Stability control measures of soft and broken surrounding rocks of super-large section tunnel constructed using benching tunneling method

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Abstract. The tunnel face of the super-large section tunnel constructed using benching tunneling method tends to lose stability in the stratum with very poor surrounding rock grade (grade V). Therefore it is necessary to employ advanced support or optimize bench construction parameters to improve the stability of tunnel construction. In order to determine the stability control measures for the super-large section tunnel constructed using benching tunneling method in soft and broken surrounding rock, a three-dimensional elastoplastic model is established. Taking the extrusion displacement of tunnel face and the failure zone of surrounding rock as indices, the influences of bench height, bench length, circulating footage and other construction parameters and the construction of advanced large pipe shed on tunnel stability were analyzed. The calculation results show that when the tunnel is constructed using benching tunneling method, the surrounding rock within 4.5m in front of the tunnel face and 1.5m above the arch collapses, and the failure develops from the arch top down to the arch foot. The measures such as shortening the circulating footage, shortening the length of the bench and reducing the height of the upper bench have little effect on the stability of the tunnel, and the maximum difference among the strength reduction coefficients of the surrounding rock is 0.1 when the tunnel losses stability. The advanced large pipe shed can significantly improve the stability of benching tunneling method construction. The deformation and failure of the tunnel mainly concentrates in the side wall area, which gradually develops from the arch foot to the wall foot, and the depth of the surrounding rock failure zone is very limited.

Keywords: Tunnel with super-large section, stability control measures, numerical analysis, benching tunneling method, soft and broken surrounding rock

1. Introduction
Tunnel face instability often occurs in the benching tunneling method construction of super-large section tunnel in soft and broken surrounding rock stratum [1]. The extrusion deformation of tunnel face is the key point of tunnel stability control [2]. The main measures to control the extrusion deformation of
tunnel face include adopting advanced support and optimizing the construction parameters of bench. The commonly used advanced support methods in China include advanced bolt and small pipe grouting, and advanced large pipe shed. However, the grouting length of advanced bolt and advanced small pipe is generally 3-5m. For the surrounding rock with poor self-stability, the front ends of bolt and pipe are still in the slip plane, so their applicability is restricted. The advanced large pipe shed extends the steel pipe and slurry solid into the undisturbed rock after passing to the failure zone of disturbed soft broken surrounding rock, and the support length is about 15-25m, which can effectively prevent the collapse of surrounding rock and has high applicability for super-large section tunnel in soft and broken surrounding rock [3]. The main measures to optimize the bench construction parameters include reducing the bench height, shortening the bench length, reducing the circulating footage, etc. At present, the construction of super-large section tunnel in soft and broken surrounding rock stratum by benching tunneling method is still in the stage of exploration and research [4]. There is no systematic and in-depth research on the effect of benching tunneling method construction parameters and advanced large pipe shed on the stability of tunnel construction, which leads to the lack of basis for the design of benching tunneling method construction parameters and the selection of advanced support measures. It is difficult to ensure the technical rationality and economy of the construction scheme. Therefore, the strength reduction method [5] is adopted to establish the numerical model of benching tunneling method for super-large section tunnel in soft and broken surrounding rock. By comparing the extrusion deformation of tunnel face with different bench heights, bench lengths and circulating footage, and analyzing the deformation and failure law of tunnel surrounding rock with advanced large pipe shed, the influence of construction parameters of benching tunneling method and advanced large pipe shed on tunnel construction stability is analyzed. It can provide references for the design of benching tunneling method construction parameters and the selection of advanced support measures of super-large section tunnel in soft and broken surrounding rock.

2. Analysis scheme

2.1. Calculation model

A three-dimensional model was established for calculation. The section of the tunnel is a three-lane with three-center circular curved side wall, with a clear width of 13.75m, a clear height of 5.0m, and a buried depth of 90m. In order to reduce the influence of the model boundary effect, the distance between the left and right boundary of the model and the center line of the tunnel is about 4 times the tunnel diameter, and the distance between the bottom boundary and the bottom of the tunnel is 4 times the tunnel height. The positive direction of the surrounding rock model in the other range is the tunnel excavation direction, the vertical upward direction is the positive direction of the Z axis, and the right direction of the tunnel excavation cross section is the positive direction of the x axis. The model length×width×height=140m×50m×162m. The model is excavated by the benching tunneling method. The initial support is C20 sprayed concrete + I22b steel frame + steel mesh, and the support thickness is 29cm. The model grid is shown in Figure 1.

