Research on the Stress Analysis and Applicability of Flexible Support Steel Strip in Soft Ground Highway Tunnels

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Abstract: By using numerical experimental models, the support characteristics of steel arch bolt shotcrete initial support structure and W-shape steel strip bolt shotcrete initial support system in grade IV surrounding rock of soft ground highway tunnels were compared and analyzed. Experimental sections were carried out in grade IV weak surrounding rock to compare the support effects of W-shape steel strip bolt shotcrete support structure and steel arch bolt shotcrete support structure in soft ground highway tunnels. The results showed that the use of W-shape steel strip bolt shotcrete support structure has the same good support effect as steel arch bolt shotcrete support structure in soft ground highway tunnels. The implementation of W-shape steel strip bolt shotcrete support structure can better exert the self-supporting capacity of surrounding rock, but its restrained deformation amplitude is weaker than that of steel arch, which can provide reference for the selection of support structure types for highway tunnels with similar geology.

1 INSTRUCTION

In the process of tunnel construction, the surrounding rock and supporting structure interact and deform together. During the deformation process, the energy released by the surrounding rock, i.e. the energy absorbed by the supporting structure, follows the principle of energy conservation (Wang et al., 2021). In the special environment of soft ground, flexible support treatment should be carried out in tunnel support, and the supporting structure can undergo appropriate deformation, thereby enabling the tunnel surrounding rock to fully exert its self stabilization ability (Wei et al., 2017).

The flexible supporting system composed of W-shape steel strip support, rockbolt, and anchor cables combines the rockbolt and steel strips as the main supporting structure under common force. With flexible steel strips, the initial support structure has better overall deformation coordination and control ability, and is widely used in coal mine soft rock roadway support (Sun, 2023; Sun, 2022; Zhang and He, 2016).

The steel strip, due to its connection with the anchor rod, can tightly adhere to the surface of the surrounding rock, effectively preventing the collapse of fragmented rock blocks when the tunnel arch or side wall is relatively broken.Combining the radial force provided by the rockbolt, a three-dimensional control system is formed, which can fully utilize the anchoring and suspension effects of the anchor cable to reinforce the surrounding rock, enhance the overall compressive strength of the surrounding rock, increase the range of the surrounding rock compressive stress zone, and prevent the overall supporting structure of the rock from being damaged, thereby controlling the displacement of the surrounding rock and improving the overall stability and bearing capacity of the tunnel (Lu et al., 2025; Zhao et al., 2022; Zhang, 2014; Li et al., 2023).

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This paper conducts numerical simulation calculations using the finite difference method to compare and analyze the support effects of traditional support structure and the flexible support system in grade IV surrounding rock of weak rock highway tunnels. The applicability of the flexible support system composed of steel strip-rockbolt in weak rock highway tunnels is explored. At the same time, the support effect is compared through on-site practical application.

2 NUMERICAL EXPERIMENTAL MODEL

The numerical experimental model is shown in Figure 1.

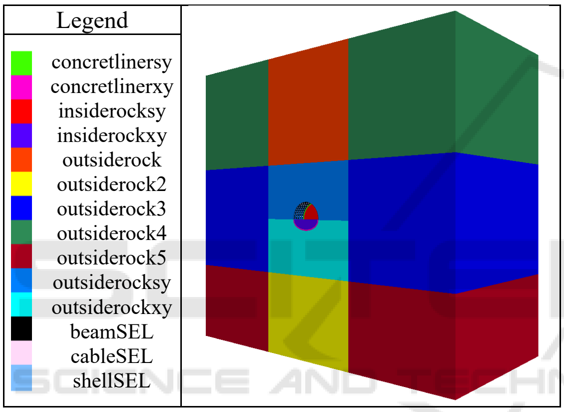


Figure 1: Numerical simulation calculation model.

The width of the tunnel in the numerical experimental model is 12.46 m and the height is 9.7 m. The X and Z directions of the model area are taken as 120 m and 110 m, respectively. The tunnel depth is 60 m in the Y direction, with a burial depth of 100 m. The longitudinal spacing between steel strips or steel arch is 0.8 m, the longitudinal spacing between rockbolt is 0.8 meters, and the circumferential spacing is 1.2 meters, arranged in a plum blossom shape. rockbolt are arranged at different locations in two types of support structures. In the initial support structure of steel arch bolt shotcrete, they are arranged between two steel arch. In the initial support structure of W-shape steel strip bolt shotcrete, they are arranged at the center of each steel strip. In numerical calculations, steel arch and steel strips are simulated using Beam elements, rockbolt are simulated using Cable elements, and shotcrete is simulated using Shell elements (Liu, 2023). The material parameters of different models are shown in Table 1.

