Research Article

Influence of Arch Foot Defect of Primary Support on Mechanical Behaviors of an Arch Frame in Underground Tunnels

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During the blasting excavation of the large-span tunnels, the instability of the blasting caused the overexcavation phenomenon, making the grille arch difficult to land completely in the primary support of the tunnel, thus forming an arch foot defect. In order to reduce the security issues of tunnel engineering construction and scientifically evaluate the influence of arch foot defects on the force performance of the overall structure of the arch frame, combining the Qingdao Metro long-span hard rock tunnel project, this paper designs two grille arch test sections with arch foot defects and one conventional section to carry out field tests. Combining with FLAC 3D numerical simulation, the results of the study were used for analyzing the stress characteristics of arch foot defect grille arch in the primary support of the tunnel. The results indicated that (1) the arch foot of conventional section arch frame is subjected to the force transferred from the upper part and the deformation pressure of surrounding rock within the arch foot range, and the upper transfer force borne by the arch foot mainly comes from the deformation of arch waist. (2) When the arch frame has arch foot defects, the deformation of surrounding rock at the arch foot and the deformation transferred from the upper part mainly depend on the shotcrete, thus resulting in the increase of shotcrete strain. (3) Anchoring bolt and shotcrete can integrate the grid arch with the surrounding rock, thus bearing local loads in the arch crown, arch waist, and shotcrete. (4) The numerical calculation of arch frame with arch crown, arch waist, and arch foot defects claims that the force reduction of the arch frame caused by the arch foot defect was the most obvious, and the calculation results were consistent with the actual project.

1. Introduction

It is the rapid development of transportation that has accelerated the construction of many tunnel projects all over China, such as Chengdu Longquanshan Tunnel, Jinan Yellow River Tunnel, and Qingdao Metro Tunnel. The successful constructions of these tunnel projects have a great correlation with the good primary support efficiency. The primary support has significant capability of adjusting the stress state of surrounding rocks, improving the mechanical parameters of surrounding rock, and reducing the deformation of tunnel rock mass.

Combined with Sanshilipu Tunnel, Han et al. [1] comprehensively studied the stress characteristics of various lining structures of shallow buried tunnel in loess area; Luo et al. [2], based on the large-span three-arch tunnel, analyzed the mechanical characteristics of the tunnel lining by using the field monitoring method. The results show that after the installment of tunnel lining, the lining pressure and steel rib stress increase rapidly and then tend to be stable until the surrounding rock is disturbed by the subsequent excavation; Li et al. [3] obtained the surrounding rock pressure and the mechanical characteristics of each subcomponent of the primary support system through on-site monitoring and pointed out that the surrounding rock pressure, steel frame stress, and shotcrete stress changed sharply with the excavation process, and the sensitivity decreased in turn; and Luo et al. [4] took Loess Tunnel as an example and combined the primary support monitoring results with FLAC3D numerical simulation, and the primary support stress
showed the law of “the stress at the arch was greater than the stress at the bottom, and the stress was symmetrical”, and the main support structures were in compression state.

Relying on the on-site tunnel engineering, many scholars have carried out a large number of model tests and numerical calculations to study the stress of the model in the cracking process under the indoor test. Based on the shallow buried tunnel in layered rock mass, Fan et al. [5] explore the cracking mechanism of lining structure in the model with different joint angle combination; Chen et al. [6] mainly studied the stress distribution and cracking process at different positions of the tunnel opening model; Fan et al. [7] studied the stress distribution and evolution of fractured block and porous block under uniaxial compression by combining test and numerical simulation; and Gong et al. [8] conducted true triaxial tests on red sandstone samples with prefabricated holes, revealing the mechanism of rock burst induced by spalling damage and the characteristics of rock burst failure caused by spalling damage.

Based on the research on the stress characteristics of tunnel primary support, many scholars have optimized the primary support combined with actual engineering. Based on the Xinzhuangling Tunnel, Qiu et al. [9] found that the load borne by the primary support structure was not large; on this basis, the corresponding optimization countermeasures were put forward, and their rationality was verified by numerical calculation; Langford et al. [10] proposed a quantitative risk method based on reliability, which can be combined with the monitoring results during construction to design safer primary support structures. Xue et al. [11] carried out an on-site monitoring and numerical simulation on the support effectiveness of three super large-span multiarch tunnels and improved the tunnel support according to the research results.

