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Study on supporting time of tunnel lining in thin-layered rock mass

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Abstract: The thin-layered rock mass of Baokang tunnel has the characteristics of large deformation and failure of soft rock under the excavation unloading. More seriously, a serious question is that the lining cracking is prominent. The cause of the cracking can be traced to different failure modes of the surrounding rock mass. Specifically, the rock layer on left arch spandrel is prone to bending failure due to the action of tangential stress, while the right-side wall is prone to sliding failure due to the action of higher shear stress. Furthermore, the lining cracking may beyond the ultimate compressive capacity when the loosely collapsed rock mass acted on the lining. According to the transversely isotropic characteristics of layered rock mass, the failure approach index (FAI) was selected to evaluate the damage and failure of thin shale. Meanwhile, the result of the example shows that this index can effectively characterize the failure characteristics of the thin-layered rock mass. Hence, the FAI was used as an evaluation index of the loose failure of layered rock mass. In order to determine the lining support time, the stability of the lining under the action by the loose rock mass was analyzed by the numerical simulation. As a result, the distance between the lining and the face should not be bigger than 120m. According to the Feedback through onsite construction, the lining cracks didn't appear under this supporting time, which ensured the stability of the lining structure. The research methods and ideas can provide reference for the similar tunnel lining construction in thin-layered rock mass.

Key words: Layered rock mass; Soft rock; Large deformation; Supporting time; Lining structure

1. Introduction

When tunnels constructed in soft rock mass, it is usually accompanied by engineering problems such as large deformation of the surrounding rock mass. For example, the Taun tunnel[1] in Austria, the Jiazhuji tunnel[2-4], the Muzhailing tunnel[5-6], and the Wulinling tunnel[7] in China have all experienced large deformation of the surrounding rock mass during the construction process. Large deformation of soft rock mass usually affects construction progress and even leads to the destruction of lining structure, which seriously affects the safety of tunnel construction and operation. In order to ensure the stability of lining structure, supporting time is one of the main factors, and scholars have carried out many researches on it. Huang et al[8] analyzed that the release of the surrounding rock stress and deformation are the key factors in the selection of the lining time; Zheng et al[9] proposed that the calculation of the optimal lining time must consider the spatial and temporal effects of the tunnel excavation process; Combined with engineering experience, Li et al[10] have studied the tunnel surrounding rock mass deformation law and the reference range for the best support lining time; Yang et al[11] determined a reasonable lining support time by simulating different construction methods. Wang et al.[12] have put forward a deformation control benchmark for the lining time in large deformation strata. However, for thin-layered rock mass, there was no theoretical formula to determine the lining time. In this paper, numerical simulation and field monitoring would be adopted to determine an optimal lining time of Baokang tunnel in China, which was encountered a problem of lining cracking caused by a large deformation of layered soft rock mass.

2. Engineering background

Baokang tunnel is located in Hubei province of China, which width is 14.02m and the height is 12.36m. It was excavated by three steps seven footwork method, and the lining thickness is 60cm. The extremely thin-layered structure (Figure 1a) makes the surrounding rock mass classification to be V. Since the compressive strength of the rock mass is smaller than 25MPa and maximum cumulative displacement is bigger than 300mm, therefore it is a kind of soft rock mass. It is very easy to collapse and become loose under the initial support by the redistribution of underground stress (Figure.1b). Meanwhile, this V grade surrounding rock mass could bring more pressure to the lining structure[13] If the lining support is not timely, the damaged rock will act on the lining structure in the form of loose pressure to cause a fracture to the lining structure. When the distance between the tunnel face and the lining was bigger than 200 m, obvious cracks appeared on the lining surface (Figure 2), which led to an instability risk state of the lining structure. Therefore, it was urgent to determine an optimal lining time of Baokang tunnel. To accomplish this, a numerical simulation method by the FLAC3D software was adopted. During the simulation analysis, a damage evaluation index of the layered rock mass was selected. Furthermore, the influence of loose rock on the lining under different stress release rates was analyzed. Finally, a reasonable lining time was determined and applied.

