Coefficient of head loss: $\lambda = 64/Re$
- $Re$: Reynolds numbers, $Re = 2\rho v r/\mu$
- $v$: the average fluid velocity of water (m/s)
- $q^*$: the wavenumber where the contact area percolate when increasing the magnification
- $\mu$: hydrodynamic viscosity coefficient (N·s/m²)
- $\theta$: the relative position of the leak point in the tunnel
$\sigma$, $\sigma_{\text{eff}}$ the conductivity of percolation channel
J the fluid volume per unit time passing through the percolation channel
$\nabla p$ the pressure field distribution
$L_x, L_y$ the geometrical dimension of sealing interface (m)
$Q$ total groundwater inflow (L/m$^2$/day)

References

1. Girnau, G. Lining and waterproofing techniques in Germany. *Tunn. Tunn. Int.* 1978, 10. Available online: https://trid.trb.org/view/79297 (accessed on 25 November 2020).

2. Nilsen, B. Characteristics of water ingress in Norwegian subsea tunnels. *Rock Mech. Rock Eng.* 2014, 47, 933–945. [CrossRef]

3. Shin, J.H.; Addenbrooke, T.I.; Potts, D.M. A numerical study of the effect of groundwater movement on long-term tunnel behaviour. *Géotechnique* 2002, 52, 391–403. [CrossRef]

4. Xu, C.; Chen, Q.; Luo, W.; Liang, L. Evaluation of permanent settlement in Hangzhou Qingchun road crossing-river tunnel under traffic loading. *Int. J. Geomech.* 2019, 19, 06018037. [CrossRef]

5. Mair, R.J. Tunnelling and geotechnics: New horizons. *Géotechnique* 2008, 58, 695–736. [CrossRef]

6. Wu, H.; Xu, Y.; Shen, S.-L.; Chai, J.-C. Long-term settlement behavior of ground around shield tunnel due to leakage of water in soft deposit of Shanghai. *Front. Archit. Civ. Eng. China* 2011, 5, 194–198. [CrossRef]

7. Cividini, A.; Contini, A.; Locatelli, L.; Gioda, G. Investigation on the cause of damages of a deep tunnel. *Int. J. Geomech.* 2012, 12, 722–731. [CrossRef]

8. Cividini, A.; Bonomi, S.; Vignati, G.C.; Gioda, G. Seepage-induced erosion in granular soil and consequent settlements. *Int. J. Geomech.* 2009, 9, 187–194. [CrossRef]

9. Wang, Z.; Wang, L.; Li, L.; Wang, J. Failure mechanism of tunnel lining joints and bolts with uneven longitudinal ground settlement. *Tunn. Undergr. Space Technol.* 2014, 40, 300–308. [CrossRef]

10. Wu, H.-N.; Huang, R.-Q.; Sun, W.-J.; Shen, S.-L.; Xu, Y.-S.; Liu, Y.-B.; Du, S.-J. Leaking behavior of shield tunnels under the Huangpu River of Shanghai with induced hazards. *Nat. Hazards* 2014, 70, 1115–1132. [CrossRef]

11. Shalabi, F.I. Behavior of Gasketed Segmental Concrete Tunnel Lining. Ph.D. Thesis, University of Illinois at Urbana-Champaign, Champaign, IL, USA, 2001. Available online: https://www.ideals.illinois.edu/handle/2142/83169 (accessed on 25 November 2020).

12. Shalabi, F.I.; Cording, E.J.; Paul, S.L. Sealant behavior of gasketed segmental tunnel lining. In Proceedings of the Workshop of the International Tunnelling and Underground Space Association, Underground Structures in Hot Climate Conditions, Riyadh, Saudi Arabia, 8–9 December 2016; pp. 8–9.

13. 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]

14. Liu, J.G. The experimental research of the contact pressure of hydrophilic sealing gasket for shield tunnel segments. *Chin. J. Undergr. Space Eng.* 2009, 5, 1122–1125. (In Chinese) [CrossRef]

15. Ming, Z.; Wenqi, D.; Yicheng, P.; Biwei, S.; Linsong, G.X.Y. Experimental study on the reliability of shield tunnel segment joints to remain watertight under high water pressure. *Mod. Tunn. Technol.* 2013, 50, 87–93. (In Chinese) [CrossRef]

16. Ding, W.; Gong, C.; 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]

17. Gong, C.; Ding, W.; Soga, K.; Mosalam, K.M.; Tuo, Y. Sealant behavior of gasketed segmental joints in shield tunnels: An experimental and numerical study. *Tunn. Undergr. Space Technol.* 2018, 77, 127–141. [CrossRef]

18. Gong, C.; Ding, W. 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]

19. Zhou, N.; Yuan, Y. Correlation of cross-river shield tunnel between longitudinal deformation curvature and segment leakage. *J. Tongji Univ. (Nat. Sci.)* 2009, 37, 1446–1451.