The primary support of tunnel is mainly composed of steel arch frame (section steel, grid), shotcrete, and anchor bolt. As the main bearing structure of rock mass pressure, many scholars have studied the structure and stress of steel arch frame. Yang et al. [12] in order to explore the support performance of high-strength reinforced grid arch in the surrounding rock of soft tunnel, combined with the circular tube elastic strain theory, the support characteristic curve of high-strength reinforced grid arch was obtained, and its mechanical properties and deformation characteristics were further analyzed by finite element numerical calculation method; Li et al. [13] established “grid arch frame + shotcrete” by using the elastic thin shell theory, and the influence of shotcrete thickness and arch spacing on the support effect was studied. Taking the full-section hard rock tunnel as an example, Wang et al. [14] monitored the stress of reinforcement on the inner and outer sides of steel arch and analyzed its distribution characteristics and variation law. The results show that the stress on the inner side is generally greater than that on the outer side at the same measuring point; Song et al. [15] designed a kind of spatial steel tubular grid (SSTG) with high strength and large stiffness, the bending test of the arch frame was carried out through the combination of test and numerical calculation, and the mechanical performance of the arch frame in the whole loading process was studied; Hou et al. [16] tested the mechanical properties of thin-walled concrete-filled steel tube arch and compared it with traditional grid steel frame, and it is concluded that the deformation resistance of thin-walled concrete-filled steel tube arch frame is stronger; Wen et al. and Li et al. [17, 18] established the foundation curved beam mechanical model of tunnel primary support and deduced the internal force of tunnel steel arch through tunnel monitoring data; and Li et al. [19] embedded the yield criterion of beam element into FLAC3D main program by using Fish language and realized the correction of beam model and the yield failure simulation of supporting arch.

The above scholars mainly study the stress characteristics of the complete steel arch frame in the initial support and conduct numerical calculation and optimization of the complete arch frame. They do not study the stress characteristics of the defective arch frame, which actually exists in tunnel engineering. This paper mainly explores the stress characteristics of the defective arch frame. In the process of on-site construction, due to blasting overexcavation, imperfect construction methods, and other reasons, the steel arches often have some defects due to blasting overexcavation, imperfect construction methods, and other reasons. These factors may have some impacts on the support function of the steel arch, which in turn makes the construction of tunnel project a safety hazard. Therefore, combined with the field conditions, two grid arches with arch foot defects were designed and monitored for a long time. The monitoring analysis results were combined with FLAC3D numerical simulation to expand the field arch problem and better study the mechanical characteristics of steel arch in Qingdao Metro Tunnel. The study has guiding significance for the support design and construction of large-span hard rock tunnel.

2. Experiment Program

2.1. Support Scheme. The test section was selected in underground excavation station of Qingdao Metro Line 6. The tunnel was mainly constructed by arch cover method, half package waterproof design, and divisional excavation. The primary support of arch lining adopted the combined support structure of “grid steel frame + shotcrete + anchor bolt” and internal support. The support parameters were as follows: grid steel frame at 0.75 m and spacing at 1.2 m, and the steel grid was laid inside and outside Φ 8 at 200 mm × 200 mm double-layer reinforcement mesh, and an additional grid with a length of 2.5 m was added at the arch foot; C30 net shotcrete, 300 mm thick; arch anchor bolt Φ 25 hollow grouting anchor bolt, L = 3.5 m, at 1.5 × 0.75 m (ring × longitudinal), and plum blossom layout.

2.2. Test Design. Three monitoring sections were set in the field test, including two test sections (section A and section B) and one conventional section. For comparative analysis, the location of the conventional section was set between the two test sections A and B. The design scheme of the grid
The arch of the test section was shown in Figure 1(a), in which the steel rib with a length of 20 cm was cut at the oblique opposite side of the grid arch, the connecting rods on both sides of the rebar stress gauge were welded at the cut position, and the arch length at the arch foot was shortened by one meter compared with the conventional section. The test arch after welding was shown in Figure 1(b). During construction, the welding will raise the temperature of the rebar stress gauge, which will inevitably lead to the inaccurate data measured by the rebar stress gauge. Therefore, after the rebar stress gauge is welded, cool the temperature with cold water and take the frequency value of the welded rebar stress gauge as the initial value of the test. And to ensure that the bottom of the arch support was not supported by the ground and shotcrete, the foam board was used to fill and the feet-lock bolts were struck at the bottom of the shortened arch. Foam board has the characteristics of small density and stress isolation. It can effectively isolate the force transmitted from the upper part, thus simulating the defect of arch foot perfectly. The installation and construction process of the