Table 1: Material parameter table for numerical model.

material	parameter
surrounding rock	Unit weight: 23 kN/m^3; Elastic modulus: 3 GPa; Cohesion force: 0.3 MPa; Friction angle: 44°; Poisson's ratio: 0.27.
shotcrete	Bulk modulus: 13 GPa; Shear modulus : 10 Gpa; Unit weight: 22.45 kN/m^3; Thickness: 22mm; Elastic modulus: 23GPa; Poisson's ratio: 0.2.
steel arch	Section area of I-beam No.16: 2610mm^2; Moment of inertia: 11300000mm^4; Elastic modulus: 210GPa; Poisson's ratio: 0.3.
W-shape steel strip	Width: 300mm; Thickness: 4mm; Cross-sectional area :810mm^2; Moment of inertia:40824mm^4; Elastic modulus: 210GPa; Moment of inertia: 0.3.
rockbolt	Diameter: 20mm, Elastic modulus: 210GPa; Poisson's ratio: 0.2.

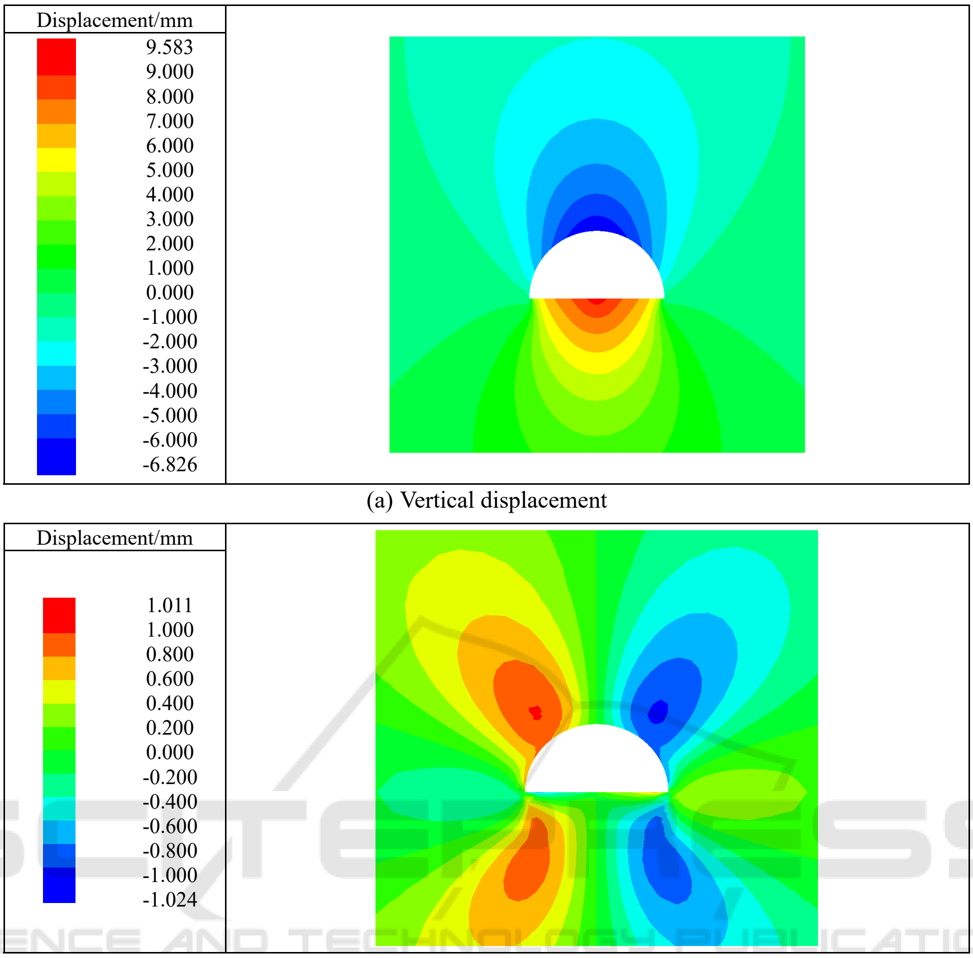
3 ROCK EXCAVATION DEFORMATION

Extract the deformation and stress conditions of two types of support structures after construction, as well as the stress conditions of the support components for analysis. Among them, the steel support components of traditional support structures and flexible support structures are steel arches and steel strips, respectively.

