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Research Article

A Case Study of Tunnel Reinforcement Measure during Traffic Upgrading in Chongqing City, China

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Because the urban tunnel is an essential knot of urban traffic and an easy blocking point in busy hours, upgrading the urban tunnel was necessary for the city after the tunnel being in service for a long time. However, to demolish the existing tunnel, some problems may be encountered, and these problems include occurrence of longitudinal cracks at the tunnel vault, increase of load due to infrastructure construction over the tunnel, unloading due to excavation of the rock over the tunnel, and uneven load due to asymmetric excavation or construction. To reinforce a cracked tunnel in Chongqing City, China, steel arches were installed to improve its bearing capacity, but some steel arches failed during the excavation of ground over the tunnel. Therefore, the scheme of "steel arch + shotcrete + tube column + transversal horizontal bracing" (hereinafter referred to as SASTCT) was proposed to ensure tunnel safety due to unloading and uneven load during the subsequent construction procedures. Numerical analysis indicated that the SASTCT measure can ensure the safety of the traffic and subsequent construction, which can provide some suggestions for similar tunnel upgrades in the future.

1. Introduction

Nowadays, lots of projects aim at upgrading old tunnels or constructing new buildings near existing tunnels to meet people's growing needs in various aspects of life. Due to various factors such as design, construction, operation, and maintenance [1], the tunnel has to an increasing extent serious issues including material deterioration, structural deformation, structural damage, water leakage, frost damage, and construction defects [2, 3]. Among these issues, lining cracking and water leakage are the most common problems, because they seriously diminish the bearing capacity, integrity, and durability of tunnel lining structure and greatly reduce the service life of tunnels [4–11].

Some scholars have conducted research on tunnel defects and maintenance issues [12, 13]. Many factors have long been thought to be the cause of tunnel lining cracking, including construction materials, complex geological conditions, improper construction, bias pressure, and inappropriate design [14–16]. Excavation over the existing tunnel reduces the load (unloading) exerted on it. The tunnel is suffers from uneven load when it is subjected to monoclinal stratum, improper treatment of surrounding rock, and asymmetric excavation. Both the unloading and uneven load are the leading cause of lining cracking [17–19]. Nevertheless, at present, the research focus mainly focused on lining cracking caused by loose pressure, the cavity behind the lining, landslide, earthquake, and other factors, but the research on lining cracking caused by unloading and uneven load was relatively limited [20–28]. At present, many experts and scholars have conducted a lot of research on the mechanical properties of prefabricated underground utility tunnel under eccentric compression or local ultimate loads [29–32]. Excavation of the surrounding rock for an existing tunnel disturbed the existing equilibrium of the surrounding rock and tunnel, and the stress adjustification process in the surrounding rock and the existing tunnel may adversely affect the tunnel's lining structure [33–36]. In addition, the tunnels, especially some masonry tunnels that have been in service for a long time, maybe highly cracked under unloading-induced rebound and construction-induced disturbance, so it is necessary to reinforce the existing tunnels, especially old masonry tunnels, before the nearby construction [37].

As a critical part of the traffic system, highways, railways, or municipal tunnels would impede the traffic system or cause traffic jams after the occurrence of issues and problems. Therefore, how to select safe and reliable maintenance (reconstruction or reinforcement) methods for these tunnels is particularly important to avoid disturbance to the traffic in the city. Urban tunnels, vital urban transportation knots, became congested during rush hours, seriously restricting urban traffic. Building a bridge to replace the roadway over the existing tunnel and then constructing a roadway by excavating and demolishing the existing tunnel, termed "flyover construction and tunnel demolishment," is an effective method to upgrade the traffic system. An urban tunnel in service was taken as the research object to solve the problems such as longitudinal cracks at the tunnel vault and noncompaction-induced cavities. To solve these problems, after grouting the cavity behind the lining, the steel arch frame was adopted to strengthen the tunnel, followed by tunnel demolishment. However, due to the unloading effects by the excavation over the tunnel and the vibration caused by passing vehicles in the existing tunnel, the steel arch reinforcement of the tunnel partially failed, and the vertical displacement of the steel arch exceeded the safety control value. The renovation construction was forced to be suspended to ensure the safety of passing vehicles and personnel in the existing tunnel. In addition, given the effects on the existing tunnel caused by the subsequent construction of one bridge over the existing tunnel and the temporary footpath construction on the south side of the existing tunnel, the temporary reinforcement scheme and rescue construction measures of "steel arch + shotcrete + tube column + transversal horizontal bracing" (hereinafter referred to as SASTCT) were put forward for quick reinforcement and emergency treatment measures.

In this paper, the influence of the bridge construction above the tunnel and the temporary footpath excavation on the south side of the tunnel on the bearing capacity and deformation of the reinforced structure were calculated and analyzed by numerical analysis and field monitoring. The simulation results and on-site data monitoring showed that the stress and deformation of the SASTCT reinforcement and existing tunnel caused by the subsequent constructions did not exceed the allowable values by the specification, proving the feasibility and safety of the temporary reinforcement and rescue construction measures. This study can provide some insights for similar projects in the future.

2. Project Overview

As shown in Figure 1(a), the tunnel is one part of Hongshi Road connecting the Songshuqiao Overpass with the Hongqihegou Overpass in Chongqing, China. The tunnel was under the Yu'ao Road passing from east to west and acted as a key knot connecting the Yubei District and the Jiangbei District of Chongqing. The 145 m-long tunnel was opened to traffic in 1989 and permitted vehicles to run on two lanes in one way from Hongqihegou to Songshuqiao. As shown in Figure 1(b), the inner width of the tunnel with arch and vertical sidewalls is 9.5 m, including 7.5 m-wide lanes, 0.5 m-wide shoulders, and 1.5 m-wide shoulders for maintenance. The primary lining was made of C20 sprayed concrete, and the secondary lining was made of C15 concrete. For the secondary lining, the thickness of the sidewall was 1.12 m, and the thickness of the arch decreased from 1.12 m at its connection with the sidewall to 0.7 m at the vault. As shown in Figure 1(c), no infrastructure was constructed over the tunnel segment from K0 + 000 to K0 + 110, and the Yu'ao road was constructed over the tunnel segment from K0 + 110 to K0 + 145. The maximum burial depth of the tunnel was 20 m, as shown in Figure 1(d). The completed Yu'ao road overpass is shown in Figure 1(e). The surrounding rock for the tunnel was composed of gray sandstone and purple mudstone. Because of the small inner width, the tunnel became a bottleneck problem restricting the traffic and interaction between Yubei District and Jiangbei District. Therefore, this study attempted to adopt the "flyover construction and tunnel demolishment" for traffic upgrade and modification.