**Figure 1:** Test design scheme and monitoring.
monitoring instrument of the test section was shown in Figure 1(c).

2.3. Test Content. In order to study the size and distribution characteristics of steel rib stress, bolt axial force and shotcrete strain of primary support arch frame of long-span hard rock metro tunnel under the condition of arch foot defects, the steel rib stress monitoring, shotcrete strain monitoring, and bolt axial force monitoring were carried out (both steel rib stress and shotcrete strain are specified as the positive compression and negative tension, and the axial force of bolt as the positive tension). The on-site monitoring parameters and instrument installation are detailed in Table 1, and the instrument installation was shown in Figure 2.

3. Test Results and Analysis

3.1. Stress of Steel Rib. Grid arch mainly bores the vertical load of surrounding rock to enhance the stability of the surrounding rock. The bearing capacity of grid arch is greatly different due to the influence of section shape, connecting nodes, and other factors [20]. In this paper, based on the arch with arch foot defects, the arch reinforcement of the above three monitoring sections is monitored for long-term stress, and the stress-time curve of the reinforcement is shown in Figure 3. It can be seen from the figure that before the excavation of the arch foot, both sides of the arch steel rib of the arch crown and arch waist of the monitoring section were compressed, and the change law can be basically divided into three stages: rapid growth stage, stress decline stage, and stable stage. The main reasons of these changes were that the tunnel section span was large, the flattening rate was small, the grid arch steel rib bores the main load, and the self-stability of the tunnel surrounding rock was good, so the steel rib stress decreased in a short time and was in a stable state.

After the excavation of the arch foot, the arch foot support and monitoring instruments were installed according to the design scheme, and the stress curves of the arch foot steel rib of the two kinds of grid arch frames were obtained, as shown in Figure 4. According to Figures 3–4, it can be found that the surrounding rock of most measuring points of arch crown and arch waist was disturbed due to the excavation of arch foot, resulting in the increase of steel rib stress; the steel rib stress at the arch foot also conformed to the above basic law of stress change. Due to the small excavation area at the arch foot, the stress distribution of the arch frame was characterized by “large at the top and small at the bottom” [21]. On the whole, the stress growth range of the arch foot of the arch frame was 38.8% lower than that of the upper arch frame, and the stabilization time was shorter, which tended to be stable in about 7 days.

After the monitoring data were all stable, the data comparison of the two monitoring sections was obtained, as shown in Figures 5–6:

(1) As can be seen from Figure 5(a), the steel rib stress at the inside of the conventional section is 87.6 MPa,
(a) Stress temporal curves of steel rib in conventional section

(b) Stress temporal curves of steel rib in A test section

Figure 3: Continued.
and the steel rib stress at the outside is 37.2 MPa; the average stress of steel rib at the inside of the two groups of test sections is 93.4 MPa and 40.2 MPa at the outside. It can be clearly seen from the average values of all points of each section that the steel rib stress at the crown of the test section was 7% higher than that of the conventional section.

(2) As can be seen from Figure 5(b), the steel rib stress at the inside of the conventional section is 35.8 MPa, and the steel rib stress at the outside is 59.7 MPa; the average stress of steel rib at the inside of the two groups of test sections is 30.3 MPa and 54.5 MPa at the outside. The steel rib stress at the waist of the test section was 12% lower than that of the conventional section.

(3) According to the monitoring data in Figure 6, it can be found that the average steel rib stress at the arch foot of the conventional section is mainly concentrated at the inside, and the steel rib stress at the inside is 52.5 MPa and 67.8 MPa, respectively. After stabilization, the average steel rib stress at each measuring point is 35.3 MPa; the stress distribution of steel rib in the test section is relatively uniform, the stress of steel rib at the inside is 23.6 MPa and 13.8 MPa, respectively, and the stress of steel rib at the outside is 10.4 MPa and 34.3 MPa, respectively. The steel rib stress at the arch foot defect of the test section was 41.8% lower than that of the conventional section.