3.1 Rock Excavation Deformation

The displacement of the surrounding rock deformation after tunnel excavation for the initial support structure of steel arch bolt shotcrete and the initial support structure of W-shape steel strip bolt shotcrete is shown in Figure 2 and Figure 3.

Due to the lower overall stiffness of the W-shape steel strip compared to the steel arch, the deformation of the surrounding rock will be slightly greater when using the W-shape steel strip bolt shotcrete support structure. However, the flexible support structure also has a good effect on controlling the surrounding rock of the tunnel.



(a) Vertical displacement

(b) Horizontal Convergence

Figure 2: Deformation diagram of the initial support structure of steel arch bolt shotcrete.

3.2 Results of Plastic Zone of Surrounding Rock

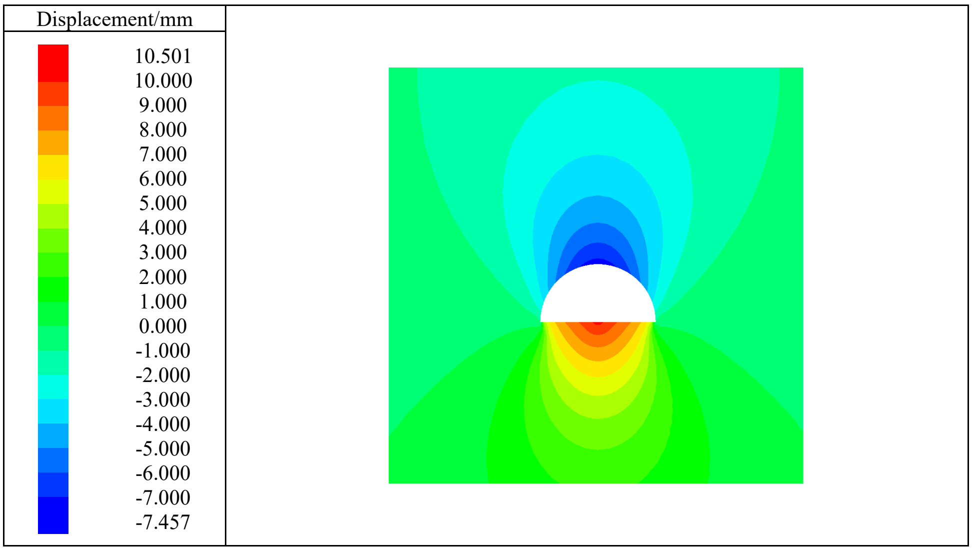
The distribution of plastic zones in the surrounding rock after tunnel excavation under two different working conditions is shown in Figure 4.

Different support structures are applied after tunnel excavation, and the distribution of plastic zones in the surrounding rock is basically the same, mainly in the shear plastic zone. In terms of the size of the plastic zone, the plastic zone of the surrounding rock after flexible support structure is applied is smaller than that of traditional support structure, indicating that flexible support structure can better exert the self-supporting capacity of the surrounding rock.

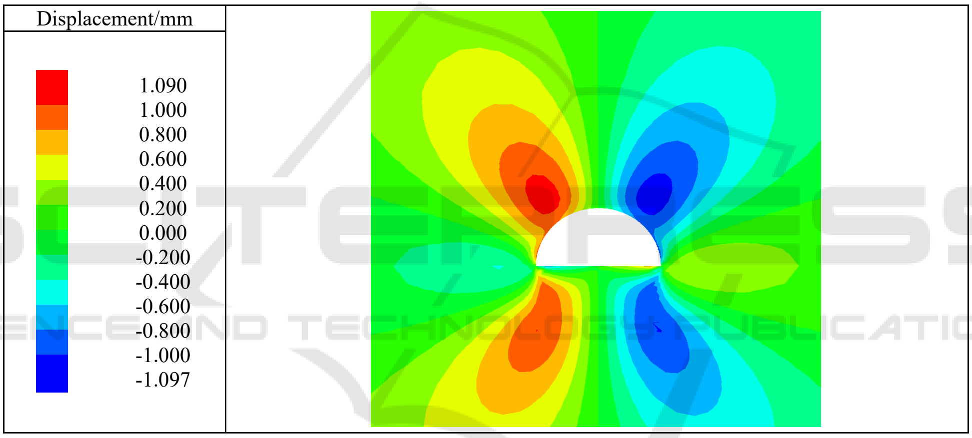
3.3 Stress Characteristics of Rockbolt

The stress distribution of the rockbolt under two working conditions after tunnel excavation is shown in Figure 5.