3. Construction Procedure

The masonry tunnel has been in disrepair for a long time. Before the implementation of this project, the competent department organized tunnel experts and testing agencies to inspect the tunnel. Field inspection indicated that six longitudinal cracks occurred at the vault of the tunnel, and each crack is approximately 10 m in length and 10–20 mm in width. In addition, 91 cavities induced by noncompaction were found behind the lining. Thereby, the tunnel was reinforced to ensure tunnel safety during the traffic upgrade and modification. Figure 2 shows the measures to reinforce the tunnel. At first, the cavities behind the lining were grouted, and then, steel arches made of I22B I-steels were installed at a longitudinal spacing of 50 cm to reinforce the tunnel. Two bolts (diameter is 22 mm) with a length of 4.0 m were set at the bottom of the left and right sidewalls of the steel arch, and longitudinal-connection rebars were installed in an annular pattern at a spacing of 1.0 m around the steel arch to reinforce the integrality of the steel arches. Steel blocks were inserted into the spacing between the secondary lining and the steel arch to transfer the load on the tunnel to the steel arch.

Figure 3 illustrates the construction procedures for the traffic upgrade and modification. First, the elevation of the ground surface over the tunnel segment from K0 + 000 to K0 + 110 was lowered to 309.70 m to provide a temporary passage for the Yu'ao Road, as shown in Figure 1(a), so the demolition of the Yu'ao Road over the tunnel segment from K0 + 110 to K0 + 145 would not be affected by the traffic.

Figure 1: Tunnel information: (a) tunnel location, (b) tunnel typical cross-section (unit: mm), (c) infrastructure over the tunnel, (d) tunnel portal facing Songshuqiao Overpass, and (e) the completed Yu'ao road overpass.

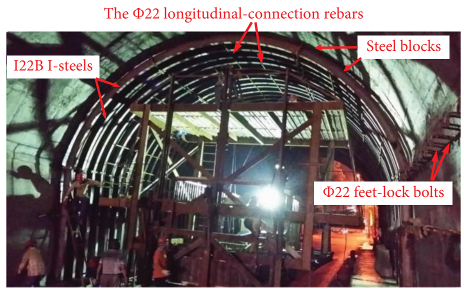


Figure 2: Steel arch reinforcement before traffic upgrade and modification.

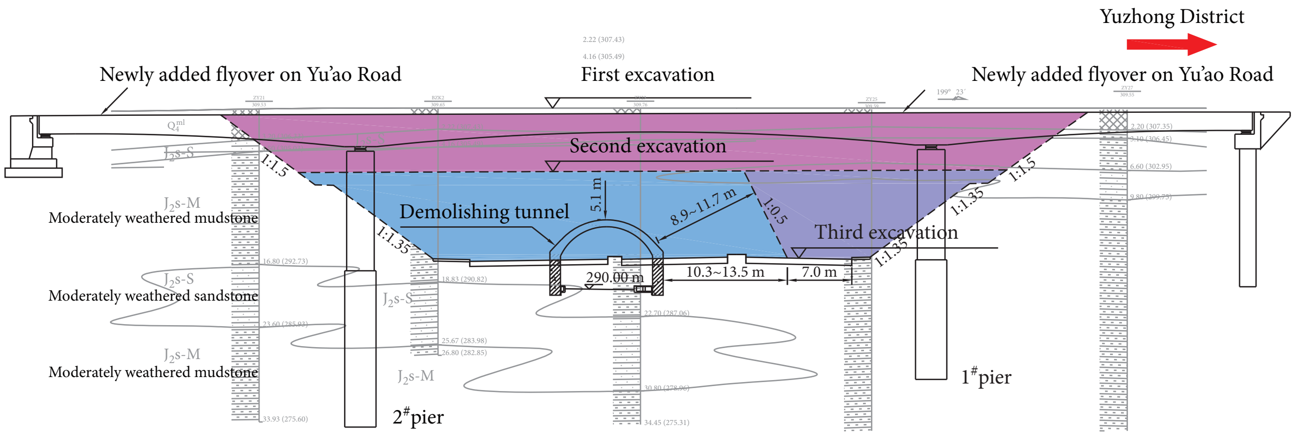


Figure 3: Construction procedures for traffic upgrade and modification.

Second, the flyover on the Yu'ao Road was constructed after excavating the ground surface over the tunnel segment from K0 + 110 to K0 + 145 to the elevation of 302.72 m, ensuring that the tunnel roof covering layer is greater than 4 m. Third, the southern side of the tunnel was excavated to the elevation of 293.00 m to provide a temporary passage from Hongqihegou to Songshuqiao as an alternative for the existing tunnel. Finally, the tunnel was demolished after excavating the surrounding rock around the tunnel to the design elevation.

The movements of the left and right sidewalls of the secondary lining and steel arch and the settlements at the vault of the steel arch were monitored during the traffic upgrade and modification to ensure construction safety. The monitoring sections were at a spacing of 10.0 m for the tunnel segment from K0 + 000 to K0 + 100 and at a spacing of 5.0 m for the tunnel segment from K0 + 100 to K0 + 145. Therefore, there were twenty monitoring sections in total. As shown in Figure 4, three monitoring points (one at the vault of the arch steel and two at the sidewall top) were set for each section to observe the settlement at the vault of the steel arch and the convergence between the left and right sidewalls of the steel arch, and two monitoring points (one at the left sidewall and another one at the right sidewall) were set for each section to observe the convergence between the left and right sidewalls of the secondary lining.

The safe control value of the vertical displacement at the arch frame vault in the tunnel was set at 15 mm, according to the engineering experiences and the relevant regulations [38]. Safety prewarnings would be triggered when the monitoring value exceeds 60% of the control value (i.e., 9 mm), and the construction would be stopped when the monitoring value exceeds 80% of the control value (i.e., 12 mm). Because the tunnel construction was more complex from K0 + 110 to K0 + 145 than from K0 + 000 to K0 + 110, the monitoring results at K0 + 120 are shown in Figure 5 to explain the effects of traffic upgrade and modification on the existing tunnel. As shown in Figure 5, the settlement at the steel arch vault for section K0 + 120 exceeded 9 mm on May 5th and May 26th, 2015, and then exceeded 12 mm on June 24th, 2015. In addition, cracks developed at the vault, and water seepage through the crack were observed during the traffic upgrade and modification, as shown in Figure 5(③).