The data analysis results showed that the steel rib stress at the defect position of the arch foot of the test section decreased and the test section isolated the force transmitted from the upper part. Therefore, the arch steel rib stress measured by the arch foot defect arch is only the surrounding rock deformation pressure within the arch foot, and there is no force transmitted from the upper part. Indicating that the arch foot of the conventional section bores the force transferred from the upper part and the surrounding rock deformation pressure within the arch foot range at the same time. The steel rib stress at the arch crown basically did not change, and the steel rib stress at the arch waist decreased a little. Therefore, the upper transfer force borne by the arch foot of conventional section arch frame mainly comes from the deformation of arch waist.

3.2. Strain of Shotcrete. The shotcrete strain of three monitoring sections was monitored for a long time. The monitoring results showed that some shotcrete strains were very large, but there were no abnormal phenomena such as cracking on the shotcrete surface. After preliminary analysis, it was considered that no cracking phenomenon was the impact of the large spraying force in the process of concrete spraying. The field test showed that when spraying directly at the concrete strain gauge, the concrete strain gauge will produce large strain. Therefore, the monitoring value after spraying concrete was regarded as the initial value for data analysis.

The adjusted shotcrete strain curves were shown in Figure 7. From the figure, it can be seen that the shotcrete strain basically presented the change law of “rise-stabilization”. After the excavation of arch foot, the shotcrete strain curves of arch crown and arch waist will have a sudden change, which was caused by the large disturbance of surrounding rock caused by arch foot excavation.

After the excavation of arch foot of conventional section, due to the good integrity of upper support and surrounding rock, the shotcrete strain at the arch foot was very small, and the overall strain is 30 με within.
(a) Stress temporal curves of arch foot steel rib in conventional section

(b) Stress temporal curves of arch foot steel rib in A test section

Figure 4: Continued.
Compared with the conventional section, some shotcrete strains of the test section were larger, for example, the C5 strain value of group A test section is 125 με and the C6 strain value of group B test section is 122 με. Due to the weak tensile capacity of shotcrete, it was necessary to carefully observe whether there was cracking on the shotcrete surface of the monitoring section after spraying. During the monitoring period of nearly 50 days, there was no cracking on the shotcrete surface, and the maximum tensile value of arch foot shotcrete is -61 με; after the shotcrete strain was stable, the strain was generally -50~100 με, and the deformation rate was stable, so it was considered that the strain of the test section was large, but it was still in a safe state.

After the monitoring data was stable, the shotcrete strain and average strain of arch crown, arch waist, and arch foot were compared, and the comparison results were shown in Figure 8.
The shotcrete strain at the crown of the test section was only 13% higher than that of the conventional section; only from the perspective of shotcrete deformation value, the shotcrete strain at the arch waist of the test section was 30% higher than that of the conventional section, and the shotcrete strain at the arch foot defect of the test section changes greatly, which was 64% higher than that of the conventional section. Grid arch and shotcrete were widely used as the primary support structure, and they affected the support effect of the tunnel through interaction.

The test results showed that compared with the conventional section, the shotcrete strain at the crown of the test section basically did not change, and the change of the arch waist position was small. The increase of shotcrete strain was mainly reflected in the defect position of the arch foot, indicating that the grid arch and shotcrete jointly controlled the deformation of the surrounding rock. When the grid arch has arch foot defects, the bearing capacity of the arch foot position decreased and the deformation of surrounding rock at the arch foot and the deformation transferred from the upper part mainly depend on the shotcrete, resulting in the increase of shotcrete strain at the defect position of the arch foot.

