Analysis of Supporting Mechanism of Steel Arch Frame in Tunnel Collapse

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Abstract. As the steel arch can withstand the rock load immediately, this is widely used in tunnel collapse treatment. Firstly, the steel arch mechanism and mechanical model in tunnel collapse supporting had been studied. Then the modeling points and solutions of the finite difference software FLAC3D were pointed out, and the effects of steel arches and steel arches with different spacings were simulated. This paper analyzed the stress field of rock, displacement field of rock and stress behavior of steel in different conditions, the following conclusions: (a) Steel arch can inhibit stress concentration of the foot arch, while the dome appears to reduce the scope of the low stress areas, and it can effectively inhibit the vertical displacement of the vault and floor; (b) The maximum axial force and bending moment were increased with the increase in the arch steel arch spacing; (c) The maximum axial force steel arch occurs mainly at the crown, while the maximum bending moment occurs mainly in the arch and vault at the waist, and arch at the moment was very small. There were basically consistent with the mechanics calculations.

Keywords. Tunnel engineering, collapse, steel arch, support mechanisms, numerical simulation.

1. Introduction

The problem of surrounding rock stability encountered during the construction of the tunnel has become increasingly prominent. Tunnel collapse is one of the most common disaster phenomena [1-9]. If improperly managed, it will not only delay the construction period, but also increase the construction cost. Steel arches have been widely used in the treatment of tunnel collapse [10-14]. Because the steel arch has greater strength and rigidity, it can immediately bear the surrounding rock load after application and can effectively control the surrounding rock deformation. At present, there is relatively little research on the mechanism of steel arch support, and the simulation of steel arches in tunnel collapse support is mostly considered to be converted into the initial lining in an equivalent way [15-16]. It is relatively simple, but it is inconsistent with the actual situation, and the calculation accuracy is low. It is also impossible to analyze the internal force of the steel arch separately.

Based on this situation, this paper first studies the mechanism and mechanical model of steel arch in tunnel collapse. On this basis, the ideal model is established by using finite difference software FLAC3D. The beam element is used to simulate the support effect of steel arch in the treatment of landslide. The stress field and displacement field characteristics of surrounding rock under different working conditions are analyzed, and the internal force simulation results are qualitatively compared with the mechanical analysis results.
Mechanical Analysis of the Mechanism of Steel Arch

2.1. Mechanism of Action of Steel Arches
Steel arches are widely used to reinforce tunnel collapse areas and fractured surrounding rocks. Its mechanism of action is mainly as follows:

1. The steel arch has high strength and large rigidity, which can ensure that the pressure of the upper surrounding rock can be immediately received after its installation.
2. The rock mass of the landslide area is poor in mechanical properties, and it is often difficult to form an effective bearing arch. However, steel arches can provide support reaction forces that can constrain the deformation of the tunnel in the radial direction. It can also change the stress state near the excavation face into a triaxial stress state, which is beneficial to improve the bearing capacity of the surrounding rock.
3. Steel arches often form a monolithic structure with spray anchor support. The main support resistance is provided by the steel arch before the pre-shot concrete has not formed strength. As the strength of the concrete continues to increase, the primary lining concrete also becomes the main load-bearing structure. Combined with the flexible support of the anchor, the stiffness and toughness of the entire support system are fully utilized. A continuous bearing arch is formed in the axial direction of the tunnel to maintain the stability of the surrounding rock.

2.2. Analysis of Mechanical Model of Steel Arch
Zhu Hanhua and others have carried out force analysis for the steel arch support structure under the ideal stress condition and uniform load [17]. It is assumed that the surrounding rock pressure is considered according to the uniform load, and the tunnel is radially distributed along the steel arch. The mechanical calculation model of the steel arch is simplified as shown in figure 1.

![Stress analysis chart of steel](image)

Figure 1. Stress analysis chart of steel.