The temporary steel arch reinforcement was convenient to install and disassemble, with fast construction and low engineering cost. However, the steel arch reinforcement and the existing tunnel cannot function integrally as a whole. The secondary lining of the tunnel is hunched up due to the unloading induced by the excavation over the tunnel. In addition, the vibration generated by passing vehicles in the tunnel led to the shedding of some steel blocks between the secondary lining and steel arches, resulting in the failure of some steel arches, as shown in Figure 5. Construction of the overfly for the Yu'ao Road can impose additional loading on the tunnel segment from K0 + 110 to K0 + 145. Moreover,

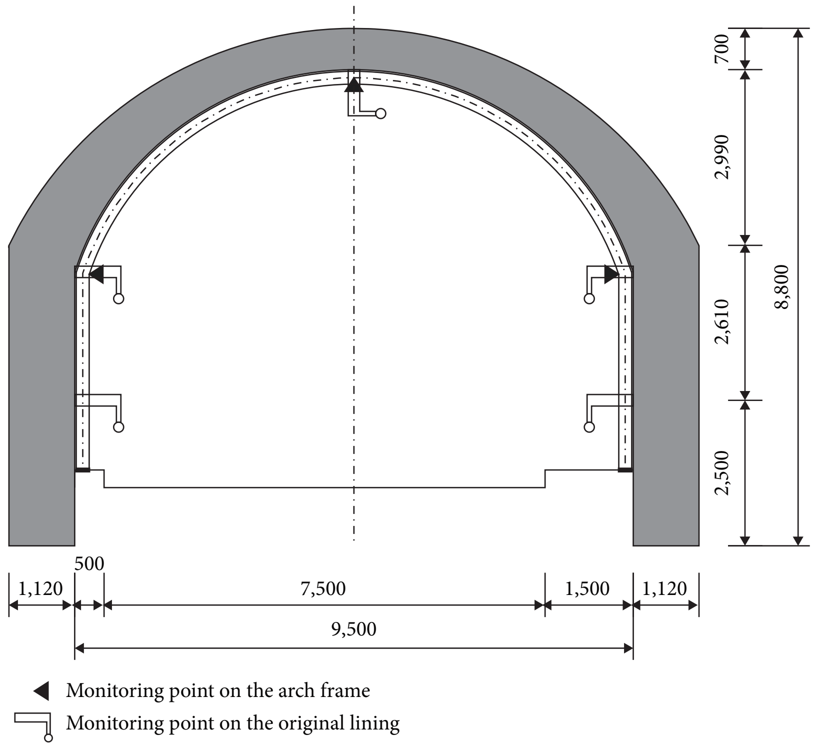


Figure 4: Layout of monitoring points (unit: mm).

excavating a temporary passage along Hongshi Road on the southern side of the tunnel can cause uneven loading on the tunnel. Therefore, the projects were stopped for emergency treatment and rescue measures in order to ensure the safety of the subsequent construction and traffic system.

How to make the steel arch and the old lining form an organic whole? The common primary support in tunnel engineering has given us good inspiration, which is to use the bonding effect of shotcrete and steel mesh to form a whole support system between the steel arch and the surrounding rock [39, 40]. Based on this mechanism, we consider using shotcrete and steel mesh to solve the problem of the inability of steel arches and old lining to form a common support system. After solving this problem, the next issue is how to increase the overall stiffness of the reinforced structure while ensuring uninterrupted tunnel traffic. This rigid operational requirement naturally reminds us to add a vertical steel tube column in the center of the tunnel to increase the vertical stiffness of the reinforced structure while avoiding excessive occupation of lane width; add a horizontal steel support at the arch to increase the horizontal stiffness of the reinforced structure while ensuring the net height required for vehicle traffic. Based on the above ideas, we propose a new emergency rescue reinforcement measure as shown below.

4. Emergency Treatment and Rescue Measures

Figure 6 shows the emergency treatment and rescue measures to ensure the safety of subsequent construction. As shown in Figure 6, vertical steel tube columns with a spacing of 1.5 m were installed between the two tunnel lanes, and transversal 20 U-steels with a spacing of 1.5 m were installed horizontally to connect the steel arch and the steel tube column, hence improving the stiffness of the steel arch and prevent its failure. In addition, C25 sprayed concrete with a thickness of 0.25 m was utilized to close the arch steel so that the steel arch and existing tunnel can work as a whole. Because the temporary emergency treatment and rescue measures include steel arch, shotcrete, tube column, and transversal U-steel, the measure is termed SASTCT in this study.

5. SASTCT Evaluation by Simulation

5.1. Simulation model. Using finite element analysis software, i.e., Midas GTS, the three-dimensional stratum-structure model was established for achieving simulation and in-depth analysis of the steel arch scheme and the SASTCT scheme. Based on the Saint Venant principle, the effective influencing range of the tunnel was thoroughly considered. The established 3D calculation model was perpendicular to the tunnel direction. As shown in Figure 7(a), the left and right boundaries of the three-dimensional model were 50 m away from the left and right sidewall of the tunnel, respectively, and the bottom boundary was 35 m away from the tunnel floor. The movement of the left and right boundaries was not allowed in the horizontal direction and the movement of the bottom boundary was not allowed in the vertical direction. As shown in Figures 7(b) and 7(c), the tunnel lining was simulated with plate elements, and the reinforcements were simulated with beam elements. Table 1 lists the physical and mechanical parameters of the surrounding rocks in the tunnel based on field and laboratory