3.3. Axial Force Test Results of Bolt. The active support construction method was adopted in the underground excavation station of Qingdao Metro. Its basic principle is to actively improve the mechanical parameters of the surrounding rock, reduce the deformation of the surrounding rock, and actively and timely provide support force for the surrounding rock, so as to give full play to the self-stability ability of the surrounding rock [22, 23].
| Monitoring days | Strain value ($10^2 \mu \epsilon$) |
|----------------|-----------------------------------|
| 0              | 0                                 |
| 5              | 0                                 |
| 10             | 0                                 |
| 15             | 0                                 |
| 20             | 2                                 |
| 25             | 2                                 |
| 30             | 2                                 |
| 35             | 2                                 |
| 40             | 2                                 |
| 45             | 2                                 |
| 50             | 2                                 |

**Figure 7: Continued.**

(a) Strain temporal curves of shotcrete in conventional section

(b) Strain temporal curves of shotcrete in A test section
The bolt-shotcrete support composed of bolt and shotcrete can significantly improve the strength and bearing capacity of the surrounding rock and effectively control the deformation of the tunnel-surrounding rock [24]. During the active support construction, the prestressed anchor bolt was used to actively provide the axial force of the anchor bolt above 100 kN, which can directly interact with the tunnel-surrounding rock and change the properties of the tunnel-surrounding rock.

The axial force of the prestressed anchor bolt of the primary support was monitored at the monitoring section. The variation curves of the axial force of the anchor bolt with time were shown in Figure 9. Through the comparison between the conventional section and the test section of each part, it can be found that

(i) The change of anchor shaft axial force was mainly concentrated in the early stage of installation, and when the anchor shaft axial force rapidly increased to more than 100 kN, the anchor shaft axial force will be partially lost. After more than 50 days of monitoring, the axial force curve of the anchor rod generally showed a slight decrease and stabilization. And it tended to be stable after 20 days. The stress after stabilization is concentrated at about 100 kN; the average is greater than 100 kN, and the rate of change is less than 1 kN/d.

The test results showed that the surrounding rock stress was released within 20 days of active support. After the excavation of the left and right arch feet, the change of the axial force of the bolt was not obvious, and there was little difference between the axial force of the bolt in each part of the test section and the conventional section, indicating that the arch foot defect arch frame has little effect on the anchoring effect of the bolt. Combined with the stress and deformation of the arch frame and shotcrete, it can be concluded that the anchoring bolt effect and shotcrete can integrate the grid arch with the surrounding rock and can bear local loads in the arch crown, arch waist, and shotcrete.

4. Analysis of Mechanical Characteristics of Primary Support Structure

4.1. Model and Parameters. According to the technical code for civil engineering construction of Qingdao Metro and basic mechanical parameters of joints obtained from the on-site rock laboratory test and on-site geological survey report, aiming at the engineering geological conditions, surrounding
rock mechanics parameters, and tunnel excavation construction process design of the tunnel, the FLAC3D numerical simulation software was adopted to simulate the force changes of the grille arch under the influence of factors such as blasting and overexcavation during the excavation of the tunnel division.

As shown in Figure 10(a), the width, height, and thickness of the numerical calculation model were 80 m, 100 m, and 0.8 m, respectively. The tunnel arch was semicircular in shape and modeled with brick grid. The surrounding rock of the model was divided into three types from top to bottom: strongly weathered, moderately weathered, and slightly weathered. The surrounding rock of the tunnel arch was excavated in four parts according to the on-site construction sequence, as shown in Figure 10(b). Except the top of the model, where the node normal velocity of all faces was fixed. Mohr-Coulomb model was selected for surrounding rock, and the material parameters are shown in Table 2.
Table 2: Mechanical parameters of granite.

| Surrounding rock          | Young’s modulus, $E$ (MPa) | Poisson’s ratio, $\mu$ | Cohesion, $C$ (MPa) | Internal friction angle, $\psi$ (°) | Density, $D$ (kg/m$^3$) |
|---------------------------|-----------------------------|------------------------|---------------------|------------------------------------|------------------------|
| Strongly weathered        | 1300                        | 0.35                   | 0.1                 | 27                                 | 2250                   |
| Moderately weathered      | 1600                        | 0.35                   | 0.2                 | 27                                 | 2300                   |
| Slightly weathered        | 2000                        | 0.34                   | 0.2                 | 30                                 | 2400                   |

Table 3: Primary support parameters of tunnel surrounding rock.