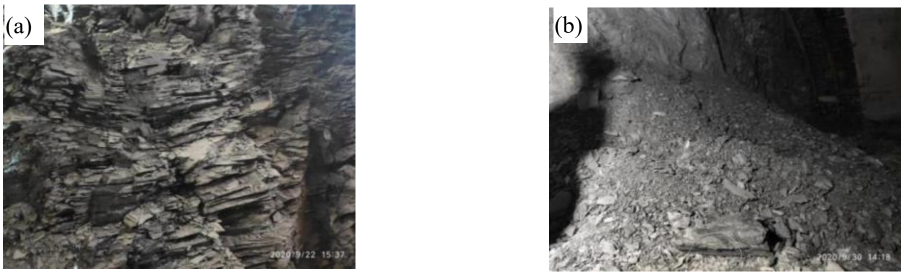

Figure 1. Structural characteristic and failure of the rock mass of Baokang Tunnel (a: thin-layered rock mass; b: Loose feature after collapse).

Figure 2. Cracking of the lining structure.

3. Evaluation damage index for thin rock mass

Since the yield state is not equal to the occurrence of damage, some indexes were proposed to simulate the damage of surrounding rock mass. Among them, the failure approach index (*FAI*) has been widely used due to its clear logic and ease of use[14-17] Furthermore, Xu et al.[18] proposed a failure proximity index considering the failure of the matrix and bedding plane of layered rock mass.

3.1. FAI for layered rock matrix

The *FAI* index of layered rock matrix FAI_m is defined as:

$$FAI_m = \begin{cases} \omega_m \quad , \quad 0 \le \omega_m < 1 \\ 1 + FD_m, \ \omega_m = 1 \ , FD_m \ge 0 \end{cases} \qquad (1)$$

where $\omega_{\rm m}$ is the matrix stress risk factor, $\omega_{\rm m} = 1 - YAI$, YAI is the yield approach index; FD_m is the failure degree: $FD_m^s = \bar{\gamma}_m^{ps} / \bar{\gamma}_{mr}^{ps}$, $FD_m^t = \bar{\gamma}_m^{pt} / \bar{\gamma}_{mr}^{pt}$; $FD_m = \max(FD_m^s, FD_m^t)$. $\bar{\gamma}_m^{ps}$ is the equivalent plastic shear strain of interlayered $\bar{\gamma}_{mr}^{ps}$ is the equivalent plastic shear strain limit corresponding to the initial point of the residue segment on the shear stress-strain curves of interlayered rock; $\bar{\gamma}_m^{pt}$ is the plastic volumetric tensile strain of interlayered rock; and $\bar{\gamma}_{mr}^{pt}$ is the equivalent plastic tensile strain limit corresponding to the initial point of the residue segment on the tensile stress-strain curves of interlayered rock.

The yield proximity *YAI* is the ratio of the distance from the most adverse stress path to the yield plane of a point in the state of spatial stress to the distance of the corresponding most stable reference point along the most adverse stress path to the yield plane in the same direction of Rhodes Angle (Figure 3):

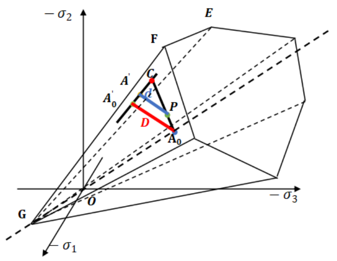

Figure 3. Relationship between stress point and yield surface in principal stress space.

The failure proximity of layered rock mass FAI_j is:

$$FAI_j = \begin{cases} \omega_j \quad , \qquad 0 \le \omega_j < 1 \\ 1 + FD_j, \ \ \omega_j = 1 \ , \ \ FD_j \ge 0 \end{cases} \qquad (2)$$

where $\omega_j = 1 - YAI_j^{\ s}$, YAI_j^s is the Shear failure yield proximity of bedding plane, FD_j is the failure degree of the layer: $FD_j^s = \bar{\gamma}_{jp}^{s} / \bar{\gamma}_{jp}^{sr}$, $FD_j^t = \bar{\gamma}_{jp}^{t} / \bar{\gamma}_{jp}^{tr}$; $FD_j = \max(FD_j^s, FD_j^t)$; $\bar{\gamma}_{jp}^{s}$ is the equivalent plastic shear strain on the bedding plane, $\bar{\gamma}_{jp}^{sr}$ is the equivalent plastic shear strain limit on the bedding plane; $\bar{\gamma}_{jp}^{t}$ is the plastic volumetric tensile strain on the bedding plane, $\bar{\gamma}_{jp}^{tr}$ is the plastic volumetric tensile strain limit on the bedding plane.