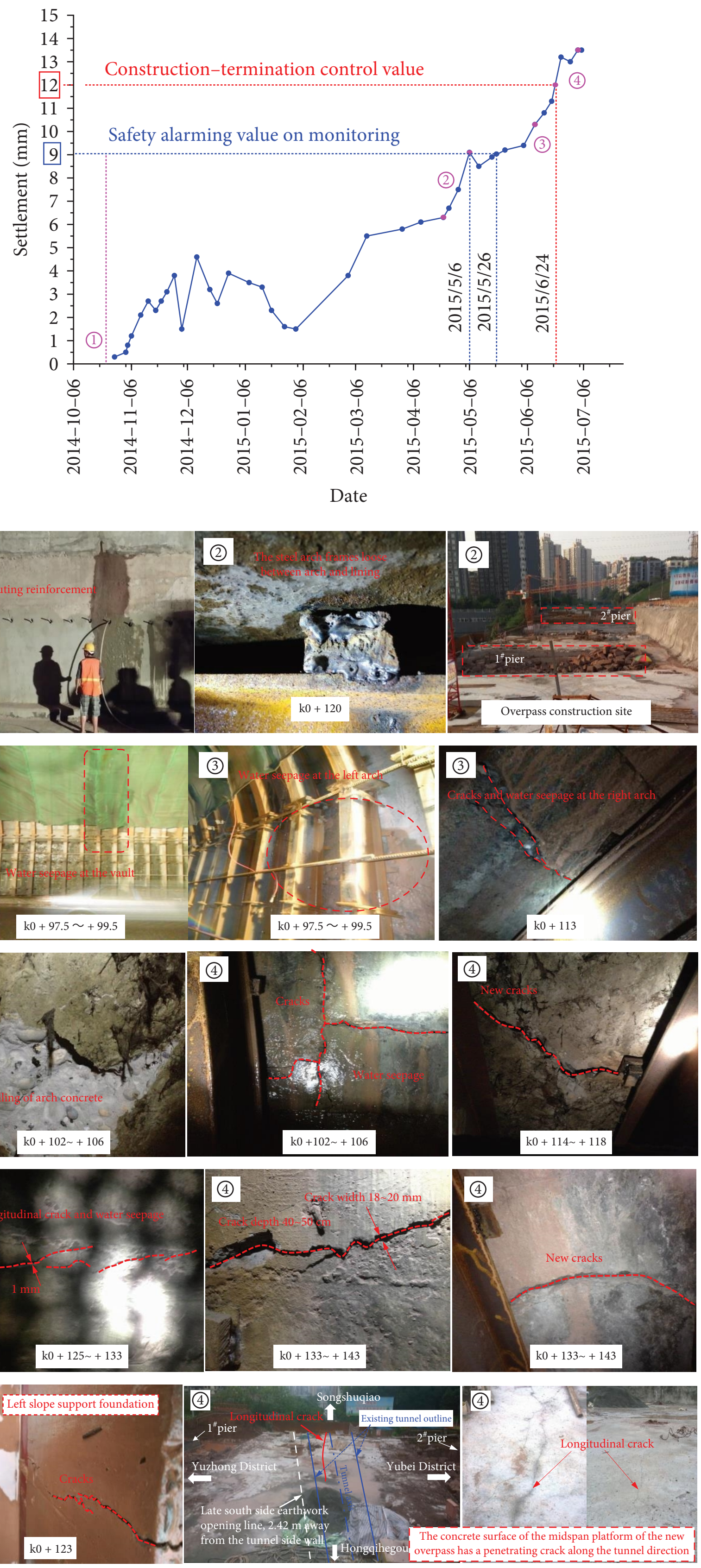
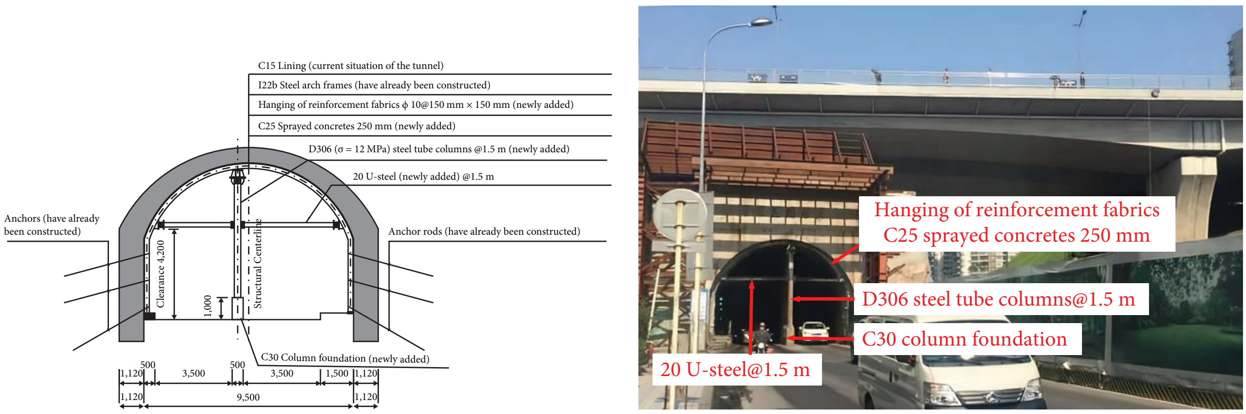
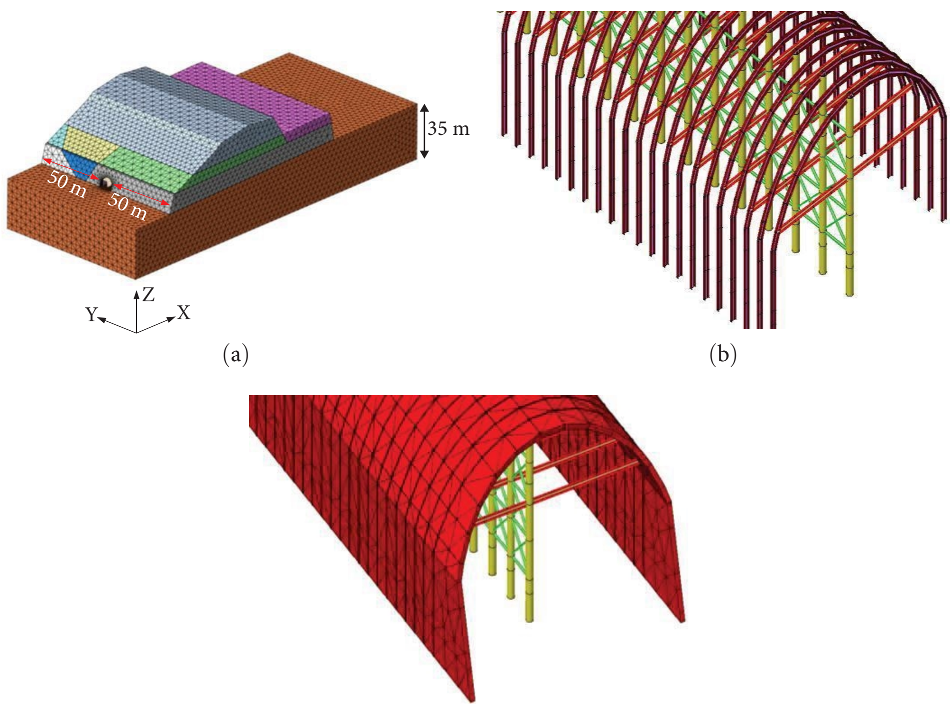


Figure 5: Steel arch vault settlement at K0 + 120 and observed tunnel issues.



(a) (b)

Figure 6: Emergency treatment and rescue measures: (a) design of typical cross-section (units in mm) and (b) in situ construction.



(a) (b)

(c)

Figure 7: Three-dimensional simulation model: (a) model dimension, (b) supporting elements, and (c) shotcrete and supporting elements.

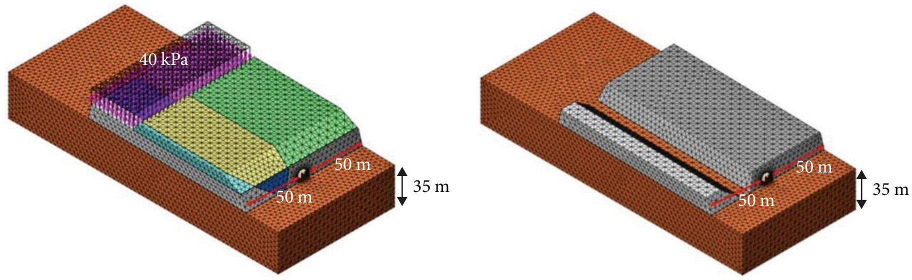
Table 1: Physical and mechanical parameters of surrounding rock.

