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Tunnel Support Structure System and Its Synergy

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Abstract: The tunnel support system is composed of lining, bolt, and steel frame. It is of great significance to effectively control the deformation of the surrounding rock of the tunnel, make full use of the characteristics of different support methods, and formulate an economical and effective support plan to ensure the safe operation of the tunnel structure. This paper clarifies the synergistic relationship between the support structure and the surrounding rock based on their fundamental characteristics and functions. Various support structures and components are also discussed in this paper. Additionally, the paper presents an optimized design of the tunnel support structure system.
Keywords: Tunnel engineering; Support structure system; Synergy; Support structure design

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1. Introduction

Based on the understanding of the surrounding rock structure and load effect, many scholars at home and abroad have expounded the basic functions of the support structure and formed various tunnel design theories and methods[1]. Tunnel design theory is out of touch with engineering practice, and the schemes and parameters of advance support, bolt support and initial support are mainly determined by engineering experience. Therefore, it is necessary and urgent to study the synergy between surrounding rock and supporting structures.

2. Analysis of supporting structure

2.1. Tunnel support structure system

It is the basic problem of tunnel engineering design to make the surrounding rock form a new stable state as soon as possible without instability and damage. Support structures such as advance support, primary support and secondary lining should be adopted.

2.2. Lining support

Domestic and foreign experts generally regard the tunnel surrounding rock as a continuum, and the study the tunnel support system is usually studied using the elastoplasticity theory. So far, great progress has been made in the research of stress field, displacement field, and constitutive equation. The basic assumptions of this study are described below.

(i) The surface of the surrounding rock is flat

(ii) The rock fragmentation structure is rigid

(iii) The strength or damage of the rock mass itself is not considered

(iv) The movement of the surrounding rock along the structural plane of the stratum is referred to as the instability of the surrounding rock.

According to the key block theory (as shown in Figure 1), the surrounding rock is categorized into different types of blocks based on the spatial structure plane under normal conditions. After the excavation and unloading of the tunnel, some blocks lose their natural balance, resulting in the instability of the surrounding rock and even partial collapse.

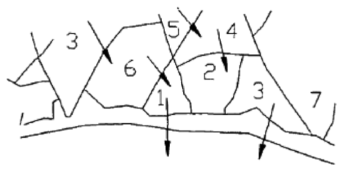

Figure 1 Conceptual diagram of "key block"

During this process, the first block that breaks the balance is the critical block, while the others are divided into stable blocks, static blocks, and potentially critical blocks. The reinforcement position of the key block is determined by analyzing the stability of the tunnel´s surrounding rock, thus effectively controlling the displacement of the entire slack zone of the tunnel[2].

The model is shown in Figure 2. Under the action of *in-situ* stress load q (MPa), the lining thickness t (mm) and inner diameter r (mm). As the thickness of the lining increases, the stress on it decreases, and the safety factor increases, resulting in better support under the action of ground stress.

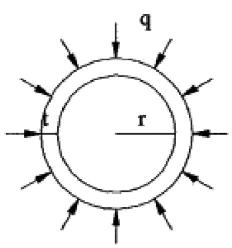

Figure 2 Circular lining model

The maximum thickness of the lining support can be set to t_g(mm), regardless of its own weight. The conditions for the lining under this model to produce non-destructive support effects are as follows:

Arrangement based on stress inequality:

$$(\sigma_s - 2q)t^2 + 2r(\sigma_s - 2q)t - 2r2q > 0$$

The discriminant of the quadratic equation $(\sigma_s - 2q)t^2 + 2r(\sigma_s - 2q)t - 2r2q = 0$ about t is $\triangle = 4r^2 \sigma_s (\sigma_s - 2q)$.

When $\triangle > 0$, that is, when $\sigma_s > 2q$, the equation has two roots set as t_1 and t_2, and $t_1 < t_2$. Assumming that $(\sigma_s - 2q)t^2 + 2r(\sigma_s - 2q)t - 2r^2q$, then the approximate image is shown in Figure 3.

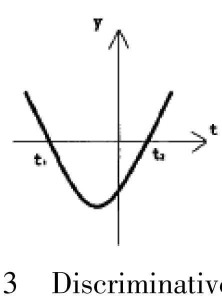

Figure 3 Discriminative image

When $\triangle \leqslant 0$, the stress inequality has no solution.

Under the assumption that the lining´s thickness is not affected by its own weight, the study examines the relationship between the stress in the safety zone and the lining thickness under the joint action of internal force and gravity. The lining arc illustrated in Figure 2 is divided into four parts.

