

Article

Electrochemical Corrosion Mechanisms of Reinforcement in Subway Shield Tunnels Under Coupled Sulfate Corrosion and Stray Current Effects

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Abstract

Shield tunnels are the primary structural form of subway tunnels. Under the influence of sulfate ions and stray currents, the internal bars in shield tunnels will corrode rapidly, affecting the safe operation of the subway. In this paper, a numerical calculation model was developed to simulate rebar corrosion in shield tunnels under coupled electric and chemical field effects, the accuracy of the numerical calculation model was verified using a model test. Based on this model, the migration patterns of sulfate ions within the tunnel under stray current conditions are investigated, as well as the corrosion mechanisms of tunnel rebars. Results show that under the coupled effects of stray currents and sulfate ions, the corrosion area in a segment rebar gradually spreads from the arch waist area of a tunnel. Compared to bilateral leakage, both the migration rate of sulfate ions and the corrosion rate of rebar were higher than those in the unilateral leakage condition. Changes in the input voltage at the top of the ballast did not alter the shape of the distribution curves for the voltage and corrosion current density of segmental rebar. When the input voltage increased from 1 V to 5 V, the voltage at the mid-section of the rebar increased by 5.2 times under a bilateral leakage condition, and the voltage at the mid-section of the rebar increased by 8.2 times under a unilateral leakage condition. Compared to the bilateral leakage case, the amplitude of fluctuations in the curve was significantly reduced under unilateral leakage, but the corrosion current density increased proportionally with increasing leakage voltage in both cases. The research conclusions provide a theoretical basis for the safety assessment and disease treatment of shield tunnel structures.

Keywords: subway shield tunnel; reinforcement corrosion; stray current; sulfate attack; electrochemical corrosion; ion migration



Academic Editors: Jesús Manuel Jáquez-Muñoz and Enrique Vera-López

Received: 3 August 2026

Revised: 20 August 2026

Accepted: 24 August 2026

Published: 30 August 2026

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1. Introduction

As urbanization accelerates, subways have become the backbone of public transportation due to their high capacity and efficiency. However, with increasing service years, various structural defects such as rebar corrosion [1–5], concrete cracking [6–8], and water leakage [9–11] have appeared in subway tunnels. Among these, stray current is the primary cause of internal rebar corrosion in subway tunnels [12–15]. The corrosion mechanism of stray currents in underground structures is a type of forced electrochemical electrolysis process [16]. The key process is the stray current leaking from external direct-current power sources, which changes the electrode potential distribution at the interface between the

steel and the surrounding concrete pore solution. When a stray current enters a section of the rebar along a low-resistance path, that area becomes the cathodic region and gains electrons. The current then travels through the tunnel rebar and flows into the ground at another location, forcing that exit point to become the anodic region. In the anodic zone, iron atoms on the steel surface are driven by the external electric field to lose electrons forcibly, undergoing intense oxidation and dissolution reactions. The resulting ferrous ions further react with water to form a rust layer. This process not only drastically reduces the effective cross-sectional area of the rebar but also occurs at a much higher rate than natural microcell corrosion caused by oxygen concentration cells. Moreover, the volume expansion of the corrosion products can reach 2 to 6 times that of the original metal. The resulting significant radial stress ultimately forces the concrete cover to crack and spall along the rebar [17], severely damaging the integrity of the underground structures [18–21]. In coastal regions of China, chloride concentrations are generally high, but in karst areas of southwestern China and certain parts of the north China plain, sulfate levels in groundwater are significantly higher than chloride levels. The numerical model in this paper is based on certain tunnel sections of the Guiyang Metro in China. The concentration of sulfate ions within the soil was determined using ion chromatography, which involves leaching sulfate from the soil with water, separating it from other ions through ion exchange, and quantitatively analyzing it via a conductivity detector.

The corrosive ions will rapidly migrate to the surface of tunnel rebar under the influence of stray currents [22–24], thereby accelerating the corrosion rate of tunnel rebar. Since the volume of rust products is 3 to 8 times that of the original steel, the tunnel concrete surrounding the rebar continuously experiences expansion pressure from the rust layer. When the expansion pressure of the rust layer exceeds the tensile strength of concrete, cracks or even spalling may occur in the tunnel lining [25–27], threatening the safe operation of the tunnel.

Many researchers have studied the effect of stray currents or erosion medium on rebar corrosion in subway tunnels. Jin et al. [28] investigated the corrosion behavior of rebar in cracked tunnel segments under a stray current using experimental and numerical calculation. The results showed that corrosion of the rebars occurred exclusively at crack locations, and the corrosion rate increased linearly with increasing voltage. Yu et al. [29] established an electrochemical–mechanical coupled model to study the corrosion of tunnel straight bolts under stray current and surface overloading conditions. The result revealed that the corrosion rate of bolts is closely related to the opening pattern of shield tunnel joints, with higher corrosion rates observed closer to the joint. Tang et al. [30] conducted full-scale tests to study the mechanical effects of salt-induced corrosion on tunnel segment under sustained loading. The findings indicated that rebar corrosion and cracking significantly affect the internal force distribution within the tunnel structure. Zhang et al. [31] combined electrochemical theory with the extended finite element method to simulate the corrosion mechanism and cracking patterns of rebars in the arch waist of a tunnel segment under chloride exposure. The results showed that the rust layer distribution on rebars follows a mixed Gaussian curve, while the internal rust cracking morphology in the segment resembles interconnected ellipses.

Most of the factors considered in the above studies are single factors such as stray current or corrosive ions, while research on the electrochemical corrosion mechanism of tunnel rebar under the coupled effects of stray currents and sulfate ions remains limited. Relevant experimental studies [32–34] indicated that sulfate ions have strong corrosion ability, binding with iron ions released at the anode to form water-soluble ferrous sulfate instead of depositing as dense ferrous hydroxide. As a result, sulfate ions are not consumed during the corrosion process but rather sustain a continuous corrosion cycle.

In this paper, a numerical calculation model was developed to simulate rebar corrosion in shield tunnels under coupled electric and chemical field effects, and the accuracy of the numerical calculation model was verified through model tests. Based on this model, the migration pattern of sulfate ions within the tunnel under direct stray current conditions is investigated, as well as the corrosion mechanisms of shield tunnel inner rebars. The research conclusions provide a theoretical basis for the safety assessment and disease treatment of shield tunnel structures.

2. Details of Shield Tunnel Numerical Calculation Model

2.1. Geometric Dimensions of Shield Tunnel Structure

The shield tunnel is the primary load-bearing structure of the subway tunnel lining. In this paper, the subway shield tunnel is composed of six segments (H, T1, T2, S1, S2, S3), with the segment angle at the tunnel top being the smallest and those near the top slightly smaller than those at the waist. The tunnel has a diameter of 6.2 m, a thickness of 350 mm, and a ring segment width of 1.2 m. The internal track bed spans 2480 mm in width and 480 mm in depth. Both the inner and outer rows of tunnel rebar have a diameter of 16 mm, with a concrete cover thickness of 50 mm. The type of tunnel rebar is hot-rolled ribbed rebar HRB400. The dimensions of the tunnel model and the layout of internal rebar are shown in Figure 1.