Rock classification*	Density, γ (kg/m^3)	Elastic modulus, E (MPa)	Poisson's ratio, (μ)	Cohesion, c (kPa)	Friction angle, φ (°)
IV	2,500	1,050	0.33	350	19.6

Notes. Classification of the surrounding rock was based on the specification [38], which considered the joints, rock strength, groundwater, etc.

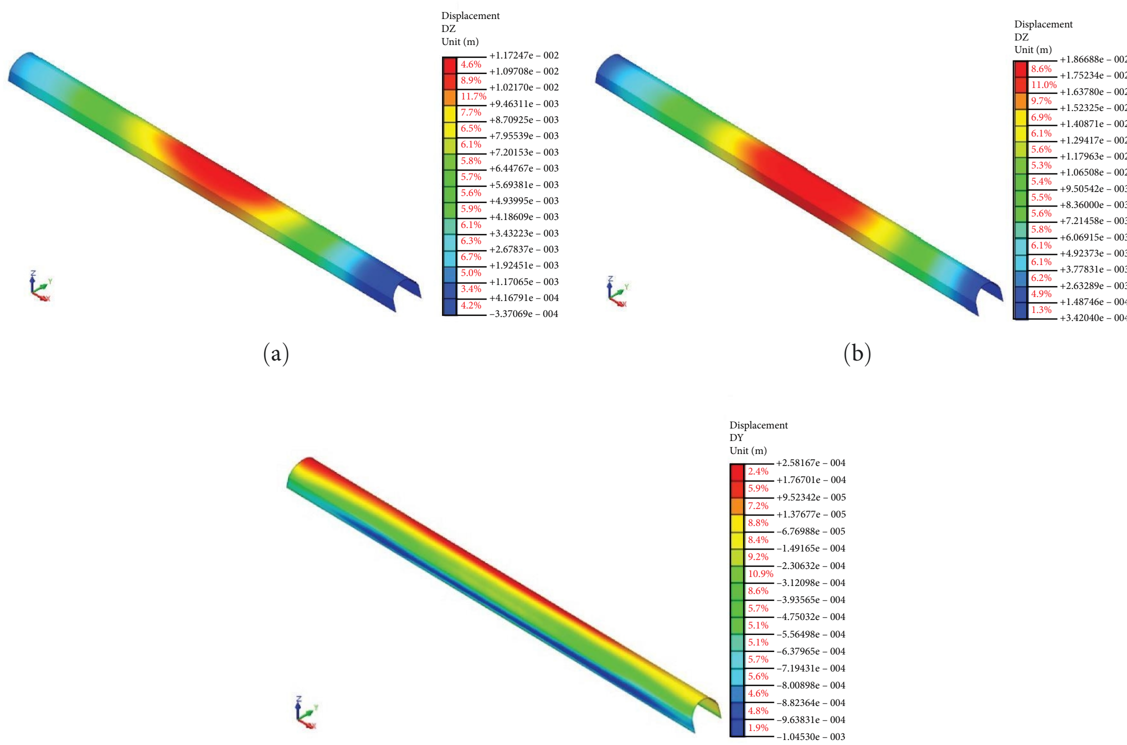
Table 2: Physical and mechanical parameters of the tunnel and supporting elements.

Item	Elastic modulus, E (MPa)	Poisson's ratio, (μ)	Density, γ (kg/m^3)
C15 concretes (original lining)	26,000	0.20	2,300
C25 sprayed concretes	23,000	0.20	2,200
I22b steel arch frames, [20 U-steel and D306 steel tubes (Q235)]	206,000	0.28	7,850



(a) (b)

Figure 8: Two main phases of subsequent construction procedures: (a) construction of the flyover and (b) excavation of the surrounding rock on the southern side of the tunnel.



(a) (b)

(c)

Figure 9: Tunnel displacements for two main construction phases when steel arch reinforcement was used: (a) vertical displacement for the first phase, (b) vertical displacement for the second phase, and (c) horizontal displacement for the second construction phase.

test results, and Table 2 lists the physical and mechanical parameters of the tunnel and supporting elements.

The simulation model shown in Figure 7(a) reached equilibrium under gravity, and then, the simulation of the subsequent construction procedures included two main phases: (a) construction of the flyover, which is simulated by applying a uniformly distributed pressure of 40 kPa on the ground surface as shown in Figures 8(a), and 8(b) excavation of the surrounding rock on the southern side of the tunnel to an elevation of 293.00 m as shown in Figure 8(b).

5.2. Simulation Results. In order to verify and compare the effectiveness of the SASTCT scheme compared to the initial steel arch scheme, simulations were conducted on the two schemes for the subsequent construction loading of the overpass bridge and the excavation of the surrounding rock on the south side of the tunnel. Figure 9 shows the simulation results of the initial steel arch scheme, while Figure 10 shows the simulation results of the SASTCT scheme.

Figures 9 shows that the tunnel underwent an apparent rebound with a maximum vertical displacement of 11.72 mm after the construction of the flyover when the steel arch was used, which agreed well with the monitoring results and that the maximum vertical displacement of the tunnel increased to 18.67 mm after the excavation of the surrounding rock on the southern side of the tunnel, which exceeds the safety