As shown in Figure 4, the self-weight direction is vertically downward. In the simplified model, it is assumed that the self-weight direction of the overlying arch is the same as the direction of the ground stress, and the direction is located at the center of the circle.

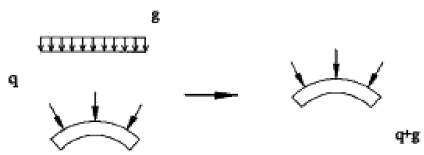

Figure 4 Upper lining arc

As depicted in Figure 5, the self-weight direction is vertically downward. The simplified model assumes that the self-weight directions of the left and right lining arches are perpendicular to the direction of φσ and have no impact on it.

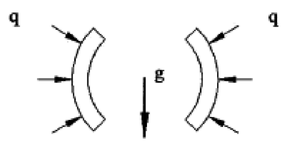

Figure 5 The central lining arc

As shown in Figure 6, the self-weight direction is vertically downward. According to the simplified model, the previous conclusions still apply to the case where the self-weight of the arch bottom lining is opposite to the direction of the ground stress. In this scenario, relative to the previous load (q), it becomes q-g, pointing to the center of the circle.

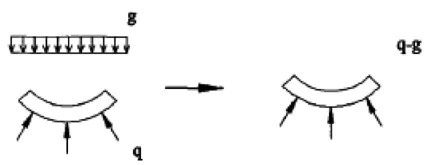

Figure 6 The lower part of the lining through the arc

2. 3. Bolt support

The classic anchor theory has gone through three stages of development.

(i) Suspension theory

The bolt works by compressing the loose rock mass at the top of the tunnel wall against the dense surrounding rock above. This prevents the loose surrounding rock from falling off, thereby preventing layer separation at the tunnel' s roof.

(ii) Composite beam theory

Similar to the suspension theory, the composite beam theory also believes that the surrounding rock of the tunnel roof is a layered rock formation. The difference is that the composite beam theory regards the junction point between the side wall and the top of the tunnel as the fulcrum, and the rock load on its upper part us supported by the rock beam. Each rock formation in the composite beam maintains coordinated deformation through the connection of anchor rods, which improves the bending resistance and reduces the deflection[3].

(iii) Reinforced arch theory

The reinforced arch theory holds that the anchor rod has a radial extrusion effect on the rock mass. After the internal stress of the top rock formation is stabilized, a fan-shaped compressed anchorage area will be formed on both sides of the anchor rod. With a suitable distance between adjacent anchor rods, the anchorage areas of a single bolt can be superimposed on each other, forming a compression zone with uniform thickness in the loose area, improving the stress state of the rock formation and effectively controlling its displacement.

2.4. Steel frame

From a construction standpoint, it is crucial to promptly install the steel frame and maximize the contact area between the steel frame and the tunnel; the gap between the steel frame and the tunnel wall rock mass should be filled and wrapped to create an integrated force-bearing system between the steel frame and the lining[1].

3. Support structure synergy

3.1. Mechanism of supporting structure synergy

Support structures that are highly rigid can bear a relatively large pressure without deforming severely. When the lining and the bolt are supported at the same time, the bolt stiffness (K_m) is greater than the lining stiffness (K_c), and combined stiffness K_z is greater than or equal to any one of K_c and K_m. When relying on a single structure, in terms of the deformation of the loose surrounding rock when the supporting structure yields, the deformation of the surrounding rock in the loose area when the anchor rod is bent is u_1, and the deformation of the surrounding rock in the loose area when the lining reaches its yield point is u_2, with $u_2 > u_1$.

3.2. Theoretical analysis of synergy mechanism

The stiffness of the bolt in the loose area is greater than that of the lining, so the bolt plays its role first in the shotcrete + bolt combined support system, and the initial support plays a leading role in controlling the deformation of the rock mass. When the bolt cannot completely restrain the displacement of the rock mass, the lining plays a leading role in controlling the deformation of the surrounding rock[2].

3.3. Numerical analysis of synergy mechanism

After two composite bolts were installed in the horseshoe-shaped tunnel, the numerical calculation was carried out. A monitoring point was set up on the tunnel wall every 2000 steps. The stress value of the anchor bolt and the lining were measured, and the synergistic effect of the lining support, prestressed anchor bolt, and non-prestressed anchor bolt support (alternate arrangement) was observed[5]. The numerical simulation parameters are shown in Table 1.

(i) The constitutive model of the tunnel surrounding rock adopted the Drucker-Prager (D-P) criterion; the tunnel lining structure was simulated using elastic isotropic materials[3].