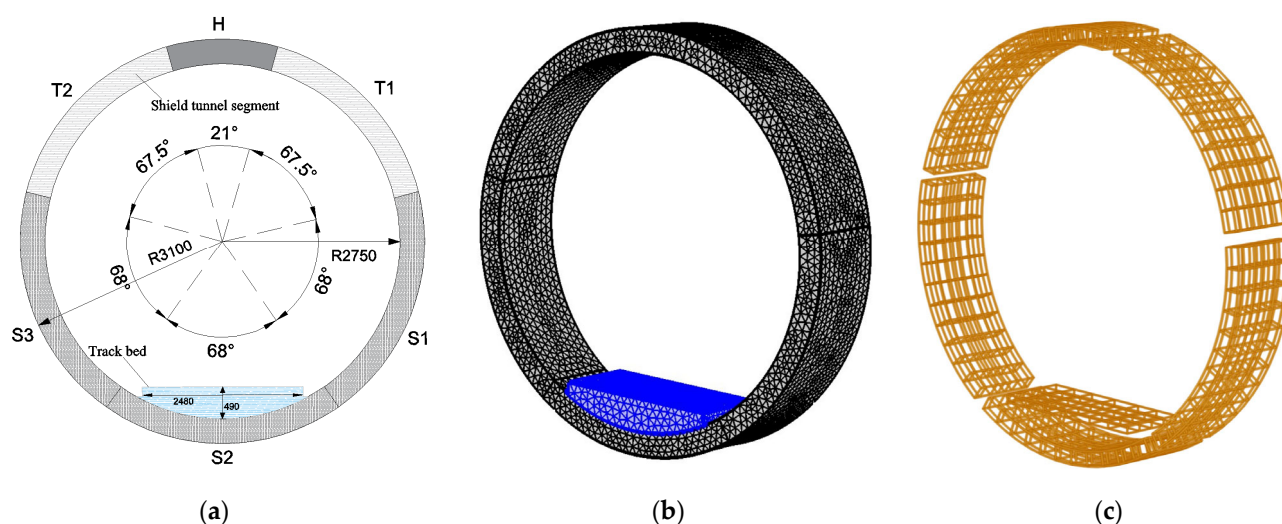
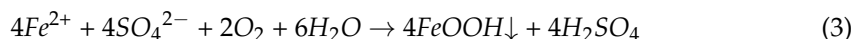
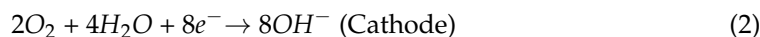


Figure 1. Diagram of the geometric dimensions and rebar layout of the tunnel model: (a) Tunnel geometric dimensions. (b) 3D tunnel model. (c) Internal rebar of tunnel model.

2.2. Theory of Stray Current and Sulfate Ion Corrosion

In the concrete pore solution, Fe^{2+} generated by anodic dissolution does not directly precipitate as a simple ferrous sulfate solid, but instead rapidly undergoes a homogeneous coordination reaction with the abundant SO_4^{2-} present in the pore liquid, forming water-soluble neutral complexes. These neutral complexes then hydrolyze in the presence of dissolved oxygen to produce stable $\alpha\text{-FeOOH}$ solid phase and release stoichiometric amounts of H_2SO_4 . The released acid immediately reacts with OH^- diffusing from the cathode (oxygen reduction reaction) through neutralization. However, when stray current continuously drives the accumulation of SO_4^{2-} toward the anode and sufficient Fe^{2+} is supplied, the formation and hydrolysis rates of FeSO_4 exceed the capacity of OH^- replenishment, causing a sharp drop in local pH at the anode interface. This acidification process not only directly dissolves the dense passive film on the steel surface but also keeps iron within the thermodynamic range of activated dissolution. It should be emphasized

that the SO_4^{2-} released during hydrolysis recombines with newly formed Fe^{2+} , establishing a closed-loop catalytic cycle that consumes no sulfate ions and relies solely on continuous oxygen supply and anodic polarization [35–37]. The entire chemical reaction is shown in Equations (1)–(3).



According to Ohm's law [38], the current density of tunnel rebar can be expressed as Equation (4).

$$\sigma_{\text{tunnel}} \nabla V = i_{\text{tunnel}} \quad (5)$$

where the ΔV is the electric potential of rebar in the tunnel, i_{tunnel} is the current density of rebar in the tunnel, σ_{tunnel} is the resistance of tunnel concrete.

Assuming the tunnel segment is in a saturated water condition, the convection term is not considered when simulating the migration of sulfate ions, and the transport flux of sulfate ions in the concrete driven by the stray current can be described by the Nernst–Planck equation [39], as shown in Equation (5).

$$J_S = -D \nabla C_0 - \frac{z_S F}{RT} D C_0 \nabla V \quad (6)$$

where the J_S is the sulfate ion flux, D is the sulfate ion diffusion coefficient, C_0 is the sulfate ion concentration, z_S is the sulfate ion electric charge number, F is the Faraday constant, R is the general gas constant, T is the temperature, and ∇V is the electric potential. The critical sulfate ion concentration inducing active corrosion of embedded rebar in the tunnel lining concrete is 0.6 mol/L.

According to the linear Butler–Volmer equation [40], the corrosion current density i_{corr} of tunnel rebar can be described as shown in Equation (6).

$$i_{\text{corr}} = i_{\text{Fe,exc}} \left(\exp \left(\frac{\alpha_{\text{ae}} F}{RT} (V_e - V_l - V_{\text{Fe,eq}}) \right) - \exp \left(\frac{\alpha_{\text{ce}} F}{RT} (V_e - V_l - V_{\text{Fe,eq}}) \right) \right) \quad (7)$$

where i_{corr} is the corrosion current density, $i_{\text{Fe,exc}}$ is the anodic exchange current density, V_e is the electric potential of the electrode, which is affected by the input boundary of the stray current, V_l is the electrolyte potential, $V_{\text{Fe,eq}}$ is the anodic equilibrium potentials, R is the general gas coefficient, T is the environment temperature, F is the Faraday constant, α_{ae} is the anode charge transfer coefficient, and α_{ce} is the cathode charge transfer coefficient.

Considering that rebar corrosion is limited by oxygen content, the maximum corrosion current density, i_L , for the tunnel rebar is set as follows [41]:

$$i_L = D_{\text{O}_2} \cdot m \cdot F \cdot C_{\text{O}_2} / D_S \quad (8)$$

where D_{O_2} is the oxygen diffusion coefficient, C_{O_2} is the oxygen concentration on the outer surface of tunnel, m is the electron number of the oxidation reaction, D_S is the oxygen diffusion distance from the oxygen exposed tunnel surface. More details of the calculation parameters of the tunnel are shown in Table 1.

Table 1. Electrochemical calculation parameters [14].

Parameter	α_{ae}	α_{ce}	$V_{Fe,eq}$	$i_{Fe,exc}$	z_s	F	m	C_{O_2}
Value	1.5	0.5	−0.76 V	7.1×10^{-5} A/m ²	2	96,485.3 C/mol	4	0.268 mol/m ³

The computation of the multi-field coupled model is primarily performed using COMSOL software, involving the coupling of three modules. The first module involves simulation and analysis of the electric field: initially, based on Equation (4), the voltage distribution in the shield tunnel under different boundary conditions is calculated. Then, the dilute substance diffusion module is introduced to simulate the migration of sulfate ions according to Equation (5). The final module is electrochemical corrosion simulation. To determine the critical threshold for sulfate ion corrosion of internal rebar in concrete, we measured the corrosion current density of multiple HRB400 steel bars (tunnel rebar) using a three-electrode method in simulated concrete pore solution (prepared with NaOH and KOH, pH = 13.0) with varying concentrations of sodium sulfate added. The results indicate that when the sulfate ion concentration exceeds 0.6 mol/L, the corrosion current density of rebar undergoes a sudden change, so the numerical model adopts 0.6 mol/L as the critical threshold for sulfate-induced rebar corrosion. Combining Equations (6) and (7), the corresponding rebar region is defined as an anode undergoing electrochemical corrosion.

2.3. Boundary Conditions of the Numerical Calculation Model

The flow pattern of the stray currents follows the principle of least resistance [42–44], meaning that the currents will exit through areas of lower resistance in the tunnel. During operation, the subway shield tunnel is subjected to external loads, causing varying degrees of deformation at the tunnel joints. As a result, groundwater from outside the tunnel may seep into the interior through these joints, allowing stray currents to enter via the top of the track bed and exit through the tunnel joints. Full-scale test [45–48] studies have shown that under external loading, the joints at the arch waist of the shield tunnel open first. Therefore, the joint at the arch waist of the shield tunnel is defined as the output boundary for stray currents, and the upper region of the track bed rebar as the input boundary for stray currents. The boundary concentration at both the outer arc surface of the tunnel and the joint surface at the tunnel waist are all set to 0.6 mol/L, as shown in Figure 2.

