Numerical Calculation of Instability of Tunnel Surrounding Rock Based on Elastic Hole Theory

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Abstract. The instability and unloading of surrounding rock structure in tunnel under TBM construction condition can easily induce large-scale rock caving in heading face, which seriously restricts safe and efficient tunneling. Aiming at the instability problem of surrounding rock structure of tunnel constructed by TBM, four types of slope induced by excavation disturbance are summarized systematically based on elastic hole theory, and the instability mechanism of roof structure and surrounding rock of tunnel is analyzed; the instability mechanism and catastrophic characteristics of surrounding rock structure of tunnel are analyzed by FLAC3D finite element numerical calculation software, and the roof transportation of tunnel after supporting is carried out. The amount of movement is greatly reduced and the overall failure degree of overlying strata is slowed down. The results show that the roof is prone to structural instability under the influence of tunneling disturbance. Tunnel support can effectively hinder the movement of overlying rock roof and floor, alleviate the probability of rock mass catastrophe, effectively control the dynamic disasters, and achieve safe tunneling.

Keywords: elastic hole theory; tunnel surrounding rock; structural instability; TBM construction; numerical calculation.

1. Introduction
TBM (Tunnel Boring Machine) tunneling is a new and advanced technology for tunnel construction with full-face road header. It has been widely used in the construction of major engineering tunnels [1,2]. Many foreign scholars have studied quite well, Kahraman S.[3] In view of the actual conditions in the field, the TBM advanced drilling technology is improved to control the stability of surrounding rock. Shahin H. M. [4] Based on the TBM construction technology, the characteristics of surrounding rock migration and stress evolution are analyzed. G. Barla [5] By analyzing the aging characteristics of rock mass, it is concluded that the main shear stress induced by rock rheology is up to the peak value. S. Yagiz [6] It is concluded that the main factor affecting the safety of TBM construction is caused by the large deformation induced surrounding rock instability. In China, such as Song Kezhi and Yuan Dajun [7,8], based on the analysis of mechanical characteristics of segment in tunnel construction stage by TBM construction method, the stress and deformation characteristics of segment in tunnel construction stage are studied, and the local failure phenomenon and its inducement are explored. On this basis, the segment mechanical model (one end fixed, one end simply supported member) is constructed to stabilize surrounding rock. Qualitative research provides a scientific basis. Chen Weizhong et al. [9] studied the stability of surrounding rock during the process of large deformation of mudstone with shield tunneling, mainly analyzed and concluded the distribution law of stress, displacement field, pore pressure and stress field of concrete lining segment in the surrounding rock of shield tunneling, and provided important conclusions for the construction of TBM tunnel in mudstone geological section in the future. Reference value. Based on the theory of elastic holes and
numerical calculation [10,11], the mechanism of instability of tunnel surrounding rock structure is studied in this paper. The application of TBM construction technology in long-distance rock roadway excavation in coal mine [12,13] is of great significance for safe and efficient construction of coal mine, and provides reference for tunnel TBM excavation construction under similar geological conditions.

2. Engineering Background
The main lithology of the sub-adit is grey-grey black siltstone in the range of 30 m in the top and 20 m in the bottom. It is fine, calcareous-sandy cemented, semi-hard and rarely cracked. Undesirable geological bodies have not yet been found. RQD=4.3-31.3%, Rock quality is described as inferior - extremely poor, poor rock integrity - crushing. The aquifer of soft rock section is shown in Table 1.

| Formation code | Numbering of water layer | Name of water (layer)                                      |
|----------------|--------------------------|------------------------------------------------------------|
| Q₃₄            | I                        | The Quaternary is permeable without water.                 |
| J₂ₓ            | II                       | The Middle Jurassic Xishan kiln group                      |
|                |                          | Weak porosity and water rich aquifer                       |
| J₂ᵗ            | III                      | Weak aquifer of Toutun River formation in Middle Jurassic  |
| J₁ₛ            | IV                       | Relative aquifers of the lower Jurassic three ohe formation|
|                | V                        | Phreatic aquifer of crevice rock fissure                    |