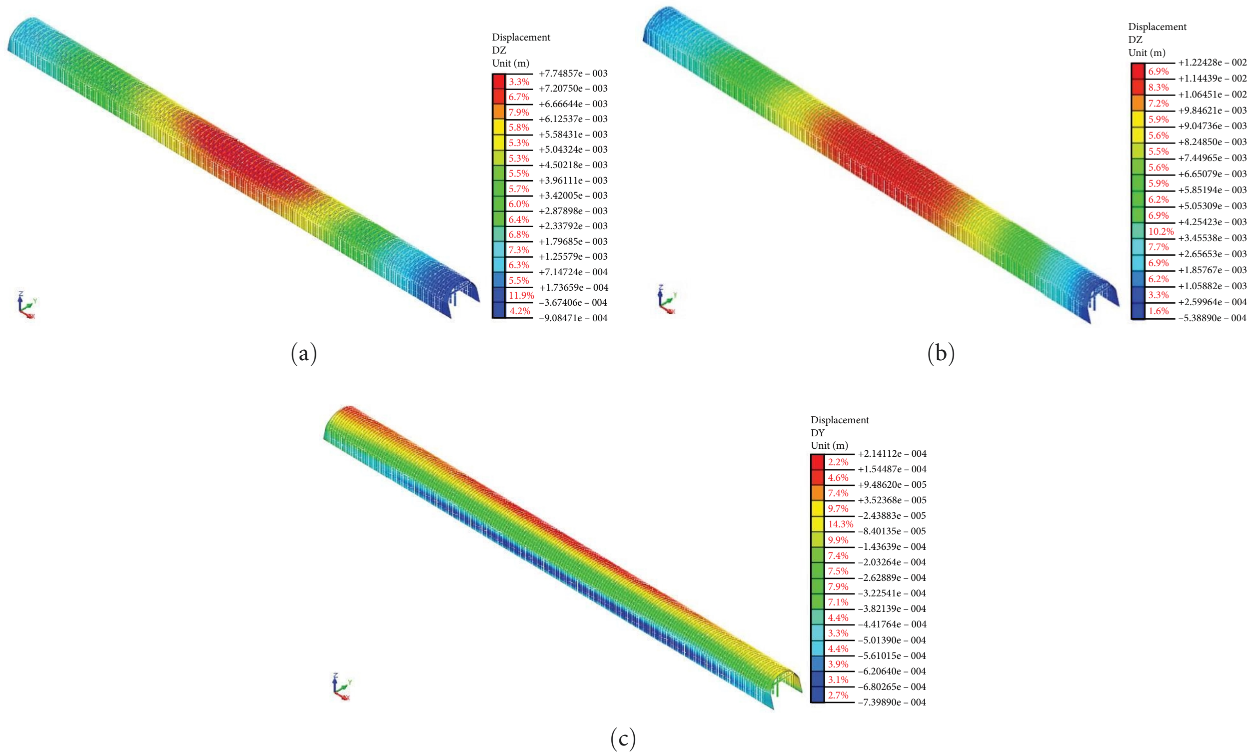


Figure 10: Tunnel displacements for two main construction phases when SASTCT measure was used: (a) vertical displacement for the first phase, (b) vertical displacement for the second phase, and (c) horizontal displacement for the second construction phase.

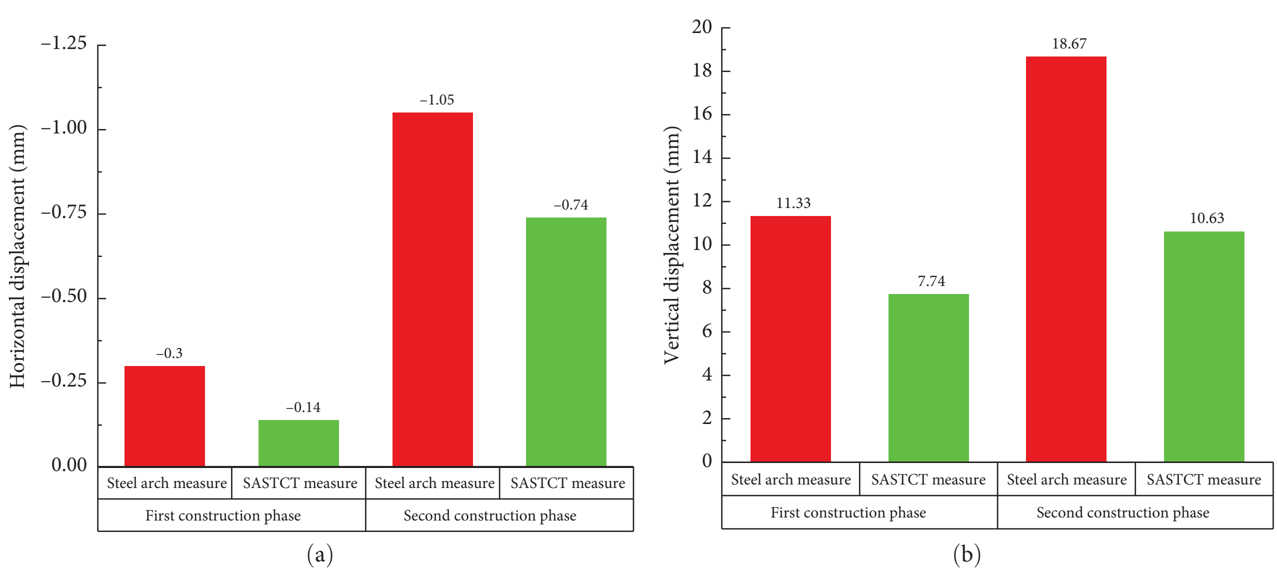


Figure 11: The tunnel displacements with the steel arch reinforcement and SASTCT for different construction phases, respectively: (a) vertical displacement and (b) horizontal displacement.

control value, i.e., 15 mm. Because of the excavation of the temporary road on the southern side, the tunnel shifted wholly to the south side, with a maximum horizontal displacement of 1.05 mm, an increase of about 42%, as shown in Figure 11. Therefore, the steel arch reinforcement would cause potential safety hazards in the subsequent construction phases and require temporary emergency treatment.

Figure 10 shows that, if the SASTCT was used, the maximum vertical displacement of the tunnel was 7.75 mm after the construction of the flyover and 12.24 mm, smaller than 15 mm, after the excavation of the surrounding rock on the southern side of the tunnel. In addition, the maximum horizontal displacement of the tunnel was 0.74 mm after the excavation of the surrounding rock on the southern side of

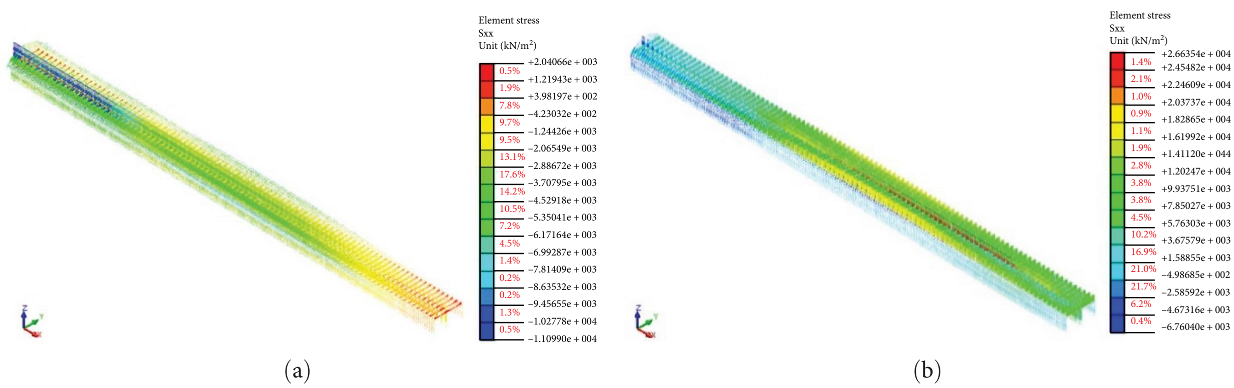


FIGURE 12: Axial stress of the supporting elements when the SASTCT measure was utilized: (a) first construction phase and (b) second construction phase.

the tunnel. It suggested that the SASTCT measures can effectively minimize the structural deformation of the tunnel during the two construction phases and reduced the construction risk of the whole project.