(ii) The bolt was simulated by the rod unit, and the advanced support (pipe shed, small conduit, grouting, etc.) was simulated by increasing the stiffness of the iso-layer around the tunnel[4].

(iii) The house was simulated with linear elastic material and solid elements.

Table 1 Numerical simulation of synergy between lining support and bolt support

Step	2000	4000	6000	8000	16000	24000	32000	40000	44000	48000	Convergence
Axial force of anchor rod 1/KN	263. 3	397. 9	571. 2	520							
Lining 1 stress/Mpa	2. 311	2. 285	2. 279	2. 485	2. 589	2. 643	2. 711	2. 744	2. 747	2. 953	2. 982
Anchor 2 axial force/KN	54. 94	55. 38	79. 18	173. 7	274. 6	293. 9	323. 4	351. 8	354. 3	341. 4	
Lining 2 stress/Mpa	1. 274	2. 018	2. 041	2. 439	2. 446	2. 588	2. 618	2. 666	2. 661	2. 897	2. 925

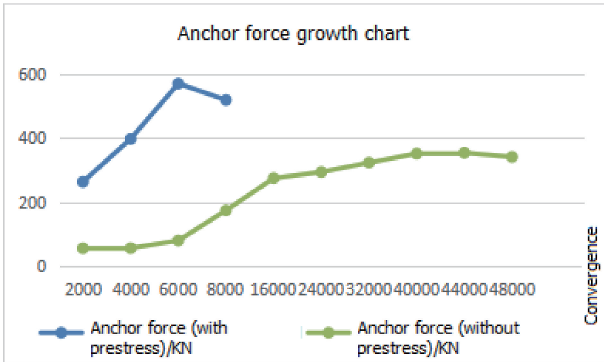

Figure 7 Anchor force growth chart

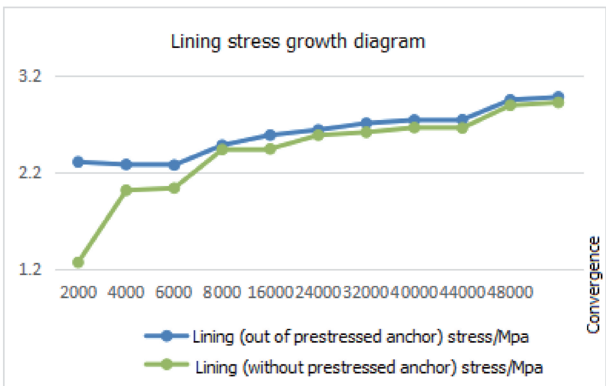

Figure 8 Lining stress growth diagram

Through an analysis of the data in Figures 7 and 8, it was found that the overall trend of the synergy between the lining and the anchor remained unchanged, and the anchor played a major role before the lining[6], but the prestressed anchor fails to yield before the ordinary anchor that is passively stressed due to active stress. The axial force of the plain anchor (without prestress) increased significantly when it failed. After all the anchors failed, the lining stress at the corresponding position increased[7].

4. Conclusion

In this paper, the new Austrian method was used to simulate the excavation process, and the supporting mechanism of the lining, bolt and steel frame was theoretically analyzed. Based on the numerical simulation and calculation, the characteristics of the interaction between the surrounding rock deformation and the supporting structure were analyzed, and the conclusions are as follows:

(i) If the support is not applied in time during the excavation process, the tunnel deformation becomes significant, and numerical simulation indicated that the calculation failed to converge. Excavation or distributed excavation with insufficient support will cause the tunnel to collapse.

(ii) The basic function of bolt anchorage is to limit the displacement of the rock layer by stimulating the self-stability of the rock mass. The bolts should be installed in time during the excavation of the tunnel, so that the horizontal displacement can be better controlled.

(iii) There is a synergistic effect after the lining support and bolt support are applied together. The stiffness of the bolt support structure is greater than that of the lining support structure. In the initial stage, the bolt plays the main supporting role before the lining, but when the bolts fail, the role of the lining supporting structure increases.

(iv) When the vertical displacement of the lining support is not ideal and the lining and bolts fail to limit the deformation of the surrounding rock, steel frame can be installed.

(v) Steel frames demonstrate better displacement control in the horizontal direction compared to the vertical direction. Moreover, a steel frame is more efficient in providing rapid stabilization compared to the lining and anchors. The steel frame support can rapidly improve the tunnel displacement. Therefore, steel frame support works well with lining and bolt support to improve the rigidity of the support system.

Disclosure statement

The authors declare no conflict of interest.

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