The yield proximity of bedding plane shear failure YAI_j can be deduced according to Figure 4:

$$YAI_j = \begin{cases} YAI_j^{\ s} \quad , \qquad l_j \ge d_j \\ l_j / d_j \cdot YAI_j^{\ s}, \quad\ l_j < d_j \end{cases} \qquad (3)$$

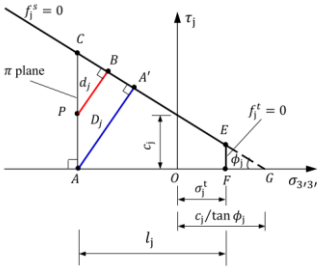

Figure 4. Composite failure criterion for bedding plane.

The failure of bedding and matrix of layered rock mass is the two main types of failure of layered rock mass. Since the rock mass is often damaged along its weakest place, the failure of bedding rock mass should be judged according to the combination of matrix and bedding. So, for FAI_m and FAI_j; The maximum value of the two was selected as the *FAI* value of layered rock mass.

When the *FAI* is applied to evaluate the stability of the surrounding rock: if 0≤*FAI*<1, the surrounding rock is at the state of elastic stress. The larger the FAI value is in this range, the closer it is to yield. If 1≤*FAI*<2, the surrounding rock is at the plastic yield state. if *FAI*≥2, the surrounding rock is at a failure state[14].

3.2. Reliability verification of the FAI

To simulate the excavation and support process of Baokang tunnel, a three-dimensional grid model was built in FLAC3D software (Figure 5). In the simulation, the supporting forms included grouting rock bolt, steel arch and sprayed concrete, which were simulated by cable, shell and beam structural unit, respectively[19] The final form of the support structure is shown in Figure 6.

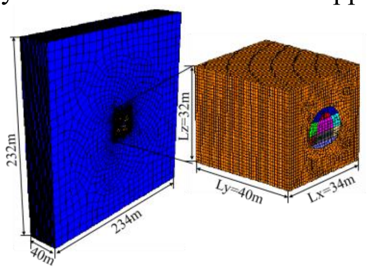

Figure 5. Three-dimensional grid model of Baokang tunnel.

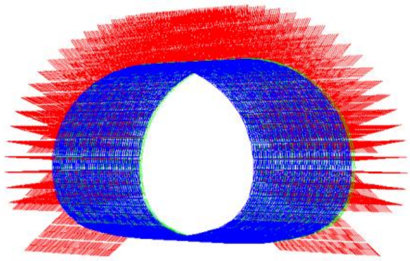

Figure 6. Three-dimensional initial supporting model of Baokang tunnel.

For simulating the layered rock mass in FLAC3D software, it is regarded as a composite material of matrix and bedding planes. Based on the linear Mohr-Coulomb criterion and the maximum tensile stress criterion, the mechanical models for matrix and bedding planes are established in the global coordinate system and local coordinate system, respectively. Then, they are synthesized to obtain an elastic-plastic model, the Aniso-soft model[20] for a layered rock mass, which considers strength and deformation with transverse isotropy. The model is essentially an equivalent continuum model with consideration of the strength and deformation anisotropy of layered rock mass. The specific geometric parameters (such as bedding plane strike and dip angle) and strength parameters (such as bedding plane cohesion and friction angel) can reflect the mechanical properties of the bedding plane. Moreover, there is no need to construct a contact interface or solid element in the grid model to simulate the properties of the bedding plane[21].The lining structure was simulated using solid units and the mechanical parameter values of the layered rock mass were taken as shown in Table 1.

Table 1. Mechanical parameters of rock mass.