Due to the influence of the joint support system formed with the steel strip, the stress distribution of the rockbolt in the flexible support structure is different from that in the traditional support structure. The axial force of the rockbolt reaches its maximum value at the end of the rockbolt and gradually decreases along the direction of the rockbolt.In terms of overall force distribution, the rockbolt of the two support structures are basically consistent, both reaching their maximum values near the arch springing. Among them, the rockbolt of the flexible support structure receive a maximum axial force of 20kN, which is 1.4 times that of the traditional support structure. This indicates that in the flexible support structure, the surface W-shape steel strip



(a) Vertical displacement



(b) Horizontal Convergence

Figure 3: Deformation diagram of the initial support structure of W-shape steel strip bolt shotcrete.

yields pressure and exerts the tensile function of the rockbolt.

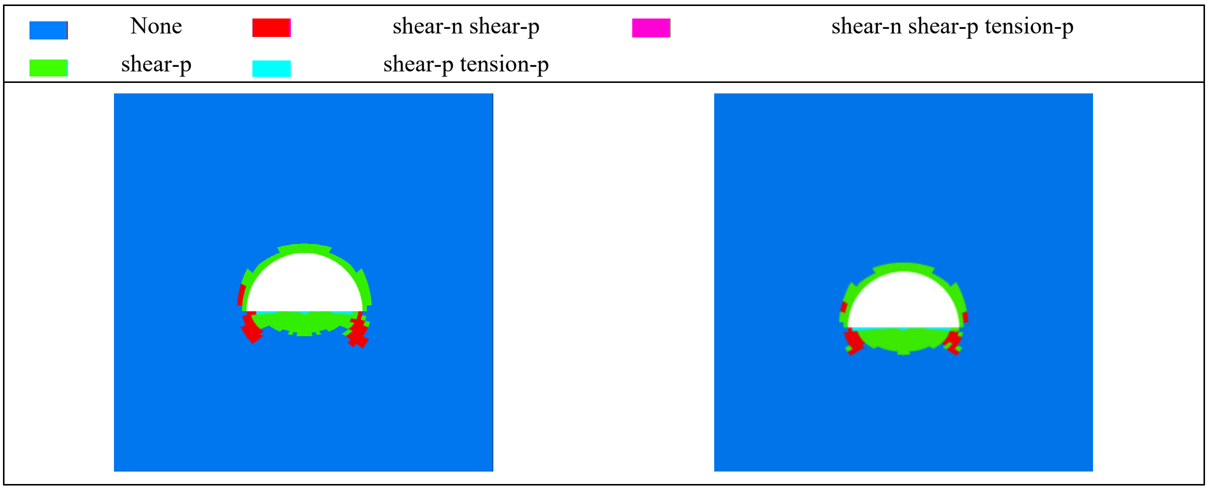
3.4 Stress Characteristics of Steel Support

The bending moment distribution of the steel support structure under two working conditions is shown in Figure 6.

Compared with traditional support structures, when constructing flexible support structures, the bending moment experienced by steel strips is much smaller than that of steel arches. The maximum bending moment of the steel strip is 7.88 N·m, and the maximum bending moment experienced by the steel arch is 3.2 times that of the steel strip, with a bending moment value of 25.26 N·m.

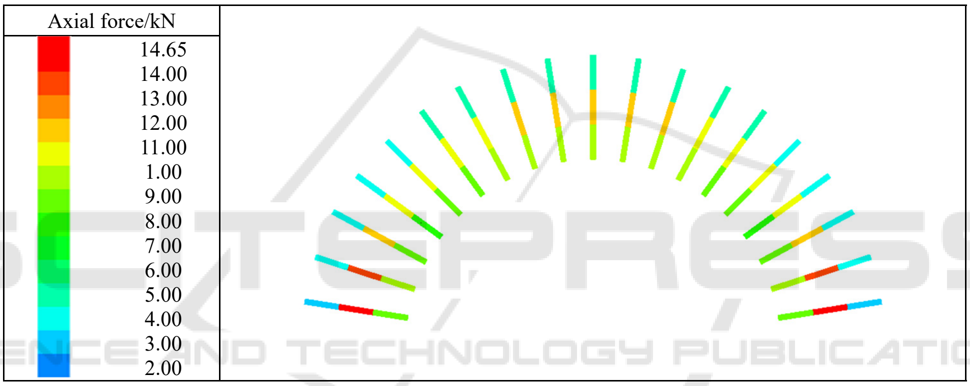
The stress distribution of the steel support structure under two working conditions is shown in Figure 7.