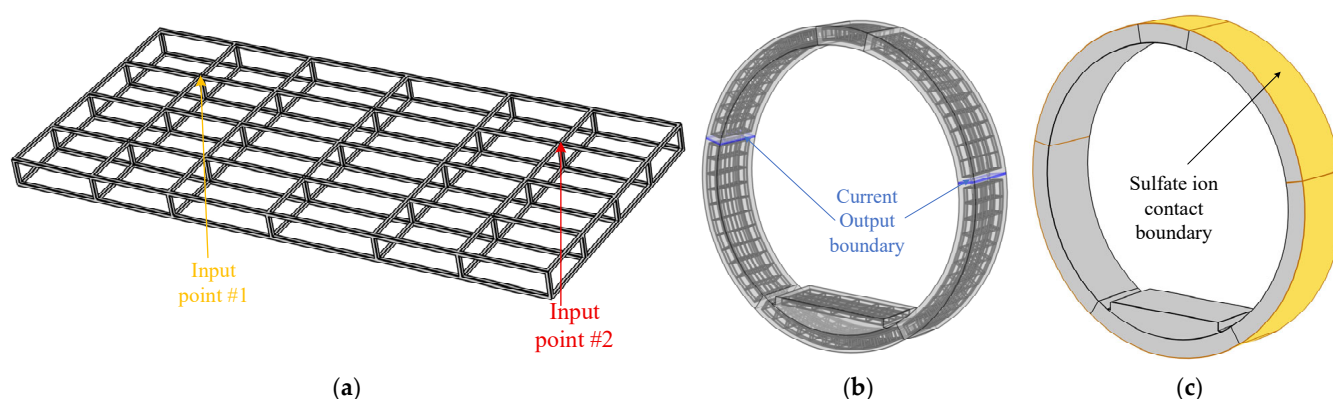


Figure 2. Diagram of boundary conditions for the numerical calculation model: (a) Current input boundary. (b) Current output boundary. (c) Sulfate ion contact boundary.

3. Model Test Verification

To verify the accuracy of the numerical calculation model, reinforced concrete specimens were cast for model testing, each measuring $150\text{ mm} \times 150\text{ mm} \times 150\text{ mm}$, with rebar positioned at the center of the concrete and a diameter of 16 mm. After curing, the specimens were placed in containers filled with sodium sulfate solution (0.6 mol/L), with the rebar connected to the positive electrode and a copper plate to the negative electrode. The applied voltage was maintained at 80 V, and the electrolysis duration was set at 30 days and 60 days respectively. After completion of the electrolysis, core samples were extracted by drilling, and the sulfate ion content was determined using automatic conductivity titration instrument (Hanon T860), as shown in Figure 3. The test standard follows GB/T 176-2017 [49] when using this device for measurement, and a standard barium nitrate solution is typically employed. Barium ions reacted with sulfate ions to form barium sulfate precipitate, and the endpoint was determined by monitoring changes in the solution's conductivity. All tests were conducted under laboratory conditions at a room temperature of $25\text{ }^{\circ}\text{C}$. In this study, eight groups test specimens were used, with the testing surface located on the side away from the rebar end. Statistical analysis showed that the maximum deviation in test results for different specimens at the same location did not exceed 6%.

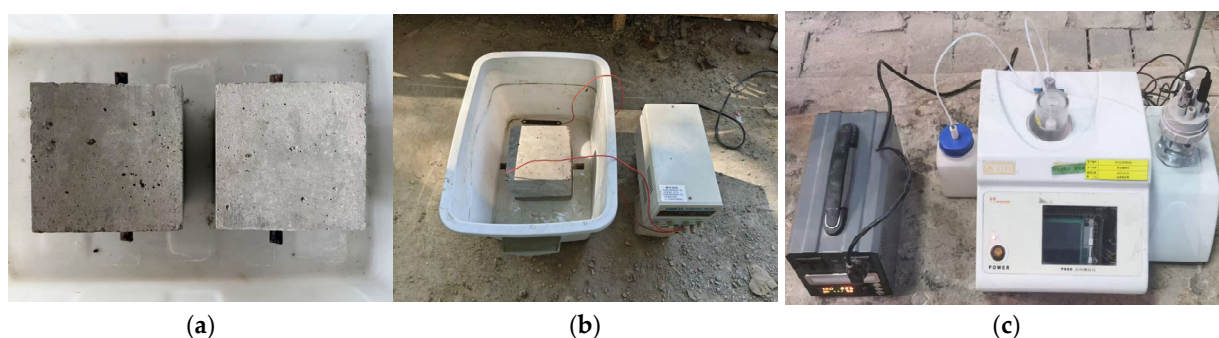


Figure 3. Photos of model test verification: (a) Test specimen. (b) Electrolytic corrosion of reinforced concrete. (c) Potentiometric titration method.

All numerical calculations were performed using COMSOL software, with an input voltage parameter of 80 V and a concrete conductivity of 0.02 S/m ; all other electrochemical calculation parameters remained consistent with those in Table 1. Figure 4a shows the voltage distribution in the specimen, indicating that the voltage was higher near the rebar and zero at the bottom region of the specimen. Figure 4b,c present the sulfate ion concentration distribution across different specimens, showing that over time, the sulfate ion concentration near the rebar gradually increased under the influence of the electric field, with the central region having a higher ion concentration than the side regions. Figure 5 also compares experimental specimens with numerical simulation models under various conditions. When the diffusion time was 30 days, the errors between the measured values at test points #1, #2, #3, and #4 and the calculated results were 12%, 7%, 10%, and 9%, respectively, with an overall root mean square error (RMSE) of 9.67%. When the diffusion time was 60 days, the errors were 5%, 6%, 5%, and 7%, respectively, resulting in an overall RMSE of 5.81%. The results demonstrate that using this numerical model for calculations is reasonable and feasible.

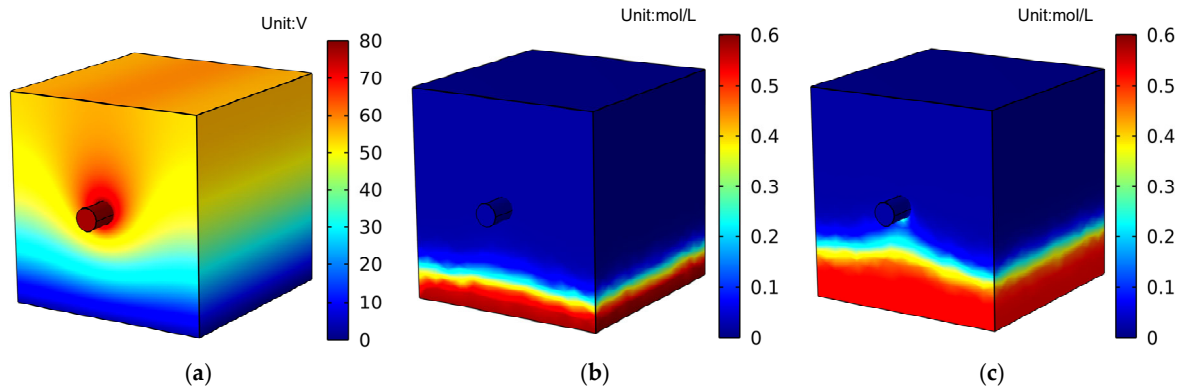


Figure 4. Contour plot of numerical simulation results: (a) Voltage distribution of specimen. (b) Sulfate ion migration after 30 days. (c) Sulfate ion migration after 60 days.