20. 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]
21. Ministry of Housing and Urban-Rural Development of the People’s Republic of China. *Code for Construction and Acceptance of Shield Tunnelling Method; Ministry of Housing and Urban-Rural Development of the People’s Republic of China: Beijing, China, 2017.*

22. Persson, B.N. Theory of rubber friction and contact mechanics. *J. Chem. Phys.* 2001, 115, 3840–3861. [CrossRef]

23. Persson, B.; Albohr, O.; Tartaglino, U.; Volokitin, A.; Tosatti, E. On the nature of surface roughness with application to contact mechanics, sealing, rubber friction and adhesion. *J. Phys. Condens. Matter* 2004, 17, R1. Available online: https://iopscience.iop.org/article/10.1088/0953-8984/17/1/R01/meta (accessed on 25 November 2020). [CrossRef]

24. Persson, B.N.J. Contact mechanics for randomly rough surfaces. *Surf. Sci. Rep.* 2006, 61, 201–227. [CrossRef]

25. Persson, B.N.J.; Yang, C. Theory of the leak-rate of seals. *J. Phys. Condens. Matter* 2008, 20, 11. [CrossRef]

26. Persson, B.; Lorenz, B.; Shimizu, M.; Koishi, M. Multiscale contact mechanics with application to seals and rubber friction on dry and lubricated surfaces. In *Designing of Elastomer Nanocomposites: From Theory to Applications*; Springer: Berlin, Germany, 2016; pp. 103–156. [CrossRef]

27. Tallian, T.; Chiu, Y.; Van Amerongen, E. Prediction of traction and microgeometry effects on rolling contact fatigue life. *J. Lubr. Technol.* 1978, 100, 156–165. [CrossRef]

28. Nayak, P.R. Random process model of rough surfaces. *J. Lubr. Technol.* 1971, 93, 398–407. [CrossRef]

29. Johnson, K.L.; Kendall, K.; Roberts, A. Surface energy and the contact of elastic solids. *R. Soc. Lond. Math. Phys. Sci.* 1971, 324, 301–313. [CrossRef]

30. Johnson, K. *Contact Mechanics*; Cambridge University Press: Cambridge, UK, 1985; Volume 95, p. 365.

31. Yang, C.; Persson, B. Contact mechanics: Contact area and interfacial separation from small contact to full contact. *J. Phys. Condens. Matter* 2008, 20, 215214. Available online: https://iopscience.iop.org/article/10.1088/0953-8984/20/21/215214/meta (accessed on 25 November 2020). [CrossRef]

32. Yadav, R.; Kumar, M.; Mittal, A.; Dwivedi, S.; Pandey, A.C. On the scaling law analysis of nanodimensional LiF thin film surfaces. *Mater. Lett.* 2014, 126, 123–125. [CrossRef]

33. Stauffer, D.; Aharony, A. *Introduction to Percolation Theory*; Taylor & Francis: Abingdon, UK, 2018; ISBN 1482272377.

34. Batchelor, C.K.; Batchelor, G. *An Introduction to Fluid Dynamics*; Cambridge University Press: Cambridge, UK, 2000.

35. Aspnes, D.E. Local-field effects and effective-medium theory—A microscopic perspective. *Am. J. Phys.* 1982, 50, 704–709. [CrossRef]

36. Liu, S.; Wang, X.; Wang, J.; Chen, J. Numerical analysis of cut-and-cover excavation part of a cross-river tunnel. *Chin. J. Geotech. Eng.* 2013, 35, 330–334. Available online: http://d.wanfangdata.com.cn/conference/8211707 (accessed on 11 July 2020). (In Chinese)

37. Bottiglione, F.; Carbone, G.; Mangialardi, L.; Mantriota, G. Leakage mechanism in flat seals. *J. Appl. Phys.* 2009, 106, 104902. [CrossRef]

38. Zhu, Z.; Zhang, P. Waterproof grade standard and detection of tunnel engineering. *Constr. Technol.* 2009, 38, 22–24, 45. Available online: http://d.wanfangdata.com.cn/periodical/lgjs200904006 (accessed on 25 November 2020). (In Chinese)

39. 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]

40. Shi, C.; Cao, C.; Lei, M.; Peng, L.; Shen, 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]

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