The stress distribution of the two support structures is basically the same, with the arch crown receiving the minimum stress and the arch lumbar receiving the maximum stress. The maximum stress value of the steel arch is 100.71 MPa, and the maximum stress value of the steel strip is 126.78MPa. Compared with the steel arch, the joint support structure formed by W-shape steel strip and rockbolt is an active support structure, and the stress distribution of the steel strip is more uniform.

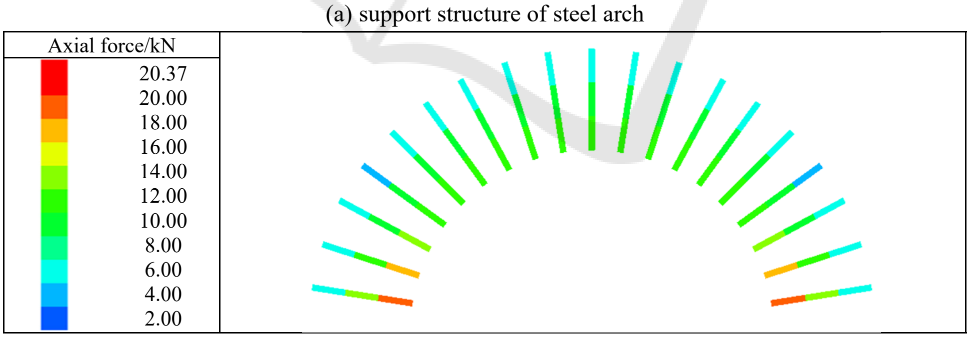


(a) support structure of steel arch (b) support structure of W-shape steel strip

Figure 4: Distribution of plastic zone in surrounding rock of support structure.



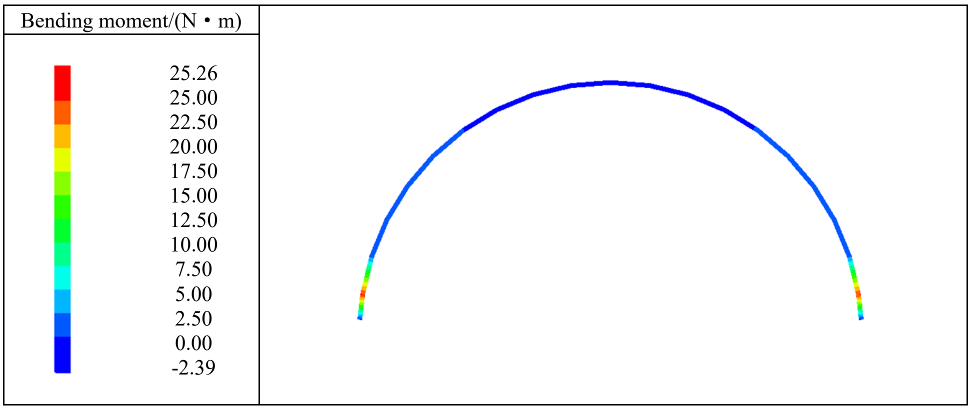
(a) support structure of steel arch



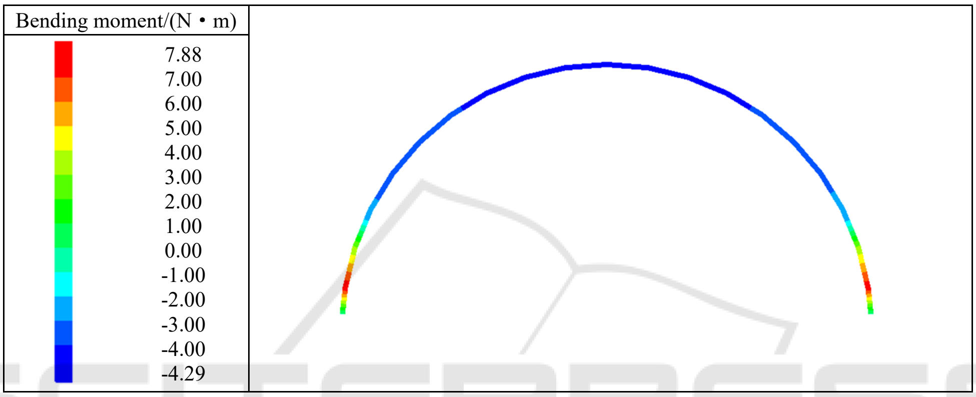
(b) support structure of W-shape steel strip

Figure 5: Axial force diagram of anchor rods with different support structures.