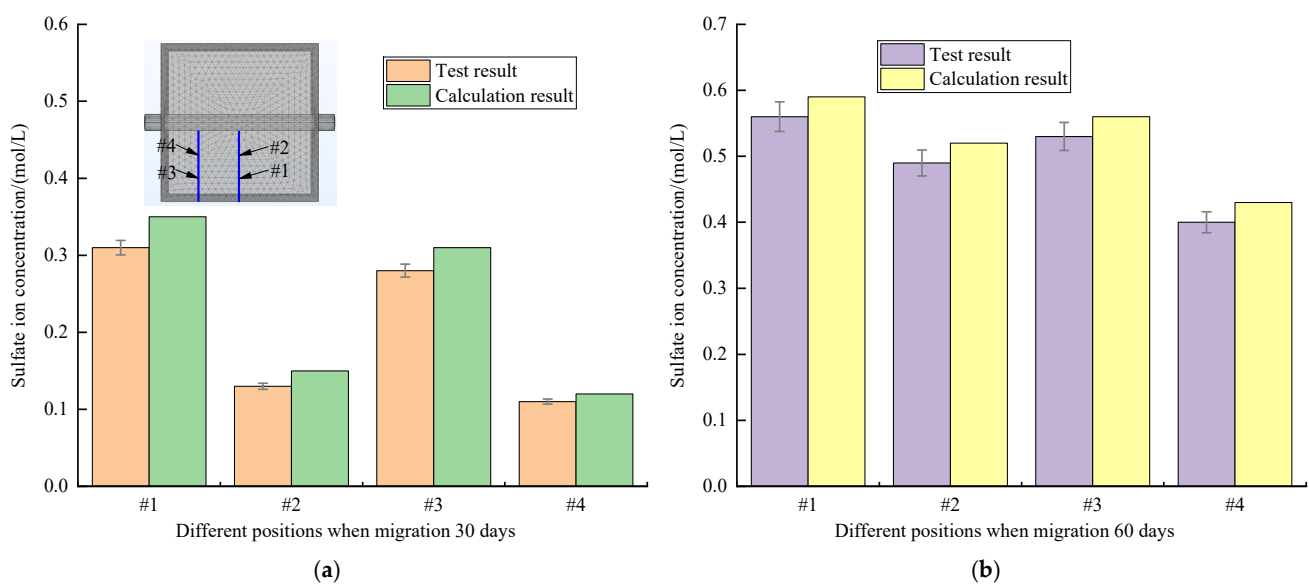


Figure 5. Sulfate ion concentration comparison analysis between test and numerical simulation: (a) Comparison of ion concentration after 30 days of migration. (b) Comparison of ion concentration after 60 days of migration.

4. Results and Discussion

4.1. Bilateral Leakage Mode of Stray Currents

Figure 6 shows the voltage distribution curve of the shield tunnel under bilateral stray current leakage conditions. It can be observed that the voltage at the tunnel bottom segments is significantly higher than in other areas. The voltage distribution range of the tunnel segment rebars is between 0 and 2.6 V, with a relatively distinct voltage gradient at the leakage points in the track bed region. Figure 7 presents the circumferential voltage distribution along rebar S2 in the arch-bottom segment under different input boundary conditions. The results indicate that increasing the input voltage does not alter the overall shape of the voltage curve, and the voltage remains consistently higher at the center than at both ends. Figure 8 also illustrates the circumferential voltage distribution along rebar S3 in the arch-side segment under various input boundary conditions. The data show that voltage decreases linearly with distance from the input end. When the input voltage increased from 1 V to 5 V, the voltage at the mid-section of rebar S3 increased by 10.3 times.

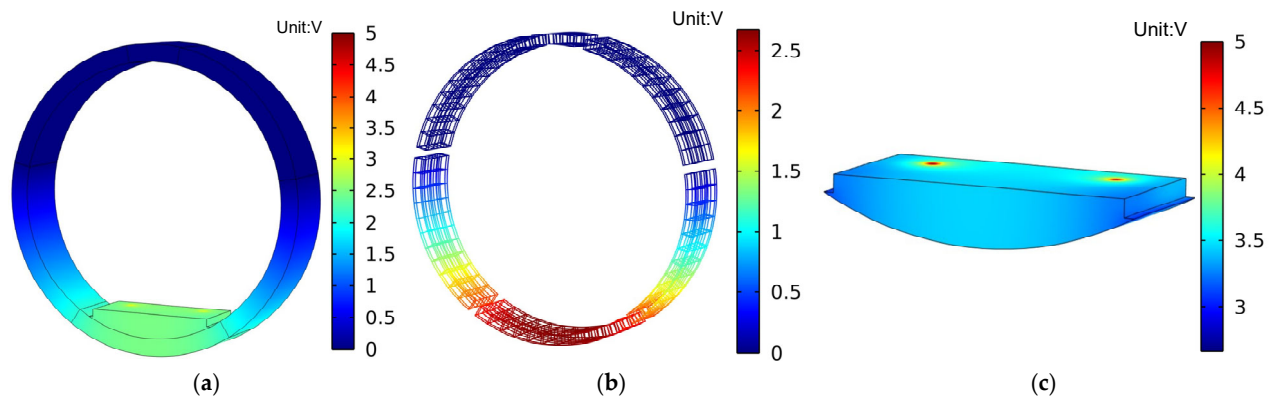


Figure 6. Voltage distribution curve of shield tunnel under bilateral leakage conditions: (a) Shield tunnel. (b) Tunnel segment rebar. (c) Track bed.

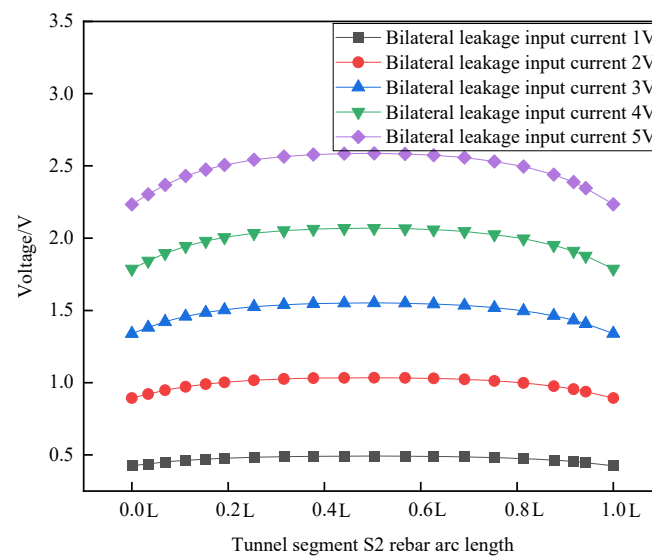


Figure 7. Circumferential voltage distribution along tunnel rebar S2 in the arch-bottom segment under bilateral leakage conditions.

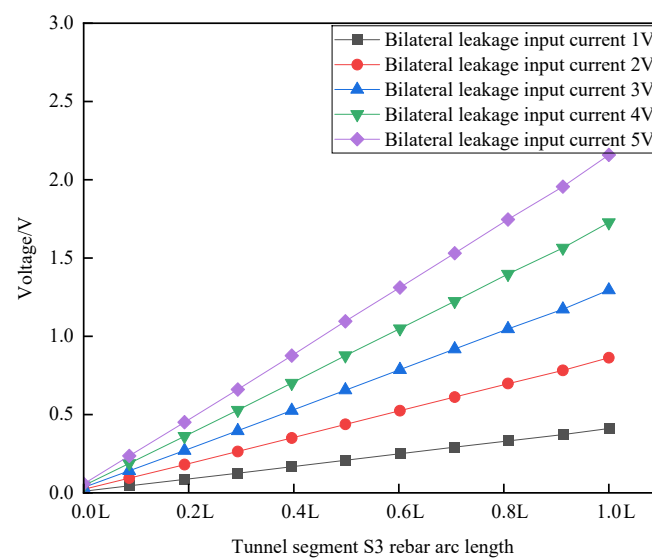


Figure 8. Circumferential voltage distribution along tunnel rebar S3 in the arch-side segment under bilateral leakage conditions.