(a) Shotcrete parameters

| Young’s modulus, $E$ (MPa) | Poisson’s ratio, $\mu$ | Bulk modulus, $K$ (GPa) | Shear modulus, $G$ (GPa) | Cohesion, $C$ (MPa) | Internal friction angle, $\psi$ (°) | Density, $D$ (kg/m$^3$) |
|----------------------------|------------------------|-------------------------|-------------------------|---------------------|------------------------------------|------------------------|
| 2000                       | 0.34                   | 16                      | 9.6                     | 2                   | 60                                 | 2500                   |

(b) Parameters of bolt and grouting body

| Simulated object | Young’s modulus, $E$ (MPa) | Cross sectional area, $A$ (cm$^2$) | Density, $D$ (kg/m$^3$) | Tensile strength, $\sigma_t$ (MPa) | Shear stiffness, $k_g$ (MPa/mm) | Outer ring perimeter $p_g$ (m) |
|------------------|-----------------------------|------------------------------------|-------------------------|---------------------------------|--------------------------------|-------------------------------|
| Bolt             | 200                         | 2.54                               | 7850                    | 0.24                            |                                |                               |
| Simulated object | Cohesion, $C_g$ (MPa)       | Internal friction angle, $\psi_g$ (°) |                          |                                 | $k_g$ (MPa/mm)                 | $p_g$ (m)                     |
| Grout            | 2                           | 30                                 |                          |                                 | 20                             | 0.0942                        |

(c) Grid arch parameters

| Simulated object | Young’s modulus, $E$ (MPa) | Cross sectional area, $A$ (cm$^2$) | Density, $D$ (kg/m$^3$) | Poisson’s ratio, $\mu$ |
|------------------|-----------------------------|------------------------------------|-------------------------|------------------------|
| Grid arch        | 200                         | 19.63                              | 7850                    | 0.25                   |
| Defective arch   | 2.2                         | 19.63                              | 20                      | 0.39                   |
Figure 11: Continued.
After the tunnel was excavated, anchor bolt, grid arch, and shotcrete were installed immediately. The concrete lining was modeled by solid elements. The anchor structure elements were used to simulate the bolt and grouting body, and the preload of 100 kN was applied; the grid arch was simulated by the beam element. According to the field test design, the low strength material such as foam was used to replace the defect position of the arch. So as to simulate the influence of defective arch on the overall stress of arch. See Table 3 for various parameters of primary support.

4.2. Analysis of Stress Characteristics of Grid Arch. According to the numerical simulation results, the force nephograms of the grid arch in the primary support of the tunnel were shown in Figure 11. The force at the low-strength material position of the arch was basically 0, which was consistent with the force at the defect position of the arch. From the calculation results, it can be found that the axial force of the four kinds of grid arch bolts basically does not change and has been maintained at about 100kN; the force of the steel rib at the arch foot of the grid arch was the smallest,
and the force of the steel rib at the arch crown was larger, which was consistent with the results of the field monitoring. Compared with the conventional grid arch, the force reduction of the defective grid arch was small, which was mainly concentrated near the defect position of the arch.

The selected different arches at the same position for data monitoring and the monitoring results were shown in Figure 12. From the curves change in the figure, it can be seen that the force of arch steel rib with defects was smaller than that of conventional section. From Figures 12(a)–12(c), it can be seen that the force of arch foot defects was reduced by 28% compared with that of conventional arch, while the force of arch with arch crown and waist defects was reduced by 7% and 2%, respectively, compared with conventional arch; this was because the upper transfer force borne by the arch crown and arch waist was small, and the upper transfer force of the whole arch frame mainly depends on the arch foot. When the arch foot has defects, the arch foot position only bores the deformation pressure of surrounding rock within the arch foot, resulting in a large reduction in the force of the arch frame at the defect position of the arch foot. The calculation results were basically the same as the test results. The above results showed that the unfavorable situation in the primary support of the arch such as defects will lead to a decrease in the support of the arch, so the occurrence of the above situation should be avoided as much as possible in the tunnel engineering. However, when the above situation is inevitable, it can be improved by adding bolts and sand to fill the over excavated part, so as to ensure the safety of primary support and reduce accidents.

5. Conclusions

Based on the on-site monitoring test of the nonfloor grid arch and the FLAC3D numerical simulation, the force characteristics of the grid arch of the subway tunnel are studied in this paper. The main conclusions are as follows:

(i)Compared with the normal section, the average reduction of reinforcement stress is 41.8% in the test section (arch foot defect location). It indicated that the foot of the arch of the conventional section is subjected to both the force transmitted from above and the deformation pressure of the surrounding rock within the foot of the arch. Basically, there is no change in the reinforcement stress at the top of the arch, and the reinforcement stress at the arch waist is reduced by 12%. Therefore, the upper transfer force of the
arch foot of the conventional section arch mainly comes from the deformation of the arch waist.