![Figure 1. The grid of the model](image-url)
2.2. Calculation parameters
The calculation model only considers the effect of initial support. The surrounding rock, advanced pipe shed and initial support are made of the ideal isotropic elastic-plastic materials in Mohr-Coulomb, which are all simulated by solid element. The initial support strength is considered by the strength equivalent method. The cohesion and friction angle of the initial support and the maximum compressive strength and maximum tensile strength of the initial supporting concrete are drawn by drawing a Mohr circle to find the common tangent; the advanced large pipe shed is φ108mm, the reinforcement length is 30m, and the elastic modulus is calculated by stiffness equivalent method.

\[ EA = E_1A_1 + E_2A_2 \]  

Where \( E \) is equivalent elastic modulus, \( A \) is the effective area of element entity; \( E_1 \) is the elastic modulus of concrete, \( A_1 \) is the concrete area; \( E_2 \) is the elastic modulus of the pipe shed steel pipe, \( A_2 \) is the pipe shed area.

According to the relevant recommended parameters of highway tunnel design specification, the values of calculation parameters of surrounding rock (considered as grade IV) and supporting structure in the numerical model are shown in Table 1.

| Materials                  | Density (kg/m³) | Elasticity modulus (GPa) | Poisson's ratio | Cohesive force (MPa) | Friction angle (°) |
|----------------------------|-----------------|--------------------------|-----------------|----------------------|-------------------|
| Surrounding rock           | 23              | 6.0                      | 0.25            | 0.10                 | 39                |
| Initial support            | 26              | 31.4                     | 0.2             | 2.27                 | 53                |
| Advanced large pipe shed   | 25              | 20                       | 0.28            | 1.0                  | 40                |

2.3. Calculation of working conditions
Firstly, the strength reduction method is used to reduce the strength parameters \( c \) and \( \phi \) of surrounding rock (with the grade of the surrounding rock from good to bad, the reduction coefficient is gradually increased from 1.1 at 0.1 intervals until the surrounding rock becomes unstable), and the reduction formula is as follows:

\[ c' = \frac{c}{\omega} \quad \phi' = \arctan \left( \frac{\tan \phi}{\omega} \right) \]  

Where \( c \) and \( \phi \) is the cohesion and friction angle before strength reduction of surrounding rock, \( \omega \) is the strength reduction coefficient, and \( c' \) and \( \phi' \) is the cohesion and friction angle after strength reduction of surrounding rock, respectively.

① Based on the strength reduction coefficient of surrounding rock when the tunnel is unstable and close to instability, the calculation results of numerical models when circulating footage \( S \) is 0.5m, 1.0m, 1.5m (bench length 6.0m, bench height 6.0m), bench length \( L \) is 4.0m, 6.0m, 8.0m (circulating footage 1.0m, bench height 6.0m), and bench height \( H \) is 4.0m, 5.0m, 6.0m (circulating footage 1.0m, bench length 6.0m) are compared and analyzed. The calculation models of different bench lengths and bench heights are shown in Figure 2.

② Based on the strength reduction coefficient of surrounding rock when the tunnel is unstable, the deformation and failure law of surrounding rock with advanced large pipe shed is analyzed.
2.4. Construction steps

The specific construction steps of the calculation models are as follows:

1. Excavate the upper bench, the excavation height of the upper bench is $H$ and the excavation footage is $S$;
2. Construct the initial support of the upper bench by length of $S$ behind the tunnel face $S$;
3. Excavate the lower bench with the excavation length of $L$, and the excavation footage is the same as that of the upper bench;
4. Construct initial support of the lower bench by length of $S$ behind the tunnel face $S$;
5. Excavate the invert. The invert is behind 12m from lower bench. The length of excavation at one time is 6m;
6. Construct the initial support for the invert, ibid.

3. The influence of bench design parameters

From the calculation results, it can be seen that the strength reduction coefficients of surrounding rock have little change (3.7-3.8) when the benching tunneling method construction parameters change and the tunnel is unstable, and the deformation and failure law of tunnel surrounding rock is basically the same. Therefore, taking the model in which bench height is 6m, circulating footage is 1m and bench length is 6m as an example, the deformation and failure process of tunnel surrounding rock by benching tunneling method construction is described in detail. For the influence of construction parameters such as circulating footage, bench length and bench height, the extrusion displacement of tunnel face and the corresponding strength reduction coefficient of surrounding rock are analyzed.