Figure 9 shows the distribution cloud of sulfate ions in the shield tunnel at different time periods. It can be observed that the diffusion rate of sulfate ions on the outer arc surface of the segment is relatively slow, while the migration rate of sulfate ions in the leakage area is significantly higher. This is because sulfate ions are negatively charged. As current flows out from the arch waist joint, the stray current causes sulfate ions to rapidly migrate into the interior of the segment. Figure 10 presents the sulfate ion concentration profiles along the thickness direction at the center cross-section of the arch bottom segment at various time intervals. The results indicate that the range of sulfate ion distribution gradually expands with increasing time. When the time increases from 5 to 15 years, the maximum diffusion distance of sulfate ions increases by 41%. Figure 11 displays the sulfate ion distribution curves along the circumferential direction on the inner arc surface of the arch bottom segment S2 at different time periods. The curves exhibit a bimodal distribution pattern, and this becomes more pronounced over time. This is due to the fact that closer proximity to the leakage point leads to a greater potential gradient, thereby accelerating the migration rate of sulfate ions. When the duration extends from 5 to 15 years, the maximum sulfate ion concentration on the inner arc surface increases by 1.1 times.

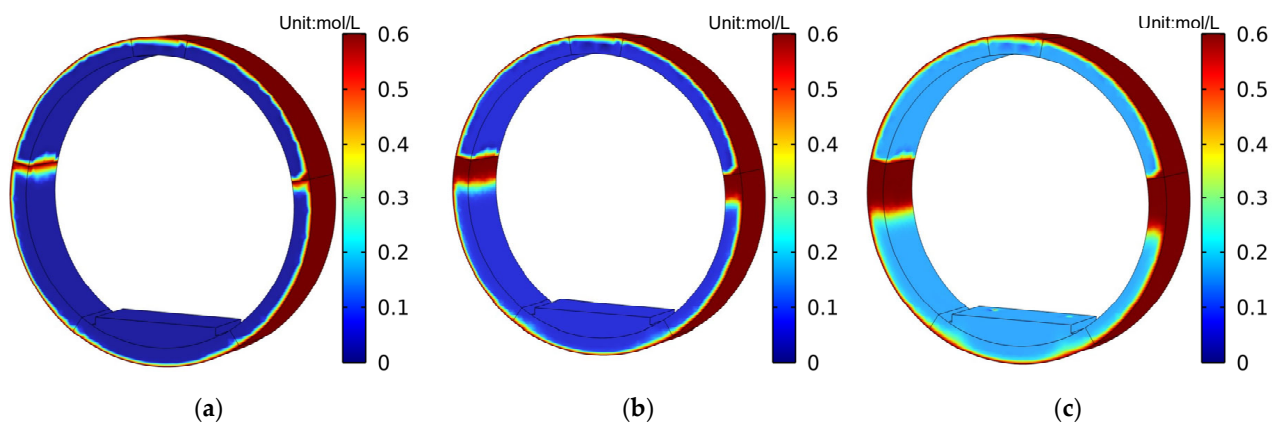


Figure 9. Distribution cloud of sulfate ions in the shield tunnel at different time periods under bilateral leakage conditions: (a) Time is 5 years. (b) Time is 10 years. (c) Time is 15 years.

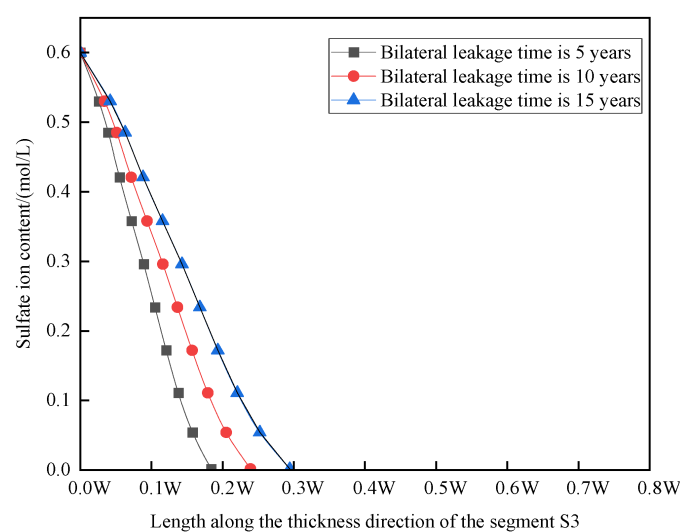


Figure 10. Sulfate ion concentration along thickness direction in center section of S2 segment under bilateral leakage condition.

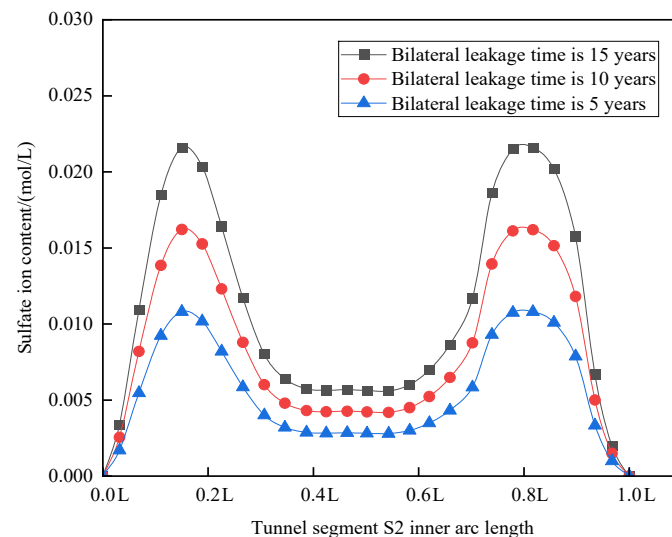


Figure 11. Sulfate ion distribution along circumferential direction on inner arc surface of S2 segment under bilateral leakage condition.

Figure 12 shows the corrosion current density distribution contour of tunnel segment rebar at different time stages. It can be observed that as the diffusion range of sulfate ions increases, the corrosion area of the rebar expands accordingly. Since the rebar chemical corrosion process was limited by oxygen concentration, the corrosion current density reached a maximum value and remained constant thereafter. Figure 13 presents the corrosion current density distribution curve along the circumferential direction for rebar A3 in the arch waist segment at various time intervals. The curve exhibits an inverted S-shape with a relatively steep decline in current density. Additionally, Figure 14 displays the corrosion current density distribution curve along the width direction at position 0.3 L for rebar A3 in the arch waist segment over different periods. As time progresses, the corrosion current density increases proportionally. A peak appears at position 0.8 L due to the rebar being closest to the stray current input point at this location, resulting in a larger potential difference.