Table 1. Aquifer in construction geological section

Under the east water body of Shimenzi Reservoir, the vertical distance between the sub-adit and the water surface is 75m. The rock and soil stability of this section is poor, the surrounding rock grade is low, the porosity is large, the shallow Quaternary and Shimenzi Reservoir are closely related to the hydraulic. The rock mass of the sub-adit is long-term bubbled by water, the poor rock and soil are disturbed, locally softened, loose and stable. Poor rigidity. Under the water body 121m west of the east boundary of Shimenzi Reservoir, there are 2225m (1440m) to 2319m (1502m) sublevel tunnels and 1386.63m measured elevation at the reservoir level, 1313.06m at the roof elevation of 2225m (1440m) and 1313.436m at the roof elevation of 2319m (1502 ring) of the sublevel tunnels, and 1925m (1240 ring) at the sublevel of the sublevel tunnels. The inlet position is 2075m (1340 rings) to 2968m (1935 rings). A total of 893m is the key area for water exploration and drainage. Therefore, how to ensure the smooth passage of the shield in the soft rock section, the segment support becomes a difficult point of control.

3. Structural Instability Analysis of Tunnel Surrounding Rock Based on Elastic Hole Theory
3.1. Circular Single Hole Theory Based on Biaxial Isostatic Stress Field
The basic hypothesis is that the rock mass is homogeneous, isotropic, linear elastic and creep-free or viscous, and the original stress of rock mass is isotropic (hydrostatic pressure) state. The tunnel is assumed to be circular, the tunnel is infinite long, and the rock mass property remains unchanged. The plane method is used to study the problem.
Stress analysis: In the bi-directional isobaric stress field, the stress state around the circular hole is compressed, and the elastic constants E and Mu are directly related to the stress distribution.

\[
\sigma_r = \gamma H \left( 1 - \frac{\sigma_t}{\sigma_r} \right) \quad \sigma_t = \gamma H \left( 1 + \frac{\sigma_t}{\sigma_r} \right)
\]

Among them: lambda lateral stress system; \( H \) - overburden thickness; \( R \) - circular hole radius.

It can be seen from Formula 1. In the biaxial constant pressure field, the sum of the tangential stress \( \sigma_t \) and the radial stress \( \sigma_r \) around the circular hole is \( 2\sigma_1 \). \( \sigma_t \) and \( \sigma_r \) are independent of angles. They belong to principal stress, and \( \sigma_t \) and \( \sigma_r \) planes are principal planes. In the biaxial isobaric stress field, \( \sigma_t \) of the surrounding holes belong to \( \sigma_{t(max)} \), the stress concentration system is \( K_{\text{max}}=2 \), and there is no correlation between the stress diameter of the plane and the stress plane. When \( \sigma_t = 2\gamma H \) is greater than the elastic limit of the surrounding rock, the surrounding rock changes, while the other stress state is related to the pore size. When \( \sigma_t > 1.05\sigma_1 \) or \( \sigma_t < 0.95\sigma_1 \), the surrounding rock stress values around the hole are affected, and \( \sigma_t \) influence radius \( R_t = \sqrt{20r_1} \approx 5 \). In practice, 10% is regarded as the influence aperture, then \( R_t \approx 3r_1 \), in the numerical calculation generally takes 5\( R_1 \) as the computation domain.

3.2. **Circular Single Hole Theory Based on Bidirectional Unequal Stress Field**

Based on the excavation conditions and geological structure of the tunnel, the rock pressure in the vertical direction of the surrounding rock is 1.5D, which is 9.3 times the actual overburden weight. Reference to lateral pressure coefficient <Code for design of Railway Tunnels>(TB10003-2005) is 0.2. The analysis of circular single hole based on bidirectional unequal stress field is shown in Figure 2.
According to the above theory, the stress solution of circular hole in two-way stress infinite plate is as follows:

\[
\sigma_r = \frac{4H}{\pi}(1 + \lambda)(1 - \frac{4\theta}{\pi}) - \frac{4H}{\pi}(1 + \lambda)(1 - 4\frac{\theta}{\pi} + 3\frac{\theta}{\pi})\cos 2\theta
\]

\[
\sigma_t = \frac{4H}{\pi}(1 + \lambda)(1 + \frac{4\theta}{\pi}) + \frac{4H}{\pi}(1 + \lambda)(1 + 3\frac{\theta}{\pi})\cos 2\theta
\]

(2) Among them: \(H\) — Overburden thickness; \(r\) — Radius of circular hole; \(\theta\) — Angle of circular hole; \(\lambda\) — Lateral stress system value.