Set the tunnel span to \(B\), the height to \(H\), and the uniform load to \(P\). The coordinate system is established as shown in figure 1. The polar coordinate equation for the curve is:

\[
\begin{align*}
  x &= B \cos \theta \\
  y &= H \sin \theta
\end{align*}
\]

In the vertical direction, the balance of forces can be derived:

\[
R_R = \frac{1}{2} \int_0^\pi \frac{B}{2} (\cos \theta)^2 + (H \sin \theta)^2 \sin \theta \, d\theta = \frac{1}{2} pB \]

(2)

Due to the symmetry, half of the steel arch is analyzed, and the horizontal force is balanced by the force to obtain the axial force on the section:

\[
N = \frac{1}{2} \int_0^\pi \frac{B}{2} (\cos \theta)^2 + (H \sin \theta)^2 \cos \theta \, d\theta = \frac{1}{2} pB
\]

(3)

For the moment A, the moment is balanced by the moment:

\[
M + N \cdot H - \frac{1}{2} \int_0^\pi \frac{B}{2} (\cos \theta)^2 + (H \sin \theta)^2 \frac{B}{2} \sin \theta \, d\theta = 0
\]

(4)
Thus, the maximum bending moment value at the cross-section can be derived, which is defined as $M$:

$$
M = \int_0^\pi p_A \left( \frac{B \cos \theta}{2} \right)^2 + (H \sin \theta)^2 \frac{B}{2} \sin \theta d\theta - N \cdot H
$$

(5)

Define $\cos \theta = \cos t$. The bending moment $M$ at the vault of the steel arch is calculated by calculation.

$$
M = \int_0^\pi p_A \left( \frac{B \cos \theta}{2} \right)^2 + (H \sin \theta)^2 \frac{B}{2} \sin \theta d\theta - N \cdot H
$$

$$
= \frac{pB^2}{M} + \frac{2pBH^2}{M} \ln \left( \frac{\sqrt{B^2 - AH^2} + B}{AH} \right)
$$

(6)

It can be seen from the above theoretical analysis that under the uniform load, the bending moment at the arch of the steel arch is zero, and the bending moment of the dome is the largest. Since the tunnel span is often greater than its height, that is, $B > H$, it can be known from equations (2) and (3) that there is often $N > R_A$. That is to say, the arch axial force is often greater than the arch axial force.

3. Numerical Simulation of Support Mechanism for Steel Arch Frame at Landslide

The support effect of the steel arch in the tunnel collapse treatment was simulated under the ideal conditions by using FLAC3D software. The support effect is compared with the internal force analysis results of Section 2.2 to explore the mechanism of the action of the steel arch in the tunnel collapse process. It provides a basis for optimizing the application of steel arches in the treatment of landslides.

3.1. Numerical model Establishment

Taking the collapse of a tunnel as the background, the calculation model is shown in figure 2. The model range of the numerical analysis is: about 4 times the hole diameter (45 m) in the horizontal direction of the X-axis direction of the tunnel, and the ground is taken in the vertical direction Z, and 30 m downward, and the axial direction of the tunnel is 5.0 m.

![Figure 2. Graph of calculation model](image)

The elastoplastic material model was used in the calculation process, and the Mohr-Coulomb criterion was adopted. The null empty model is used to simulate excavation, and the surrounding rock and the sacral reinforcement area are simulated by solid elements. The steel arches were modeled using beam elements and the shell elements were used to simulate shotcrete.

3.2. Parameter Selection

The material parameters of each part of the model are shown in table 1.
Table 1. Properties of materials.

| Material type                              | $E$ (GPa) | $\nu$ | $\rho$ (g cm$^{-3}$) | $c$ (MPa) | $\psi$ (°) |
|-------------------------------------------|-----------|-------|----------------------|-----------|-----------|
| surrounding rock                          | 3.0       | 0.25  | 2.2                  | 0.3       | 32        |
| Collapse cavity pre-reinforcement zone    | 5.0       | 0.24  | 2.5                  | 1.5       | 35        |
| Collapse reinforcement area               | 4.2       | 0.25  | 2.5                  | 0.4       | 25        |
| Steel arch                                | 260       | 0.3   | /                    | /         | /         |
| Concrete lining                           | 21        | 0.25  | 2.3                  | /         | /         |

Note: Where $E$, $\nu$, $\rho$, $c$ and $\psi$ are the elastic modulus, the Poisson’s ratio, the density, the cohesion, and the internal friction angle, respectively.