(ii) The concrete strain at the location of the arch footing defect increase by 64% compared to the conventional section. The increase in concrete strain is caused by the presence of arch footing defects in the grating arch leading to the reduction of the bearing capacity at the arch footing position. Furthermore, the deformation of the surrounding rock at the arch footing location and the deformation transmit from above mainly rely on concrete to bear.

(iii) Anchoring bolt and shotcrete can integrate the grid arch with the surrounding rock and can bear local loads in the arch crown, arch waist, and shotcrete; however, the grid arch still exerted the overall bearing arch effect, and the arch foot bores the load transferred from the upper part.

(iv) Through FLAC$^{3D}$ numerical calculation, the results show that the stress of the deficient arch frame was less than that of the complete arch frame, while the stress of the arch with arch foot defects was the most obvious, and the stress of the arch with arch crown and arch waist defects was only slightly reduced, which was consistent with the fact that the upper transfer force in the actual project was mainly borne by the arch foot.

**Data Availability**

The data used to support the findings of this study were supplied by [Junwei Guo] under license and so cannot be made freely available. Requests for access to these data should be made to [Junwei Guo, 1802895825@qq.com].

**Conflicts of Interest**

The authors declared that they have no conflicts of interest to this work.

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**References**

[1] G. W. Han, B. Liu, and H. Fan, "Mechanical characteristics of tunnel lining structure in shallow-buried loess area," *Chinese Journal of Rock Mechanics and Engineering*, vol. 26, no. Supp.1, pp. 3250–3256, 2007.

[2] J. Luo, D. Zhang, Q. Fang, D. Liu, and T. Xu, "Mechanical responses of surrounding rock mass and tunnel linings in large-span triple-arch tunnel," *Tunnelling and Underground Space Technology incorporating Trenchless Technology Research*, vol. 113, article 103971, 2021.

[3] P. F. Li, S. M. Tian, Y. Zhao, Y. Q. Zhu, and S. D. Wang, "In-situ monitoring study of mechanical characteristics of primary lining in weak rock tunnel with high grostress," *Chinese Journal of Rock Mechanics and Engineering*, vol. 32, no. Supp.2, pp. 3509–3519, 2013.

[4] Y. Luo, J. Chen, Z. Shi, J. Li, and W. Liu, "Mechanical characteristics of primary support of large span loess highway tunnel: a case study in Shaanxi Province, loess plateau, NW China primary," *Tunnelling and Underground Space Technology incorporating Trenchless Technology Research*, vol. 104, article 103532, 2020.

[5] X. Fan, Z. J. Yang, and K. H. Li, "Effects of the lining structure on mechanical and fracturing behaviors of four-arc shaped tunnels in a jointed rock mass under uniaxial compression," *Theoretical and Applied Fracture Mechanics*, vol. 112, article 102887, 2021.

[6] H. Chen, X. Fan, H. Lai, Y. Xie, and Z. He, "Experimental and numerical study of granite blocks containing two side flaws and a tunnel-shaped opening," *Theoretical and Applied Fracture Mechanics*, vol. 104, article 102394, 2019.

[7] X. Fan, X. Jiang, Y. Liu, H. Lin, K. Li, and Z. He, "Local stress distribution and evolution surrounding flaw and opening within rock block under uniaxial compression," *Theoretical and Applied Fracture Mechanics*, vol. 112, article 102914, 2021.

[8] F. Q. Gong, Y. Luo, X. B. Li, X. F. Si, and M. Tao, "Experimental simulation investigation on rockburst induced by spalling failure in deep circular tunnels," *Tunnelling and Underground Space Technology*, vol. 81, pp. 413–427, 2018.

[9] W. G. Qi, K. G. Sun, L. C. Wang et al., "Primary support optimization of large section tunnel based on surrounding rock stability," *China Civil Engineering Journal*, vol. 50, Suppl.2, pp. 8–13, 2017.

[10] J. C. Langford, N. Vlachopoulos, and M. S. Diederichs, "Revisiting support optimization at the Driskos tunnel using a quantitative risk approach," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 8, no. 2, pp. 147–163, 2016.