When \(\lambda = 0\), the tensile stress at the left and right parts of the circular hole will change, and the stress concentration factor of the circular hole will be \(K_{\max} = 3\). If the original rock stress takes the weight of self weight, the lateral stress value is between \(0 \leq \lambda \leq 1\). If the stress distribution at \(\theta = 0^\circ, 90^\circ, 180^\circ, 270^\circ\), the lateral stress concentration factor of the circular hole will be 2-3. When the tangential stress \(\lambda = 1/3\) is \(\sigma_t\) and the time is \(\sigma_t = \frac{1}{2}\sigma_r(1 + \frac{4\theta}{\pi}) + \frac{3}{4}\sigma_r(1 + 3\frac{\theta}{\pi})\cos 2\theta\) and \(\theta = 90^\circ, \theta = 270^\circ\), the tensile stress around the circular hole will disappear at \(\sigma_t = 0\).

3.3. Theoretical Analysis of Stress Distribution around Porous Surfaces

It is generally assumed that the degree of influence between adjacent holes and the stress distribution around the holes are affected by the following factors: the shape, size, spacing of holes, the number of holes in the same horizontal plane, the stress field in the original rock and related parameters.

1) The stress distribution law between adjacent sections. The circular holes in the two-way isobaric stress field are taken as the research object. When the spacing of holes is more than \(>2R\), the stress distribution between adjacent holes is not affected by each other, and the stress distribution of the circular holes is consistent with that of the single hole.

2) The stress distribution law of two adjacent holes with different sizes. The stress concentration factor of small holes can be obtained from two adjacent holes with different diameters. \(K_{\text{Tangential stress}} = 4.26\), Macropore stress concentration factor \(K_{\text{Tangential stress}} = 2.75\). The results show that the pores are affected by the macropores, but the macropores are little affected by the pores. This rule applies to the interaction between the mining face and the adjacent tunnel.

![Figure 3. Tangential stress distribution of tunnel holes](image)

The tangential stress distribution of tunnel holes is shown in Fig. 3. It is considered that the adjacent elastic holes are of different diameters. According to the theory of adjacent elastic holes with different diameters, it is concluded that the tunnels have no influence on each other during tunneling.
4. Analysis of Surrounding Rock Instability Based on Finite Element Numerical Calculation

4.1 Model Establishment
Based on the stress analysis results of surrounding rock of tunnel by elastic hole theory, the numerical calculation model of surrounding rock structure instability of FLAC\textsuperscript{3D} circular tunnel is established, the model size is 100m×100m×80m, a total of 234000 meshes and 243330 nodes were divided, and the model areas were divided from top to bottom as basic top, loose body and base. The scope of excavation control is restricted to vertical movement from the bottom of the model, and the horizontal movement is restricted before and after the model. The numerical calculation model is shown in Figure 4.

![Numerical calculation model](image)

Figure 4. Numerical calculation model

According to the rock mechanics test results provided by field geological investigation and related research, the rock mechanics parameters used in the simulation calculation are shown in Table 2.

| lithology       | Bulk density/KN/m\textsuperscript{3} | Bulk modulus/GPa | shear modulus/GPa | Poisson ratio | tensile strength/MPa | Cohesive force/MPa | internal friction angle/° |
|-----------------|---------------------------------------|------------------|-------------------|---------------|----------------------|---------------------|--------------------------|
| Siltstone       | 25.50                                 | 3.43             | 3.87              | 0.19          | 1.9                  | 3.9                 | 37.5                     |
| mudstone        | 24.20                                 | 4.16             | 2.86              | 0.22          | 1.8                  | 3.5                 | 37                       |
| fine sandstone  | 25.30                                 | 3.37             | 3.81              | 0.14          | 1.7                  | 4.5                 | 20.4                     |