E [a] (GPa)	ν [a]	c [b] (MPa)	φ [b] (°)	c_j [c] (MPa)	φ_j [c] (°)	ψ [d] (°)	ψ_j [d] (°)	σ^t [e] (MPa)	σ_j^t [e] (MPa)	dd [f]	dip [f]
1	0.3	4	32	1.8	10	12	8	1	0.1	290	70

[a] E is elasticity modulus, ν is poisson's ration.

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[b] c and φ are matrix cohesion and internal friction angle of matrix, respectively.
[c] c_j and φ_j are cohesion of layers and internal friction angle of layers, respectively.
[d] ψ and Ψ_j are matrix and bedding dilatancy angle, respectively.
[e] σ^t and σ_j^t are matrix and bedding tensile strength, respectively.
[f] *dd* is tendency, *dip* is bedding dip angle.

The distribution of the surrounding rock damage zone (FAI≥2) is shown in Figure 7. It can be seen that the surrounding rock damage zone has significant asymmetric characteristics, and the surrounding rock damage zone is mainly distributed in the left-side arch and the right-side wall. This is consistent with the failure positions of rock mass on site (Figure 8). Besides, the damage depth of the left arch and right-side wall is 3.8m and 2.1m respectively, which is close to the numerically calculated collapse depth (4m and 2m, respectively). Based on numerical simulation and field damage, the failure of layered rock mass of Baokang tunnel is caused by well-developed structural planes (i.e., bedding planes) of thin layered rock strata which yield rock mass of poor quality. For the left arch (Figure 9a), due to perpendicular stress relief, excavation can open the exposed bedding planes and convert them into thin rock plates. Since lateral loads are applied to these plates, they can be easily bent, buckled and fractured. Further, if micro-cracks in the open bedding planes intersect at obtuse angles, the thin rock plates tend to break into pieces. As a consequence, this rock mass can disintegrate and finally collapse under the gravity. For the right-side wall (Figure 9b), under the action of high tangential stress caused by stress redistribution, the wall may open and slide along the layer, which makes the rock plate loss stability. According to the above calculation and analysis, it shows that the constitutive model and parameters of the numerical simulation, especially the failure approach index can be used to calculate the failure rock mass which will act on the lining structure in the form of loose pressure.

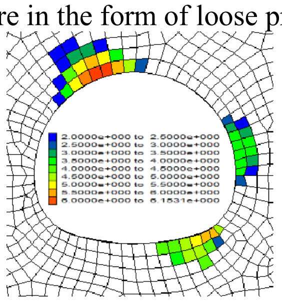

Figure 7. Distribution of failure zones of the rock mass.

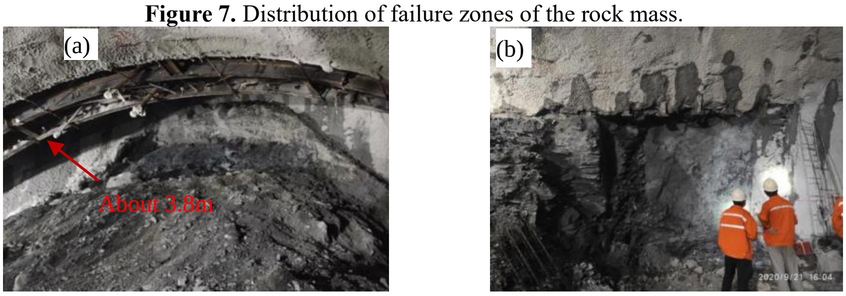

Figure 8. Actual collapses during tunnel excavation (a: collapse on the left arch; b: collapse on the right-side wall).

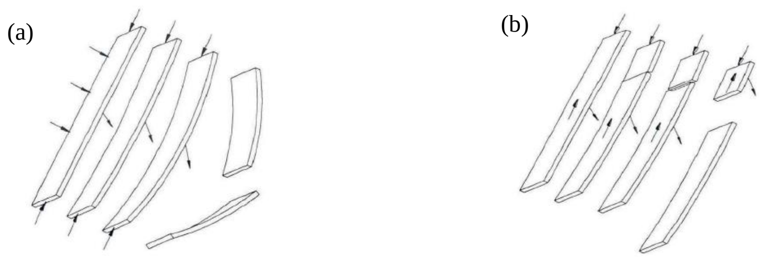

Figure 9. Failure mode of layered rock mass during tunnelling. (a: left-side arch; b: right-side wall).