[11] Y. G. Xue, H. Gong, F. Kong, W. Yang, D. Qi, and B. Zhou, "Stability analysis and optimization of excavation method of double-arch tunnel with an extra-large span based on numerical investigation," *Frontiers of Structural and Civil Engineering*, vol. 15, no. 1, pp. 136–146, 2021.

[12] Y. A. N. G. Yang, T. A. N. Zhong-sheng, X. U. E. Jun, and L. I. Song-tao, "High-strength lattice girders supporting performance of highway tunnel with soft broken surrounding rock," *China Journal of Highway and Transport*, vol. 33, no. 2, pp. 125–134, 2020.

[13] S. C. Li, B. Y. Feng, T. F. Ma, S. C. Li, and X. Ping, "Researches on mechanics behavior of lattice girder reinforced shotcrete support for tunnels," *Journal of China Coal Society*, vol. 39, no. S1, pp. 57–63, 2014.

[14] L. M. Wang, F. Y. Li, B. Zhang, B. Wen, and G. Yang, "Mechanical property and stability of tunnel boring machine tunnel steel arch support field test," *Science Technology and Engineering*, vol. 20, no. 34, pp. 14223–14228, 2020.

[15] Y. Song, M. Huang, X. Zhang, Z. Li, and X. Peng, "Experimental and numerical investigation on bearing capacity of circumferential joint of new spatial steel tubular grid arch in mined tunnel," *Symmetry*, vol. 12, no. 12, pp. 2065–2065, 2020.

[16] H. Hou, S. Ma, Q. Wang, Y. Jin, W. C. Zhu, and L. Chen, "Experimental study on mechanical behavior of concrete-filled thin-walled steel tube supported in tunnel," *Journal of Central South University (Science and Technology)*, vol. 48, no. 5, pp. 1316–1325, 2017.

[17] J. Z. Wen, Y. X. Zhang, C. Wang, and Z. H. Jiang, "Back analysis for the mechanical properties of initial tunnel support based on steel arch stresses," *China Civil Engineering Journal*, vol. 45, no. 2, pp. 170–175, 2012.
[18] J. J. Li, Q. N. Chen, X. G. Wang, X. D. Zhang, and G. Zou, "Internal force analysis on tunnel supporting structure considering axial strain," *Chinese Journal of Underground Space and Engineering*, vol. 17, no. 2, pp. 430–438, 2021.

[19] W. T. Li, N. Yang, T. C. Li, Y. H. Zhang, and G. Wang, "A new approach to simulate the supporting arch in a tunnel based on improvement of the beam element in FLAC3D," *Journal of Zhejiang University-SCIENCE A*, vol. 18, no. 3, pp. 179–193, 2017.

[20] J. H. Chen, B. J. Chen, Y. Zhuang, L. X. Wang, and M. J. Liu, "Comparison of vertical bearing capacity of tunnel grille arch frame with different cross-section shapes," *Tunnel Construction*, vol. 40, no. s3, pp. 364–370, 2020.

[21] J. Guo, J. S. Yang, W. Chen, D. Shen, T. Liu, and W. Chai, "Research on large deformation of surrounding rock and mechanical characteristics of lining of carbonaceous slate tunnel based on field measurement," *Chinese Journal of Rock Mechanics and Engineering*, vol. 38, no. 4, pp. 832–841, 2019.

[22] S. M. Tian, K. F. Wu, D. G. Liu, M. N. Wang, and Z. L. Wang, "Study on active support technology for deformation control of tunnels in soft surrounding rock," *Journal of the China Railway Society*, vol. 43, no. 6, article 158, 2021.

[23] W. A. N. G. Bo, Y. U. Wei, L. I. U. Jin-chao, W. A. N. G. Zhen-yu, X. U. Jian-qiang, and W. U. De-xing, "Timely-active support theory and its application in transportation/hydraulic tunnels based on pre-stressed anchorage system," *China Journal of Highway and Transport*, vol. 33, no. 12, pp. 118–129, 2020.

[24] H. Wei, M. Qin-yong, Y. Wenhua, and Y. Pu, "Study on mechanism of bolt-shotcrete support and analysis of its mechanical properties in deep rock roadway," *Chinese Journal of Underground Space and Engineering*, vol. 7, no. 1, pp. 28–32, 2011.