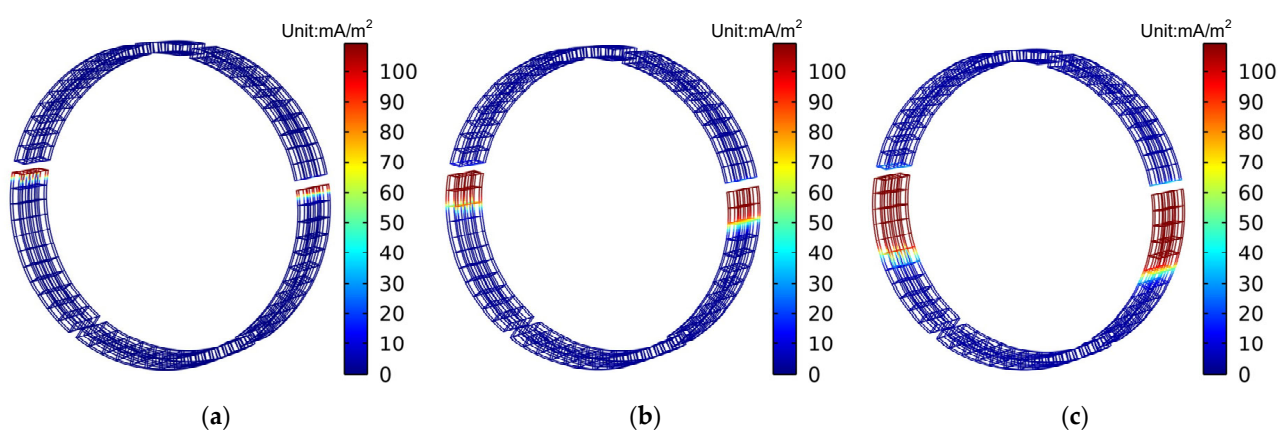


Figure 12. Corrosion current density distribution contours of tunnel segment rebar under bilateral leakage conditions: (a) Time is 5 years. (b) Time is 10 years. (c) Time is 15 years.

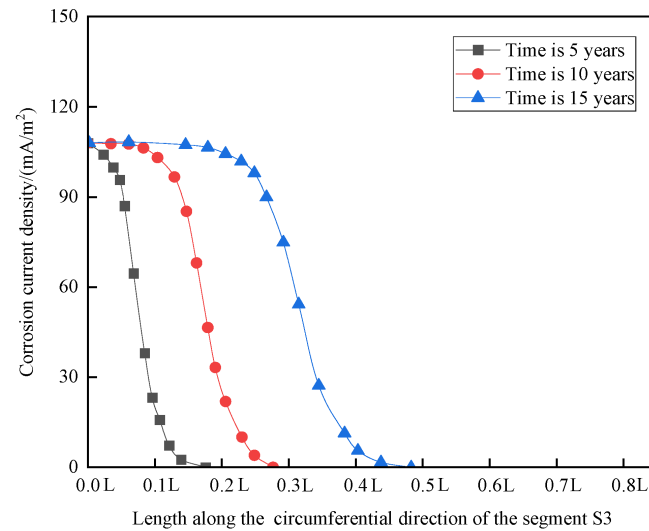


Figure 13. Corrosion current density distribution curve along circumferential direction for tunnel rebar S3 under bilateral leakage.

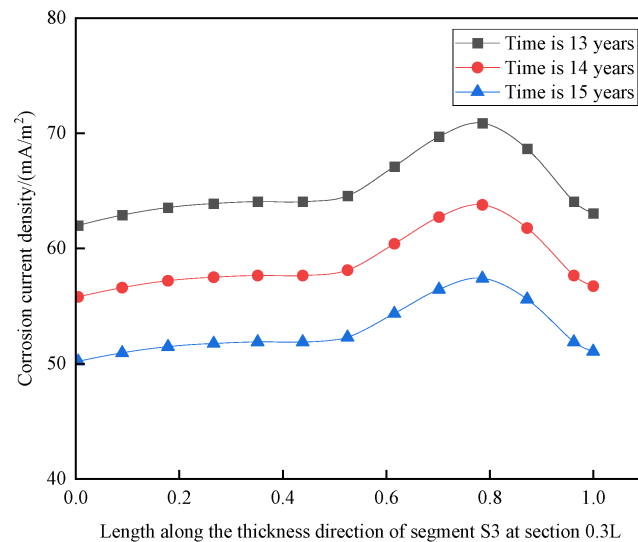


Figure 14. Corrosion current density distribution curve along the width direction at section 0.3 L for tunnel rebar S3 under bilateral leakage.

4.2. Unilateral Leakage Mode of Stray Current

Figure 15 shows the voltage distribution under the condition of unilateral stray current leakage. It can be observed that the voltage distribution was mainly concentrated in the area slightly to the left at the bottom of the tunnel segment, with the voltage on the rebar of the tunnel segments ranging from 0 to 2.1 V. Figure 16 presents the circumferential voltage distribution along rebar S2 of the arch-bottom segment under different input boundary conditions. The results indicate that, compared to the bilateral leakage case, the peak point of the curve shifted from the center toward the left side under unidirectional leakage conditions. Furthermore, under equal voltage levels, the maximum voltage on the arch-bottom segment rebar decreased by 18% to 33% in the unidirectional leakage condition. Figure 17 also illustrates the circumferential voltage distribution along rebar S3 of the arch-side segment under various input boundary conditions during unidirectional leakage. The voltage distribution patterns for both unidirectional and bilateral leakage cases were similar, showing a linear decrease; when the input voltage increased from 1 V to 5 V, the voltage at the mid-section of rebar S3 rose by 8.2 times.

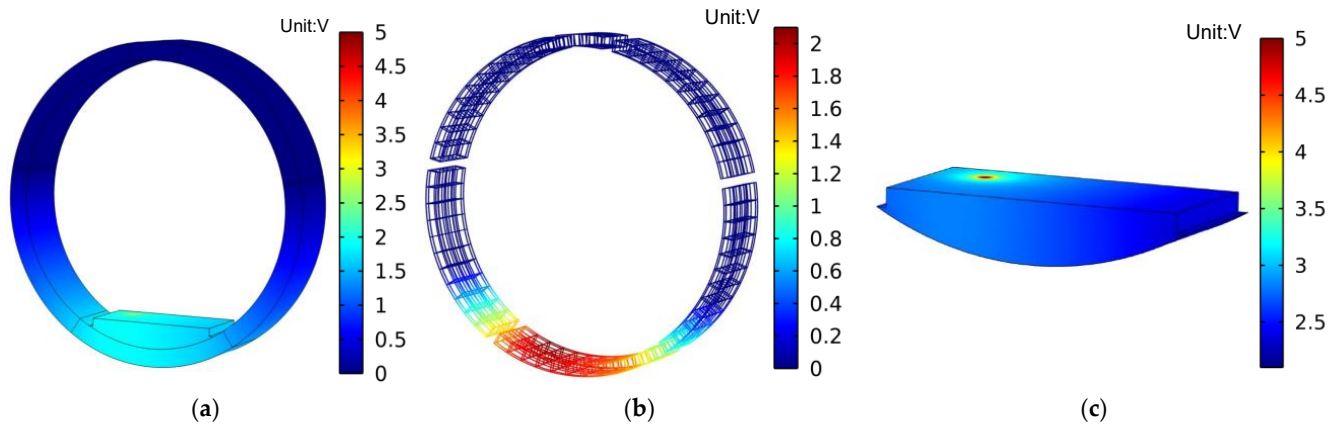


Figure 15. Voltage distribution curves of shield tunnel under unilateral leakage conditions: (a) Shield tunnel. (b) Tunnel segment rebar. (c) Track bed.

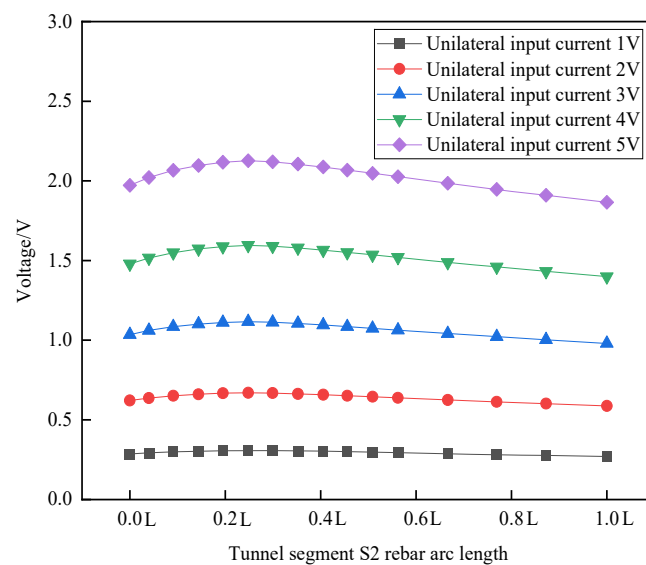


Figure 16. Circumferential voltage distribution along tunnel rebar S2 in the arch-bottom segment under unilateral leakage condition.