Figure 12 shows the axial stress of supporting elements when the SASTCT measures were utilized. For the first construction phase, the maximum axial stress of the supporting elements was 11.10 MPa, in the tunnel segment right below the flyover to be constructed. For the second construction step, i.e., after the excavating of surrounding rock on the southern side for the temporary road, the maximum axial stress of the steel supporting elements increased to 26.64 MPa, within the allowable range as specified in the standard, which further indicated the feasibility of the SASTCT measure.

6. Discussion

Urban tunnels are vital knots of urban transportation and would get congested during busy hours. The occurrence of tunnel issues, e.g., lining cracking and water leakage, would impede the traffic system, which would be a dilemma for city managers. Therefore, it is necessary to explore temporary reinforcement to ensure the safety of urban tunnels in service. In addition, infrastructure constructions near an existing tunnel are complicated, which may cause unloading and uneven loading of the existing tunnel. As a result, some issues, e.g., lining cracking and water leakage, occurred for the existing tunnels, especially for some masonry tunnels in service already for a long time. The steel arch reinforcement for an existing tunnel has a satisfactory result if the loading on the tunnel increases, and its installation was convenient. Therefore, it is a preferred construction measure for tunnel reinforcement and emergency rescue. However, it could not form integrity with the lining of the existing tunnel during unloading conditions. The SASTCT measure was a temporary reinforcement and rescue construction measure based on the development of tunnel issues and tunnel operation requirements. The steel arch and existing lining were bonded together by shotcrete to resist the possible unloading and uneven loading induced by the nearby construction as a whole. Meanwhile, the transversal bracing and vertical steel tube column effectively increased the overall stiffness of the supporting elements, ensuring the safety of passing vehicles in the tunnel during the subsequent constructions. There are many unpredictable factors affecting the reconstruction or demolition of tunnels. In order to ensure the smooth implementation of the project, the on-site monitoring and measurement should be strengthened. Benefiting from the dynamic monitoring measurement, potential problems can be foreseen and temporary reinforcement emergency construction measures can be implemented to ensure the safety of vehicles and subsequent construction.

7. Conclusions

This study mainly focused on a tunnel in Chongqing and discussed the temporary reinforcement emergency rescue construction measures. The feasibility of temporary reinforcement emergency rescue construction measures was explored by numerical analysis, and the following conclusions can be drawn from this study.

(1) The steel arch is a preferable measure to reinforce the existing tunnel if the load on the tunnel increases during the subsequent construction, but it cannot ensure the safety of the existing tunnel if the tunnel is subjected to unloading during the subsequent construction.

(2) The SASTCT reinforcement is a flexible and effective temporary reinforcement for emergency construction. By the utilization of shotcrete, the steel arch and existing tunnel lining can resist the loading changes of the tunnel together. In addition, the transversal bracing and vertical steel tube column can improve the stiffness of the steel arch, hence ensuring the safety of passing vehicles in the tunnel which is being subjected to loading changes due to nearby constructions.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] P. Zhou, M. Lin, F. Zhou, L. Gong, and W. Ao, "Bearing characteristics and failure mechanism of a novel plate-short anchor structure for tunnel crack reinforcement," *Engineering Failure Analysis*, vol. 135, Article ID 106160, 2022.

[2] F. Ye, N. Qin, X. Liang, A. Ouyang, Z. Qin, and E. Su, "Analyses of the defects in highway tunnels in China," *Tunnelling and Underground Space Technology*, vol. 107, Article ID 103658, 2021.

[3] S. Liu, Y. Shi, R. Sun, and J. Yang, "Damage behavior and maintenance design of tunnel lining based on numerical evaluation," *Engineering Failure Analysis*, vol. 109, Article ID 104209, 2020.

[4] G. Xu, C. He, Z. Chen, C. Liu, B. Wang, and Y. Zou, "Mechanical behavior of secondary tunnel lining with longitudinal crack," *Engineering Failure Analysis*, vol. 113, Article ID 104543, 2020.

[5] C. Liu, D. Zhang, and S. Zhang, "Characteristics and treatment measures of lining damage: a case study on a mountain tunnel," *Engineering Failure Analysis*, vol. 128, Article ID 105595, 2021.

[6] B. Min, C. Zhang, W. Zhu, X. Zhang, and P. Li, "Influence of cracks at the invert on the mechanical behavior of the tunnel structures," *Thin-Walled Structures*, vol. 161, Article ID 107405, 2021.

[7] B.-G. He, E.-R. Liu, Z.-Q. Zhang, and Y. Zhang, "Failure modes of highway tunnel with voids behind the lining roof," *Tunnelling and Underground Space Technology*, vol. 117, Article ID 104147, 2021.

[8] H. Feng, X. Zhang, D. Gou, J. Chun, X. Ou, and X. Zhou, "Cause investigation of side-wall cracking in an operational tunnel," *Engineering Failure Analysis*, vol. 101, pp. 157–171, 2019.

[9] J. Lai, J. Qiu, H. Fan et al., "Structural safety assessment of existing multiarch tunnel: a case study," *Advances in Materials Science and Engineering*, vol. 2017, Article ID 1697041, 11 pages, 2017.

[10] F. Ye, X. Han, N. Qin, A. Ouyang, X. Liang, and C. Xu, "Damage management and safety evaluation for operating highway tunnels: a case study of Liupanshan tunnel," *Structure and Infrastructure Engineering*, vol. 16, no. 11, pp. 1512–1523, 2020.

[11] S. Xu, E. Ma, J. Lai et al., "Diseases failures characteristics and countermeasures of expressway tunnel of water-rich strata: a case study," *Engineering Failure Analysis*, vol. 134, Article ID 106056, 2022.

[12] H. Cao, L. Peng, M. Lei, F. Chen, and Q. Tang, "Causes analysis, reinforcement and repair technology of segment crack and damage during shield tunnelling process: a case study," *Geotechnical and Geological Engineering*, vol. 37, no. 2, pp. 765–773, 2019.

[13] W. Han, Y. Jiang, N. Li, G. Wang, H. Luan, and C. Liu, "Failure behavior and reinforcing design of degraded tunnel linings based on the three-dimensional numerical evaluation," *Engineering Failure Analysis*, vol. 129, Article ID 105677, 2021.

[14] F. Ye, C. He, and Y. X. Xia, "Post-construction monitoring and analysis for highway tunnel lining cracks," *China Civil Engineering Journal*, vol. 43, no. 7, pp. 97–104, 2010.