4. Determination of lining time of Baokang tunnel

Tunnel excavation is accompanied by the stress release, and the stress release will redistribute the stress field which cause the failure of rock mass. Under the action of loose pressure, the fracture of lining corresponds to the critical stress release rate. Combined with the typical displacement monitoring results, the distance between lining support and the tunnel face can be calculated from the critical stress release rate, and finally a reasonable supporting time can be determined. Using the tunnel model and parameters in section 3.2, the stress release rate of the rock after excavation was set in increments of 10% from 10% to 100% to obtain the distribution of the damage zones of the layered rock mass. The damage state of the surrounding rock mass with stress release rates of 10%, 40%, 70% and 100% are shown in Figure 10.

In order to simulate the damage rock mass acting on the lining structure in the form of loose pressure, the elements of the rock mass which FAI are smaller than 2 were deleted in the upper part of the tunnel. Taking the stress release rate of 100% as an example, the result is shown in Figure 11.

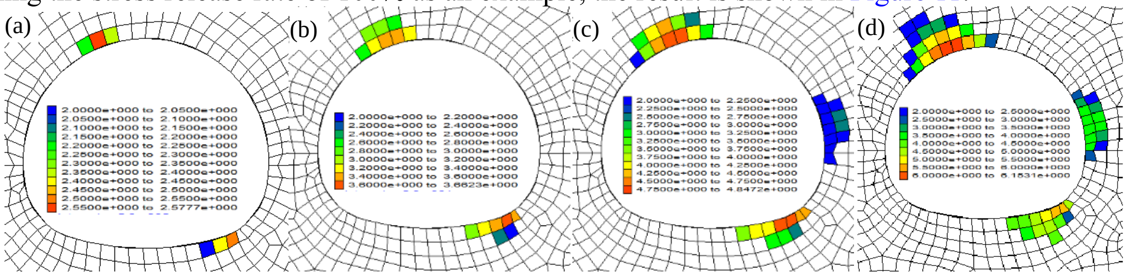

Figure 10. Distribution of damage zones in surrounding rock under different stress release rates (a: 10%; b: 40%; c: 70% d: 100%).

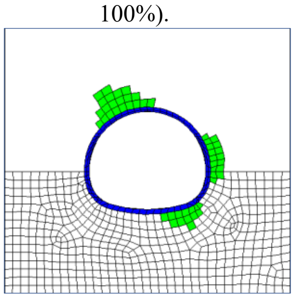

Figure 11. Equivalent treatment of loosening action of damage rock mass with a stress release rate of 100%.

Under the different stress release rates, the lining fracture distribution is shown in Figure 12. It can be seen that the lining is stable when the stress release rate is 10% to 70%. However, the fracture occurs on the left arch shoulder of the lining when the stress release rate is bigger than 80%. Therefore, lining support should be carried out before 80% stress release of the surrounding rock mass.

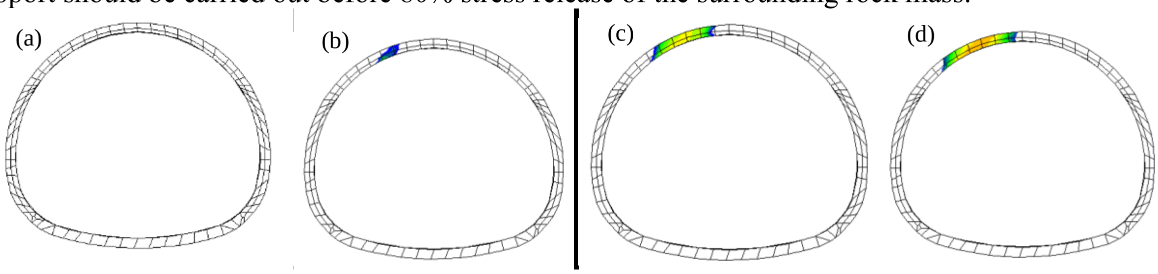

Figure 12. Failure of the lining under different stress release rates (a: 10%—70%; b: 80%; c: 90%; d: 100%).