It is considered for calculation under two different operating conditions. One is when there is no steel arch support during excavation, and the other is tunnel excavation under the support of steel arches with different spacing. The main points of the simulation are as follows:

1. Simulated excavation process: First, the initial stress balance under self-heavy stress is calculated, and then according to the actual treatment excavation method, one step of excavation is immediately supported. The excavation step takes 0.5 m until the entire excavation is completed.

2. When the steel arch is simulated by beam element, it should be noted that the ID number of each beam element of the beam unit should be the same to ensure that the entire steel arch is completely simulated. At the same time, it is very important that the nodes at both ends are in the same position as the node of the shell unit when the beam element is generated to facilitate the connection.

3. The difficulty of this simulation is mainly to deal with the problem of the link between the zone unit and the structural unit (such as the beam unit and the shell unit) and the link problem between the nodes of different structural units. The solution is to delete the link between the shell unit and the zone unit zone, and then establish the link between the shell unit and the beam unit, and control the generation of the beam unit so that it does not generate a link with the zone.

4. Since the mesh of the solid element cannot drive the steel arch to rotate, the link between the node of the beam unit and the node of the shell unit should be set to “hinged”.

3.3. Analysis of Numerical Calculation Results

3.3.1. Stress field Analysis. Figures 3 to 6 show the vertical stress distribution when the tunnel is excavated without truss support and the 0.5 m, 0.8 m and 1.2 m pitch arches are laid.

With the excavation of the tunnel, the stress of the rock around the cave is redistributed, and the stress of the surrounding rock is symmetrically distributed by the axis of the cavern. The surrounding rock of the arch and the floor has a low stress zone, which is mainly due to the excavation unloading. The surrounding rock stress of the two parts is reduced and formed. The main performance is the tendency of the vault to sink and the bulging of the bottom plate. When the steel arch is not set, a large range of stress release occurs in the dome, and at the same time, a significant stress concentration area appears in the arch. Conversely, when the steel arch is set, the range of stress concentration is reduced, indicating that the addition of the steel arch can promote the stress concentration of the arch. The high stress area appearing on the arches on both sides increases slightly with the increase of the arch spacing, but it is not very obvious.
3.3.2. Displacement Field Analysis. Figures 7 to 10 show the vertical displacement distribution of the archless frame, 0.5 m, 0.8 m and 1.2 m pitch arches.

It can be seen from figure 7 that when the steel arch is not provided, the displacement of the dome in the vertical direction reaches 20.0280 mm. When the steel arch is supported, the vertical displacement of the dome is obviously reduced, and the maximum is only 2.4993 mm (figure 10). And the floor bulge trend is also suppressed. It shows that the steel arch frame has a good support and strengthening effect. With the encryption of the spacing of the steel arches, this support ability is getting stronger and stronger, which is manifested by the vertical displacement of the dome and the reduction of the displacement of the floor ridge. The vertical displacement of the dome is reduced from 2.4993 mm at an arch spacing of 1.2 m to 2.0003 mm at an arch spacing of 0.5 m. And the reduction ratio is 19.97%. The displacement of the floor ridge is reduced from 3.3602 mm at an arch spacing of 1.2 m to 2.9605 mm at an arch spacing of 0.5 m, and the reduction ratio reached 11.9% which was no significant decrease in the displacement of the dome. As the spacing of the steel arches continues to increase, not only the vertical displacement of the dome and the floor increases, but also the area where the larger displacement occurs has a tendency to expand toward the arch.
3.3.3. Analysis of Internal Force Calculation Results. The main internal force calculation results of the steel arch simulation are shown in Table 2. Only some internal force results are listed here. Figures 11 to 14 show the maximum axial force and maximum bending moment in the arch at 0.5 m and 1.0 m arch spacing, respectively.