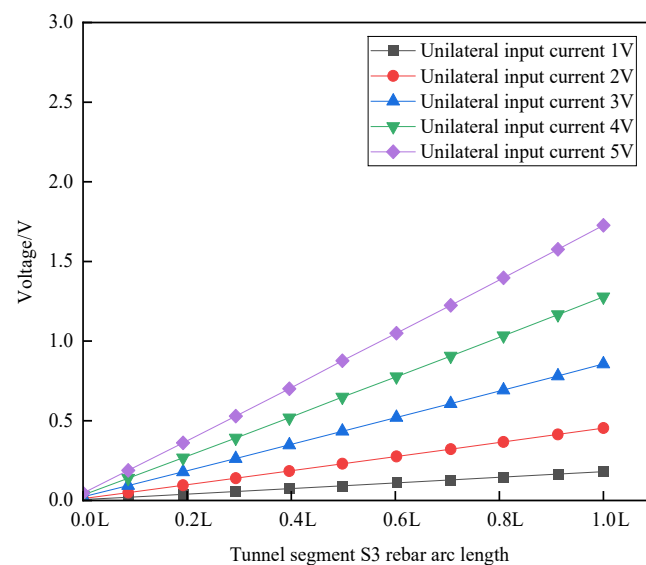


Figure 17. Circumferential voltage distribution along tunnel rebar S3 in the arch-side segment under unilateral leakage condition.

Figure 18 shows the distribution contour of sulfate ions under unilateral leakage conditions at different time intervals. It can be observed that, compared to the bilateral leakage scenario, the diffusion rate of sulfate ions near the input end is significantly higher than that on the opposite side in the unidirectional case, indicating that leakage conditions notably affect the migration rate of sulfate ions. Figure 19 also presents the sulfate ion concentration profiles along the thickness direction at the center cross-section of the arch-bottom segment under unidirectional leakage conditions over various periods. The results show that when the time increases from 5 to 15 years, the maximum diffusion distance of sulfate ions increases by 39%. Compared with the bidirectional leakage condition, the variation range of sulfate ion distribution under unidirectional leakage is reduced. This is due to the decreased number of input points, which reduces the potential difference at the output end and thus slows down the migration process of sulfate ions. Figure 20 illustrates the sulfate ion distribution curves along the circumferential direction on the inner arc surface of the arch-bottom segment at different time intervals. It is evident that, compared to the bidirectional leakage condition, the bimodal shape under unidirectional leakage is asymmetric, with a higher peak on the side closer to the input end. When the duration extends from 5 to 15 years, the maximum sulfate ion concentration on the inner arc surface increases by 0.8 times.

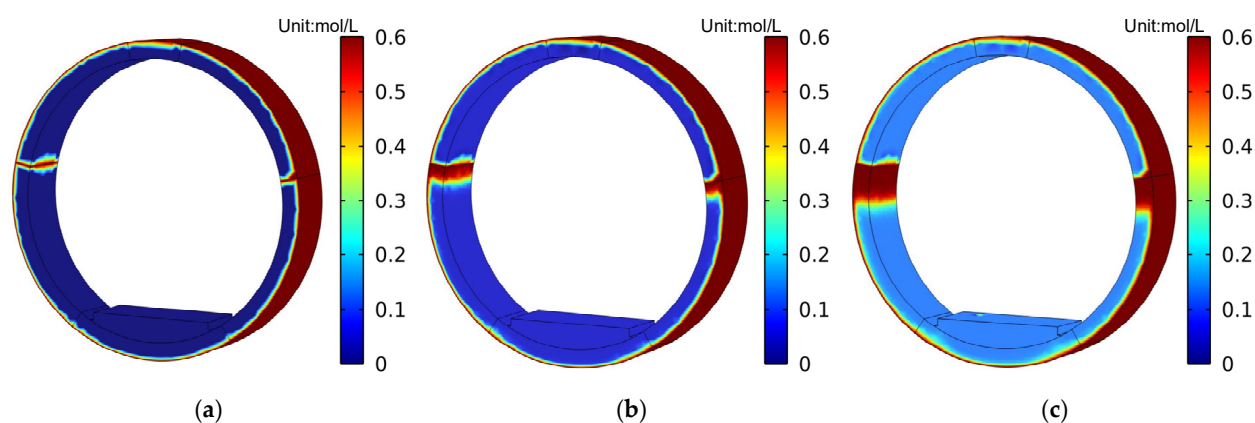


Figure 18. Distribution cloud of sulfate ions in shield tunnel at different time periods under unilateral leakage condition: (a) Time is 5 years. (b) Time is 10 years. (c) Time is 15 years.

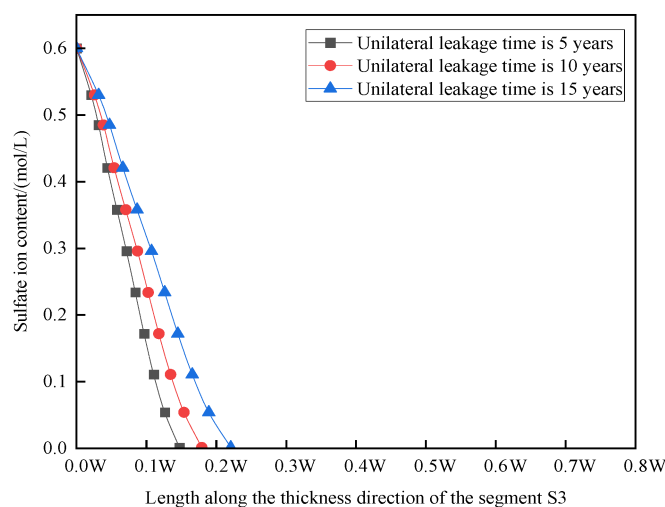


Figure 19. Sulfate ion content along thickness direction in center section of S3 segment under unilateral leakage condition.

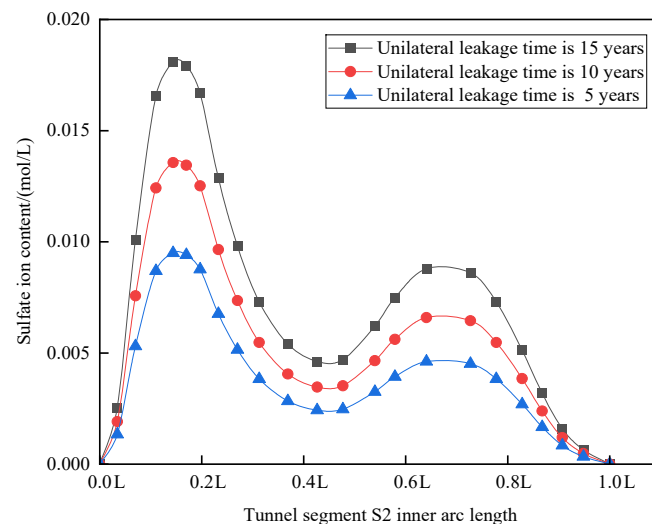


Figure 20. Sulfate ion distribution along circumferential direction on inner arc surface of S2 segment under unilateral leakage condition.