4.2 Stress Strain Evolution Law of Tunnel Surrounding Rock Structure Instability
Under the influence of tunneling disturbance, stress concentration appears in different directions, especially at the top and sides of the tunnel, the color of the tunnel becomes darker and the color of the tunnel floor becomes lighter. As can be seen from Fig. 5, the vertical stress increases from 1.00 MPa to 2.75 MPa, and the vertical stress concentration factor reaches 2.75 times of the original stress. In Fig. 6, with the continuous advance of the tunnel, the failure area of overlying rock in many areas gradually expands, and the scale of overlying rock migration also increases. Roof instability is more likely to occur under the disturbance of tunneling. Tunnel support can effectively hinder the movement of roof and floor of overburden rock and effectively control the stability of surrounding rock. The stress strain distribution of surrounding rock of tunnel is shown in figures 5 and 6.
Based on the finite element numerical results, the vertical displacement curves of roof and floor surrounding rocks are drawn according to the vertical overburden change characteristics of the roof and floor surrounding rocks of coal mine tunneling. After the tunnel is supported, the roof movement decreases greatly, and the overburden failure is reduced. Roof instability is more likely to occur under the influence of tunnel disturbance. Tunnel support can effectively hinder the movement of overlying rock roof and floor, and the stability of surrounding rock can be effectively controlled, laying a foundation for further work. The vertical displacement curve of tunnel roof is shown in Figure 7. The longitudinal displacement of the roof and floor of tunnel can be divided into three parts: the temporary excavation stage, the excavation stage and the excavation support section. Under the support condition, the vertical displacement of the tunnel decreases gradually, and the displacement of surrounding rock decreases slightly under the interaction of face force and soil stress after the tunnel is excavated. The longitudinal displacement of surrounding rock of tunnel roof and floor is respectively: excavation support section > heading section > temporary heading section. The temporary abrupt change of displacement after tunneling indicates that there is a temporary irregular drop at the junction of tunnel excavation. The amount of uplift settlement produced by the three segments is also different. Excavation of support section > heading section > temporary heading section. The vertical vertical uplift curve of the floor is shown in Figure 8.
4.3 Plastic Zone Distribution and Characterization of Tunnel Surrounding Rock Structure Instability

Under the influence of tunneling disturbance, local plastic failure first occurs at the roof of the tunnel, which further leads to the occurrence of roof failure. From the range of the plastic zone, it can be found that the failure of the tunnel is more serious under the condition of no support, the plastic zone is obviously reduced under the condition of support, so the stability of surrounding rock is effectively controlled, and the plastic zone area is gradually reduced, which indicates that the rock with plastic failure is more likely to be destroyed under the condition of no support. With the extension of excavation depth and horizon, the failure zone of tunnel roof hinges each other to form a stable structure, which hinders the movement of the roof. It plays a positive role in the surrounding rock stability control system of the TBM tunnelling tunnel, and lays the foundation for the follow-up work. The structural classification of tunnel surrounding rock instability is shown in Figure 9.
4.4 Analysis of Tunnel Overburden Movement Law

FLAC$^3$D software was used to simulate the internal force distribution of the tunnel. Under the influence of tunneling disturbance, different stress concentration phenomena appear in different directions. The stress color at the top and bottom of the tunnel is obviously deepened. The stress value increases from 0.493 MPa to 5.65 MPa, and the stress concentration coefficient reaches 11.5 times of the original stress. Therefore, with the continuous advance of tunneling, the degree of stress concentration and the vertical stress range of the tunnel are reduced under the supporting conditions. The stress distribution of tunnel overburden is shown in Figure 10.

![Figure 10. Stress distribution of tunnel overburden](image)

Figure 10. Stress distribution of tunnel overburden

![Figure 11. Deformation characteristics of surrounding rock under different loads](image)

Figure 11. Deformation characteristics of surrounding rock under different loads
The deformation law of tunnel surrounding rock under different loads is studied. The magnitude and distribution of internal stress (self-weight stress, structural stress, expansion stress, etc.) under different natural occurrences, the deformation performance, internal force distribution characteristics and failure characteristics of various types of tunnel lining under different structural types and structural parameters are analyzed. According to the deformation characteristics of surrounding rock under different loads in Fig. 11, it can be seen that the deformation of tunnel side is the most serious area, and the maximum displacement of overlying rock increases gradually with the increase of load.

5. Conclusion

1) Based on the elastic hole theory, the surrounding rock stress of Xiaozhuang Coal Mine Tunnel is analyzed. The model of adjacent elastic hole with unequal diameter is adopted. According to the theory of adjacent elastic hole with unequal diameter, it is concluded that the excavation of each tunnel has no influence on each other.

2) Study on the instability mechanism of tunnel surrounding rock structure and put forward control measures. After supporting, the roof movement of the tunnel is greatly reduced, and the overall damage degree of overlying rock is slowed down. Under the influence of tunneling disturbance, roof structure instability is more likely to occur. Tunnel support can effectively hinder the movement of roof and floor, and the stability of surrounding rock can be effectively controlled.

3) Based on the finite element numerical analysis method, it is concluded that with the continuous advance of tunneling, the settlement of tunnel after supporting is reduced by 50% on average, and the peak value of stress decreases linearly.

4) After the tunnel is supported, the displacement of the roof decreases greatly, and the overall failure of the overlying rock slows down. The roof is prone to structural instability under the disturbance of tunnel driving. The tunnel support can effectively hinder the movement of the roof and floor of the overlying rock, and the stability of the surrounding rock is effectively controlled.

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