Although the W-shape steel strip has a weaker constraint on the excavation deformation of the surrounding rock compared to the steel arch bolt shotcrete support structure, and the stress amplitude of the W-shape steel strip is also larger than that of the steel arch, it is still within the yield strength. Compared with the steel arch bolt shotcrete support structure, through deformation, it can fully exert the deep migration of the surrounding rock stress and the self bearing capacity of the surrounding rock. The steel strip is closely attached to the surface of the surrounding rock and works together with rockbolt to provide "active support" for the surrounding rock, which could make the effectiveness of the steel strip is higher than that of the steel arch.



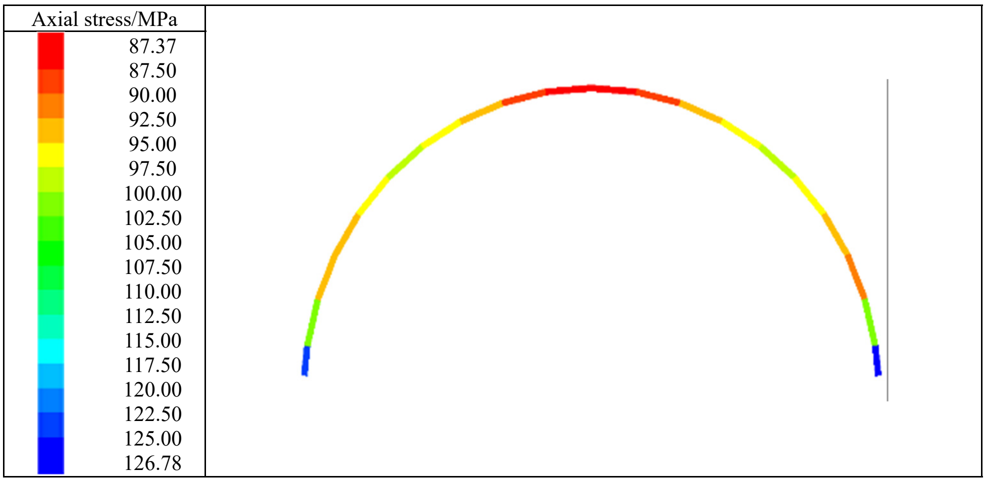
(a) support structure of steel arch



(b) support structure of W-shape steel strip

Figure 6: Bending moment diagram of steel support for different support structures.

(a) support structure of steel arch



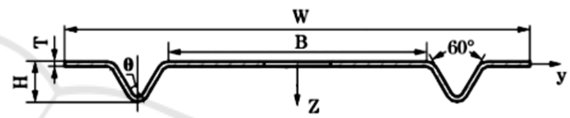
(b) support structure of W-shape steel strip

Figure 7: Stress diagram of steel support for different support structures.

4 ENGINEERING APPLICATION TESTS

4.1 Experimental Design

Based on a certain highway tunnel, a field test section was conducted. The ZK101+500-ZK101+650 tunnel is designed with grade IV surrounding rock, with a tunnel burial depth of 110m~133m. The formation is composed of moderately weathered thin sandstone interbedded with mudstone, with well-developed joints and fissures, and the surrounding rock is relatively fragmented. The original design adopted the grade IVa support method, with initial support parameters of HRB400 grade 3 threaded steel; the diameter of the rockbolt is 20mm, the type of it is mortar rockbolt, the length of it is 3.0m; the diameter of the steel mesh is 6.5mm, and the arrangement is 25×25cm; the steel arch adopts I16 I-beam with a longitudinal spacing of 80cm; the shotcrete adopts C20 strength and is applied with a thickness of 22cm; the design requirement is to reserve a thickness of 8cm after excavation. The construction of this section adopts the two-step method for excavation, with a height of 4.5 meters for the excavation of the upper center bench . After excavation, 13 steel strips are continuously used instead of the original design I16 I-beam steel arch at ZK101+560-ZK101+570.4. The steel strip structure is shown in Figure 8.