Figure 21 shows the corrosion current density distribution contour map of tunnel segment rebars under unidirectional leakage at different time stages. It can be observed that, compared to the bilateral leakage condition, the corrosion area on both sides of the segments is reduced under unidirectional leakage, with a more pronounced reduction on the right side. This is because the input end is closer to the output end on the left, resulting in a steeper potential gradient and thus greater corrosion of the rebar on the left side by sulfate ions. Figure 22 presents the corrosion current density distribution curve along the circumferential direction of rebar A3 in the arch waist segment under unidirectional leakage at various time periods. The curves show similar shapes under both unilateral and bilateral leakage conditions, with only a slight decrease in the length of rebar affected by corrosion. Figure 23 illustrates the corrosion current density distribution curve along the width direction at position 0.3 L for rebar A3 in the arch waist segment under unidirectional leakage at different time intervals. Compared to the bilateral leakage case, the amplitude of fluctuations in the curve is significantly reduced under unilateral leakage, but the corrosion current density increases proportionally with increasing leakage voltage in both cases. When the voltage increased from 1 V to 5 V, the maximum corrosion current density of the internal rebar in the tunnel increased by 70%.

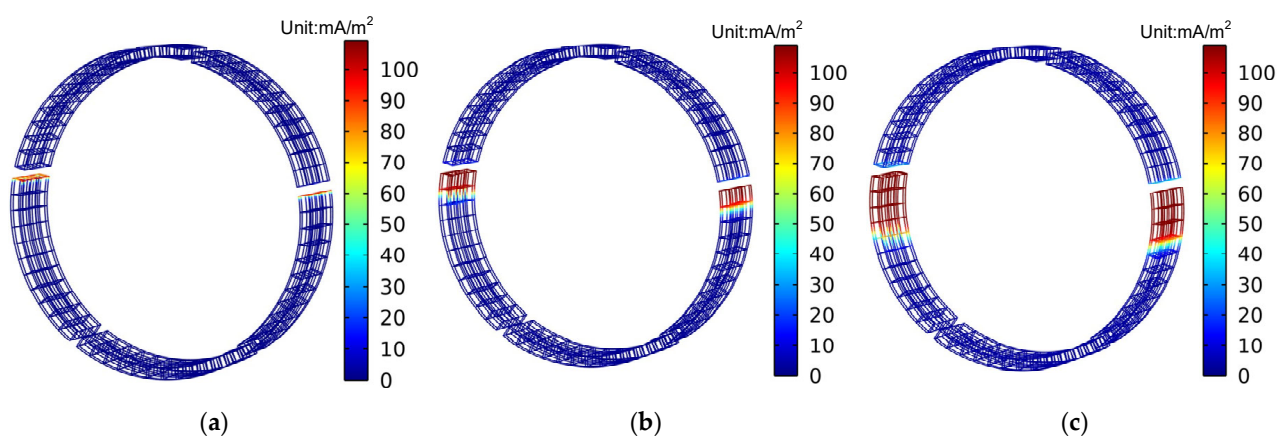


Figure 21. Corrosion current density distribution contours of tunnel segment rebar under unilateral leakage conditions: (a) Time is 5 years. (b) Time is 10 years. (c) Time is 15 years.

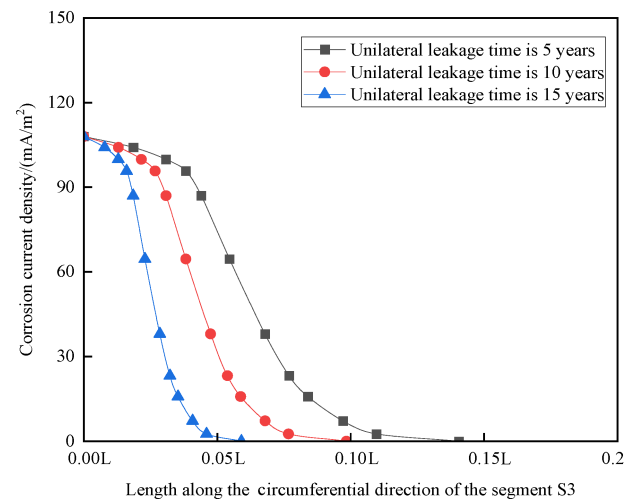


Figure 22. Corrosion current density distribution curve along circumferential direction for rebar S3 under unilateral leakage.

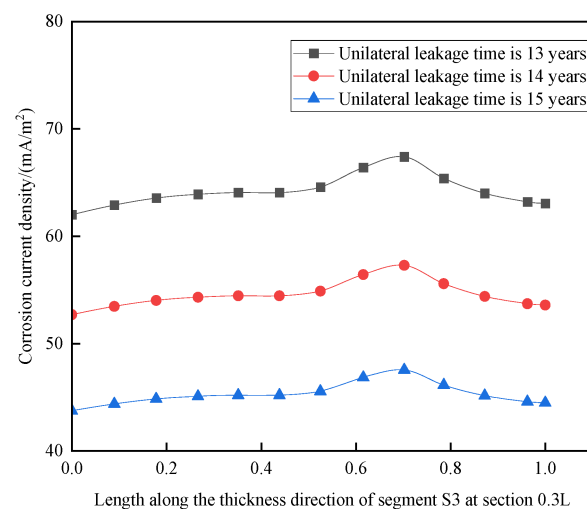


Figure 23. Corrosion current density distribution curve along width direction at section 0.3 L for rebar S3 under unilateral leakage.

5. Conclusions

1. The calculation results indicate that under the coupled effects of stray currents and sulfate ions, the corrosion area in the segment rebar gradually spreads from the arch waist area of the tunnel, and the corrosion rates at the near end of the tunnel rebar are all equal. Compared to bilateral leakage, both the migration rate of sulfate ions and the corrosion rate of rebar are higher than those in the unilateral leakage condition. The reason is that the larger potential difference in the bilateral leakage condition enhances the migration rate of charged ions, the sulfate ion concentration near the rebar in the tunnel is relatively high, causing the corrosion rate of the rebar to rapidly reach the limiting current density. Therefore, the rebar corrosion current density at the front end of the tunnel is equal.
2. Changes in the input voltage at the top of the ballast do not alter the shape of the distribution curves for the voltage and corrosion current density of the segmental rebar. When the input voltage increases from 1 V to 5 V, the voltage at the mid-section of the rebar increases by 10.3 times under bilateral leakage conditions, and the voltage at the mid-section of the rebar increases by 8.2 times under unilateral leakage conditions.

3. Compared to the bilateral leakage case, the amplitude of fluctuations in the curve is significantly reduced under unilateral leakage; however, the corrosion current density increases proportionally with increasing leakage voltage in both cases.
4. The sulfate ion concentration on the tunnel inner surface exhibits a bimodal distribution. The two peaks are symmetrically distributed under bilateral leakage conditions, whereas under unilateral leakage conditions, the two peaks are asymmetrically distributed, with the peak closer to the input point being higher. When the duration extends from 5 to 15 years, the maximum sulfate ion concentration on the inner arc surface of tunnel arch bottom in unilateral leakage and bilateral leakage increases by 1.1 times and 0.8 times respectively.
5. In actual situations, the points of stray current input may not all lie on the same tunnel ring, and the input boundaries could be at the joints between multiple tunnel rings. Although most urban power supply systems use direct current, the varying speeds of trains result in dynamic fluctuations in stray current voltage. In addition, the concentration of sulfate ions in groundwater may change due to external environmental influences. In this study, based on the theories of direct current transmission, ion migration, and electrochemical corrosion, a numerical computational model coupling electric and chemical fields was established. A single tunnel ring was selected for investigation. But the analysis results may differ somewhat from real-world conditions. In the future, a more detailed multi-ring shield tunnel model will be developed to analyze the corrosion mechanism of internal rebar in tunnel segments under the coupled effects of stray currents and sulfate ions.

Author Contributions: Writing—review and editing, Q.Z. and B.Y.; methodology, Z.Z.; software, C.Z.; formal analysis, Y.L.; writing—original draft, Q.Z.; project administration, C.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Quanwei Zhu, Ziyue Zhao, and Yuancheng Lin were employed by China Railway Southwest Research Institute Co., Ltd. Author Baijun Yue was employed by Sichuan Chuanjiao Road and Bridge Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

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