### Table 2. Results of calculation of internal forces.

| Serial number | Steel arch spacing (m) | Maximum axial force in the arch (kN) | Maximum bending moment in the arch (kN·m) |
|---------------|------------------------|-------------------------------------|------------------------------------------|
| 1             | 0.5                    | 277.8                               | 15.30                                    |
| 2             | 0.6                    | 326.4                               | 16.21                                    |
| 3             | 0.8                    | 388.5                               | 17.21                                    |
| 4             | 1.0                    | 507.5                               | 18.80                                    |
| 5             | 1.2                    | 613.1                               | 19.61                                    |

It can be seen from Table 2 that as the spacing of the steel arches increases, the maximum axial force and bending moment value in the arch increase simultaneously. For each 0.2 m increase in spacing, the axial force increases by 57.2~105.6 kN, and its increase is 18.67%~34.99%. At the same time, the bending moment increases by 0.81~1.82 kN·m, and its increase is 4.31%~11.90%. In the early stage of surrounding rock support, the steel arch frame played the role of “bearing skeleton” when the shotcrete did not reach the standard compressive strength. Moreover, the influence of the variation of the steel arch spacing on the maximum axial force in the arch is relatively more obvious than the effect on the maximum bending moment.
From figures 11 to 14, the basic law can be drawn: the maximum axial force of the steel arch mainly occurs at the vault, and the maximum bending moment mainly occurs at the vault and the arch waist, and the bending moment at the arch is extremely small, almost zero. This is basically consistent with the theoretical analysis of the previous mechanical model.

4. Conclusion

(1) In the numerical simulation process, the following points should be noted: (a) When the steel arch is simulated by beam element, it should be noted that the ID number of each beamsel of the beam unit should be the same. At the same time, it is necessary to control the nodes at both ends of the beamsel to be in the same position as the node of the shell unit of the simulated shotcrete to achieve an effective connection. (b) First delete the link between the shell unit and the zone unit, and then establish the link between the shell unit and the beam unit, and the generation of the beam unit needs to be controlled so that it does not generate a link with the zone. This method perfectly solves the link problem between the zone unit and the structural unit (such as the beam unit and the shell unit). (c) Since the mesh of the zone unit cannot drive the rotation of the steel arch (beam unit), the link between the node of the steel arch and the node of the jet raft should be set to “hinged”. This is more suitable for the requirements of steel arches and surrounding rock should be as close as possible during actual construction.

(2) The numerical simulation results show that: (a) setting the steel arch can effectively restrain the stress concentration of the arch, and at the same time reduce the range of low stress areas in the dome. (b) Under the support of different distance steel arches, the high stress area appearing on the arches on both sides increases slightly with the increase of the arch spacing, but it is not very obvious. (c) The arrangement of the steel arch has a significant effect on controlling the sinking of the surrounding rock. As the spacing of the steel arches increases, the vertical displacement of the dome and the floor increases, and the area where the larger displacement occurs has a tendency to expand toward the arch.
The internal force calculation results show that the maximum axial force and bending moment value of the arch increases with the increase of the spacing of the steel arches. The maximum axial force of the steel arch mainly occurs at the vault, and the maximum bending moment mainly occurs at the vault and the arch waist, and the bending moment at the arch is extremely small.

In this paper, the numerical simulation of the steel arches and the analysis of the mechanism of action have only been initially discussed in the treatment of tunnel collapse. More in-depth and mature research needs to be further developed. It is hoped that the results of this paper have certain reference value for optimizing the application of steel arch and guiding the construction of steel arches on site in the treatment of tunnel collapse.

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