W-steel strip width, 300mm; B-Steel strip support width, 155.6mm; H-steel strip height, 23.5mm; T-steel strip thickness, 4mm, Sectional area, 810mm^2

Figure 8: Structural diagram of experimental steel strip.

The middle position of the section ZK101+565 is selected as the monitoring section, and compared with the adjacent section ZK101+555 steel arch support structure section. The experimental section setting is shown in Figure 9.The actual installation of steel support components on site is shown in Figure 10.

4.2 Test Results

The deformation monitoring data of two sections for 40 days of support deformation monitoring are shown in Figure 11.

By comparing the deformation of two cross-sectional support structures, it was found that under the same surrounding rock conditions, their deformation patterns were basically the same. The deformation increased rapidly in the first 7 days and eventually stabilized over time.

In addition, no cracking or block shedding was found in the on-site support structure. The initial support structure composed of W-steel strips replacing steel arches can also maintain the stability of weak surrounding rock for the support of excavated highway tunnels.

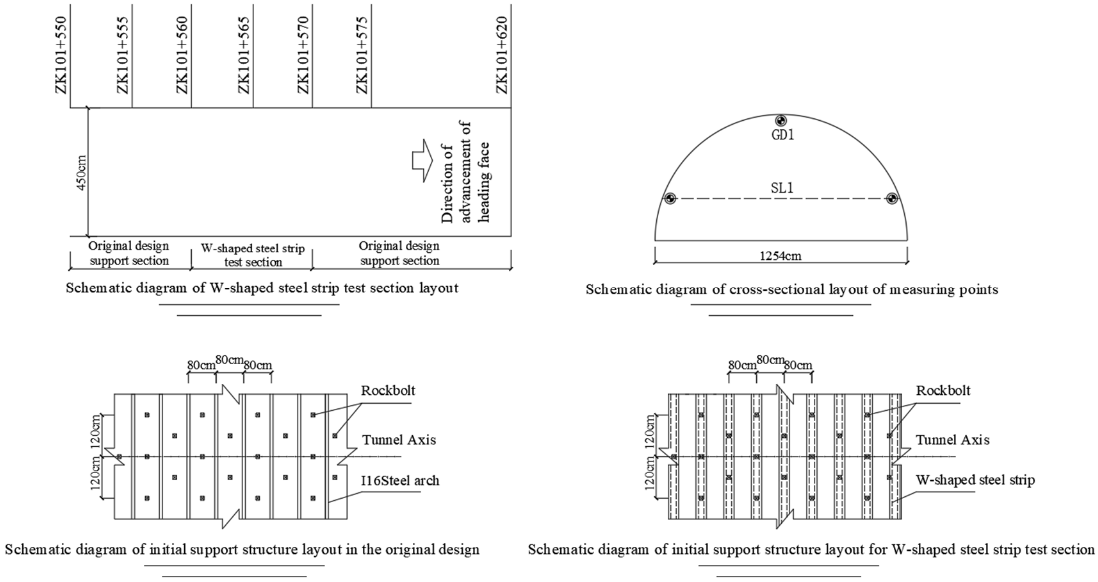
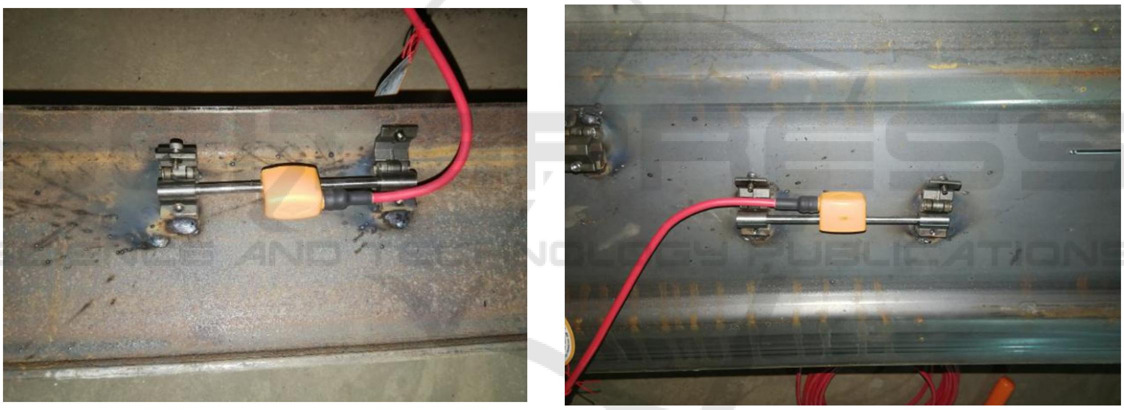


Figure 9: Schematic diagram of engineering test layout.