[15] Y. Liu, C.-A. Tang, P.-Y. Wang, Y.-P. Guan, and S.-H. Wang, "Study on disease mechanism and theoretical quantification method of tunnel structure," *Advances in Civil Engineering*, vol. 2019, Article ID 4398524, 14 pages, 2019.

[16] K. Bian, J. Liu, M. Xiao, and Z. Liu, "Cause investigation and verification of lining cracking of bifurcation tunnel at Huizhou pumped storage power station," *Tunnelling and Underground Space Technology*, vol. 54, pp. 123–134, 2016.

[17] D. Liu, M. Li, J. Zuo et al., "Experimental and numerical investigation on cracking mechanism of tunnel lining under bias pressure," *Thin-Walled Structures*, vol. 163, Article ID 107693, 2021.

[18] D. Liu, Q. Shang, M. Li, J. Zuo, Y. Gao, and F. Xu, "Cracking behaviour of tunnel lining under bias pressure strengthened using FRP grid-PCM method," *Tunnelling and Underground Space Technology*, vol. 123, Article ID 104436, 2022.

[19] D. Liu, F. Zhong, H. Huang, J. Zuo, Y. Xue, and D. Zhang, "Present status and development trend of diagnosis and treatment of tunnel lining diseases," *China Journal of Highway and Transport*, vol. 34, no. 11, Article ID 178, 2021.

[20] M. Lei, L. Peng, and C. Shi, "Model test to investigate the failure mechanisms and lining stress characteristics of shallow buried tunnels under unsymmetrical loading," *Tunnelling and Underground Space Technology*, vol. 46, pp. 64–75, 2015.

[21] Y. Zhang, Y. Shi, Y. Zhao, L. Fu, and J. Yang, "Determining the cause of damages in a multiarch tunnel structure through field investigation and numerical analysis," *Journal of Performance of Constructed Facilities*, vol. 31, no. 3, Article ID 04016104, 2017.

[22] W. Song, H. Lai, Y. Liu, W. Yang, and Z. Zhu, "Field and laboratory study of cracking and safety of secondary lining for an existing highway tunnel in loess ground," *Tunnelling and Underground Space Technology*, vol. 88, pp. 35–46, 2019.

[23] B. Min, C. Zhang, X. Zhang, H. Wang, P. Li, and D. Zhang, "Cracking performance of asymmetric double-arch tunnels due to the voids behind linings," *Thin-Walled Structures*, vol. 154, Article ID 106856, 2020.

[24] Y.-C. Chiu, C.-H. Lee, and T.-T. Wang, "Lining crack evolution of an operational tunnel influenced by slope instability," *Tunnelling and Underground Space Technology*, vol. 65, pp. 167–178, 2017.

[25] T.-T. Wang, "Characterizing crack patterns on tunnel linings associated with shear deformation induced by instability of neighboring slopes," *Engineering Geology*, vol. 115, no. 1-2, pp. 80–95, 2010.

[26] H. Yu, J. Chen, A. Bobet, and Y. Yuan, "Damage observation and assessment of the Longxi tunnel during the Wenchuan earthquake," *Tunnelling and Underground Space Technology*, vol. 54, pp. 102–116, 2016.

[27] X. Zhang, Y. Jiang, and S. Sugimoto, "Seismic damage assessment of mountain tunnel: a case study on the Tawarayama tunnel due to the 2016 Kumamoto earthquake," *Tunnelling and Underground Space Technology*, vol. 71, pp. 138–148, 2018.

[28] H. Xu, J. Xu, R. Sun, H. Pu, and Y. Cheng, "Rapid assessment and classification for seismic damage of mountain tunnel

based on concentric circle method," *Shock and Vibration*, vol. 2021, Article ID 9944797, 16 pages, 2021.
[29] X. Yang, F. Lin, and M. Huang, "Experimental analysis of bending stiffness characteristics of grouted double mortise–tenon joint for prefabricated metro station structure," *Advances in Civil Engineering*, vol. 2021, Article ID 9958436, 13 pages, 2021.
[30] Z. Lin, C. Guo, P. Ni et al., "Experimental and numerical investigations into leakage behaviour of a novel prefabricated utility tunnel," *Tunnelling and Underground Space Technology*, vol. 104, Article ID 103529, 2020.
[31] Q. Xu, C. Bai, J. Peng, Q. Lu, and J. Zhao, "Model test of prefabricated underground utility tunnel crossing active ground fissures," *Tunnelling and Underground Space Technology*, vol. 140, Article ID 105279, 2023.
[32] Y. Kuang, Z. Peng, J. Yang et al., "Physical and numerical simulations on mechanical properties of a prefabricated underground utility tunnel," *Materials*, vol. 15, no. 6, Article ID 2276, 2022.
[33] K. Wang, M. Miao, and H. Zhou, "Effects of large-scale unloading on existing shield tunnels in sandy gravel strata," *Geotechnical and Geological Engineering*, vol. 39, no. 5, pp. 3401–3416, 2021.
[34] H.-M. Lyu, S.-L. Shen, A. Zhou, and K.-L. Chen, "Calculation of pressure on the shallow-buried twin-tunnel in layered strata," *Tunnelling and Underground Space Technology*, vol. 103, Article ID 103465, 2020.
[35] D. Song, X. Liu, Z. Chen, J. Chen, and J. Cai, "Influence of tunnel excavation on the stability of a bedded rock slope: a case study on the mountainous area in southern Anhui, China," *KSCE Journal of Civil Engineering*, vol. 25, no. 1, pp. 114–123, 2021.
[36] R. Li, D. Zhang, Q. Fang, D. Liu, J. Luo, and H. Fang, "Mechanical responses of closely spaced large span triple tunnels," *Tunnelling and Underground Space Technology*, vol. 105, Article ID 103574, 2020.
[37] S. Ghyasvand, A. Fahimifar, and F. Nejad, "On the optimum design of reinforcement systems for old masonry railway tunnels," *Geomechanics and Engineering*, vol. 28, no. 2, pp. 145–155, 2022.
[38] JTG D70-2004 and Ministry of Transport of People's Republic of China, *Code for Design of Road Tunnel*, China Communications Press, Beijing, 2004.
[39] Z. Shi, J. Xu, X. Xie, P. Li, L. Chai, and S. Li, "Failure mechanism analysis for tunnel construction crossing the water-rich dense fracture zones: a case study," *Engineering Failure Analysis*, vol. 149, Article ID 107242, 2023.
[40] J. Xu, X. Xie, G. Tang, B. Zhou, D. Xu, and Y. Huang, "A new adaptive compressible element for tunnel lining support in squeezing rock masses," *Tunnelling and Underground Space Technology*, vol. 137, Article ID 105124, 2023.