From the displacement convergence curve of a typical monitoring section of the rock mass in Baokang tunnel (Figure 13), the deformation of the surrounding rock mass is long-lasting and highly susceptible to external environmental disturbances. The convergence time of the deformation at the first stage is about 20 days, and the displacement rate on the total deformation convergence is about 40%. Similarly, the convergence time of the deformation at the second stage is about 40 days, and the displacement rate on the total deformation convergence is about 80%. Related studies have shown that there is a positive correlation between the surrounding rock displacement and the rock stress release rate[22-23]. Since the lining is fractured when the stress release rate is 80%, the corresponding displacement rate of the surrounding rock mass is approximate 80%. Therefore, in order to ensure the lining stability, the distance between the lining and the tunnel face should be smaller than 120m according to the average excavation footage and time which is respectively 3m and 40 days.

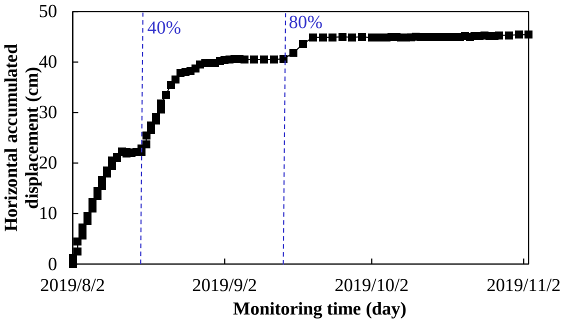

Figure 13. Displacement convergence curve of a typical monitoring section of Baokang tunnel.

According to the above analysis result, it is necessary to change the lining supporting time of the distance between the lining and the tunnel face of 200m to less than 120m. In fact, 100m has been adopted. In order to check the actual stable state of the lining structure, the stress of the key parts of the lining structure was tested by using the soil pressure box test. From Figure 14, it can be seen that the lining pressure converges quickly and there is no sudden increase in the lining force due to the loose rock mass effect. Besides, from construction feedback, there was no local cracking occurred in the lining structure during the later tunnel construction (Figure 15). From what has been discussed above, the reasonable lining support timing can effectively ensure the lining stability.

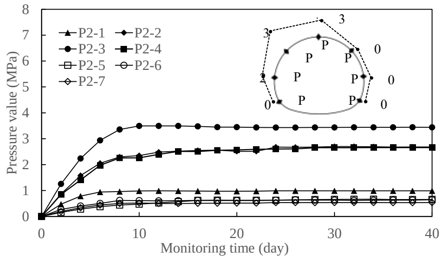

Figure 14. Pressure monitoring curve of lining key points.

Figure 15. Stable state of lining structure under the reasonable supporting time.

5. Conclusions

In this paper, a damage index was selected to evaluate the failure of layered rock mass in Baokang tunnel. Furthermore, the influence of the rock mass loose pressure on the lining structure was carried out by numerical simulation under different stress release rates. Finally, according to the critical stress release rate of the fractured rock mass and displacement monitoring curve, a reasonable lining supporting time was determined, and several conclusions are drawn from this study:

(1) The tunnel damage calculated by the index FAI was located on the left arch shoulder and the right-side wall. Meanwhile, the calculated failure depth is close to the actual failure depth of the rock mass, which shows that the numerical simulation results are consistent with the actual failure. The index FAI used in this paper can characterize transversal isotropic characteristics of the layered rock mass.

(2) According to the characteristics of the failure rock mass which is easy to be loosen in Baokang tunnel, the effect of this loose pressure must be considered for the stability of the lining. On this basis, the critical stress release rate of surrounding rock mass failure for lining failure was determined to be 80%.

(3) In terms of the distance between the lining and the tunnel face, the lining supporting time can be determined from the displacement rate which is corresponding to the critical stress release rate. For Baokang tunnel, the distance between the lining and the tunnel face should be smaller than 120m.

(4) Field monitoring and feedback show that the optimized lining supporting time can effectively

ensure the stability of the lining structure of Baokang tunnel. The research methods and ideas of this paper can provide reference for the determination of lining supporting time for a similar tunnel construction in layered soft rock mass.

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