(a) Rigid connection of sensors in steel arch (b) Rigid connection of sensors in W-shape steel strip

Figure 10: Layout of engineering test site.

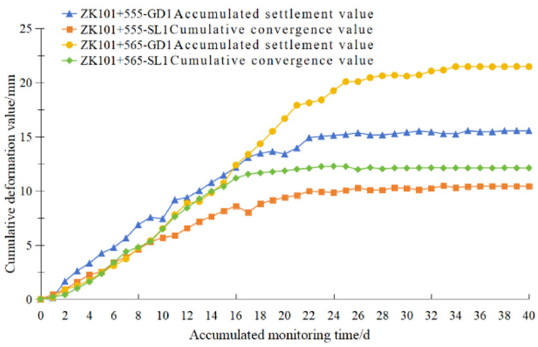


Figure 11: Monitoring section deformation curve.

5 CONCLUSION

By establishing a numerical model, a stress analysis was conducted on the flexible support structure constructed in soft ground highway tunnels. The feasibility of using steel strips instead of traditional steel arches was compared and verified through field experiments, and the following conclusions were drawn.

(1) In soft ground, the initial support structure composed of W-steel strips replacing steel arch has basically the same support effect on the excavated highway tunnel, but the constraint amplitude for

tunnel excavation deformation control of steel strip is smaller than that of steel arches.

(2) Compared with the initial support structure composed of steel arch, the range of damage or yield in the plastic zone of the surrounding rock caused by the initial support structure of W-steel strip is basically the same. The initial support structure of W-steel strip can better exert the self-supporting capacity of the surrounding rock.

(3) Within the safe strength range, the initial support structure of W-steel strip can better utilize the strength advantages of steel materials and rockbolt, and fully exert its support effect.

(4) Through on-site testing, it has been verified that the initial support structure composed of W-steel strips replacing steel arch can also maintain the stability of weak surrounding rock for the support of excavated highway tunnels.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

Wang, W., et al. 2021. Mechanical Analysis of Non-circular Tunnel Lining Considering Ground-support Interaction. *Chinese Journal of Underground Space and Engineering*, 17(S2): 631-636+649.

Wei, Z., He, F., Zhang, G., et al. 2017. Failure mechanism and cable truss control of large-scale section gob-side entry roof with fully mechanized caving. *Journal of Mining & Safety Engineering*, 34(1): 1-8.

Sun, H. 2023. *Interaction and Stability Analysis of Surrounding Rock and Lining Structure of High Temperature Hydraulic Tunnel*. Shihezi University, Shihezi.

Sun, H. 2022. *Research on the large deformation mechanism of soft rock and support countermeasures of NPR anchor cable-truss in Tayi tunnel*. China University of Mining & Technology-Beijing, Beijing.

Zhang, G., He, F. 2016. Asymmetric failure and control measures of large cross-section entry roof with strong mining disturbance and fully-mechanized caving mining. *Chinese Journal of Rock Mechanics and Engineering*, 35(4): 806-818.

Lu, W., et al. 2025. Study on the mechanism of roof collapse and anchoring-grouting support parametric sensitivity in deep goaf based on upper limit method. *Journal of Mining & Safety Engineering*, 1-16.

Zhao, Z., Yang, P., Zhang, M., et al. 2022. Stability of weakly cemented soft surrounding rock under combined effect of water environment and inhomogeneous ground stress. *Journal of Mining & Safety Engineering*, 39(1): 126-135.

Zhang, J. 2014. Engineering Geological Properties of Soft Surrounding Rocks of Mountain-crossing Tunnels and Construction Countermeasures. *Tunnel Construction*, 34(08): 749-753.

Li, J., et al. 2023. Study on Structural Effect of Steel Belt of Prestressed Anchorage System for Soft Rock Tunnel. *Journal of Disaster Prevention and Mitigation Engineering*, 43(01): 41-49.

Liu, F. 2023. Treatment of Highway Tunnel Disease and Finite Element Analysis of Steel Belt Reinforcement Technology. *Construction& Design For Project*, (01): 96-98.