3.1. Instability and failure law of surrounding rock

When the strength reduction coefficient of surrounding rock is 3.8, the extrusion displacement of tunnel face is 590 mm (losing stability at S29). In order to analyze the failure process of surrounding rock, the maximum shear strain and tensile strain greater than 0.2 are taken as the failure threshold, that is, when the shear strain and tensile strain are greater than 0.2, the material is considered to have shear sliding crack and tensile crack failure. Figure 4 shows the longitudinal section of the changes in the surrounding rock failure zone at construction steps S22, S23, S24, S27, S28, and S29.
It can be seen from Figure 4 that in the process of tunnel excavation (before S28), surrounding rock at the arch of the supported section in a certain range behind the tunnel face has been damaged, but the tunnel is still stable due to the effect of the supporting structure. At S29, large-scale damage at the surrounding rock of the tunnel face causes the tunnel to lose stability. The damage range is about 4.5m in front of the tunnel face and 1.5m above the vault.

In order to further analyze the development law of the surrounding rock failure zone in the section, the cross-section changes of the surrounding rock failure zone at Y=28m and Y=29m are extracted, as shown in Figure 5.

As can be seen from Figure 5:

1. In the process of tunnel excavation, the damage pattern of surrounding rock is from vault to arch hance to arch foot and to side wall.

2. Before the excavation section arrives, the upper surrounding rock of the face has been partially (28m section) or largely damaged (29m section). After excavation, the surrounding rock at the arch has been damaged. As the excavation surface advances, the damage area of the supporting section of the upper bench is gradually enlarged.

3.2. Influence of circulating footage

See Table 2 for the extrusion displacements of tunnel face when the circulating footage is 0.5m, 1.0m and 1.5m, with different strength reduction coefficients of surrounding rock.

| Reduction coefficient | Circulating footage |   |   |
|-----------------------|---------------------|---|---|
|                       | 0.5m                | 1.0m | 1.5m |
| 3.6                   | 288                 | 305  | 410  |
| 3.7                   | 400                 | 443  | |
| 3.8                   |                     |      |      |

From table 2, it can be seen that:
(1) When the tunnel face is stable (the strength reduction coefficient of surrounding rock is 3.6), the tunnel face has serious extrusion deformation, and the reduction range of the extrusion deformation is small by shortening the circulating footage in benching tunneling method. For example, if the circulating footage is 1.0~0.5m, the longitudinal extrusion deformation of the tunnel face is 305-288mm (when the circulating footage is 1.5m, the tunnel is close to instability (the strength reduction coefficient of surrounding rock is 3.7), and the tunnel face has large plastic deformation. Thus the extrusion deformation is not considered in the analysis).

(2) When the grade of surrounding rock becomes further worse (the strength reduction coefficient of surrounding rock is 3.7~3.8) and the tunnel face is unstable, the adjustment of circulating footage in benching tunneling method has little influence on the stability of the tunnel. The tunnel is unstable when the circulating footage is 0.5m and 1.0m and the strength reduction coefficient of surrounding rock is 3.8. When the instability occurs, the calculation steps of construction are 57 and 29 respectively; When the circulating footage is 1.5m, the instability occurs when the strength reduction coefficient of surrounding rock is 3.7, and the construction calculation steps are 26 at that time.

3.3. Influence of bench length

When the bench length is 4.0m, 6.0m and 8.0m, the extrusion displacements of tunnel face are shown in Table 3.

Table 3. Maximum displacement and instability of tunnel face with different bench lengths

| Reduction coefficient | Bench lengths |
|-----------------------|---------------|
|                       | 4.0m | 6.0m | 8.0m |
| 3.6                   | 271   | 305   | 342   |
| 3.7                   | 367   | 381   |       |
| 3.8                   |       |       |       |

According to Table 3:

(1) When the tunnel face is stable (the strength reduction coefficient of surrounding rock is 3.6), serious extrusion deformation occurs on the tunnel face, and the longer the bench length is, the greater the extrusion deformation is. When the step length changes from 4.0m to 8.0m, the corresponding extrusion deformation changes from 271mm to 342mm.

(2) When the grade of surrounding rock further becomes worse (the strength reduction coefficient of surrounding rock is 3.7~3.8), the longer the bench length is, the easier instability occurs. The tunnel face with the bench length of 8.0m is unstable when the strength reduction coefficient is 3.7m, and tunnel faces with the bench length of 6.0m (S29) and 4.0m (S33) are unstable when the strength reduction coefficient is 3.8.

3.4. Influence of bench height

When the bench height is 4.0m, 5.0m and 6.0m, the extrusion displacements of tunnel face are shown in Table 4.
Table 4. Displacement and instability of tunnel face with different bench heights

| Reduction coefficient | Bench heights |
|-----------------------|---------------|
|                       | 4.0m | 5.0m | 6.0m |
| 3.7                   | 283   | 300  | 381  |
| 3.8                   | S35   | S35  | S29  |

According to Table 4:
(1) When the tunnel face is stable (the strength reduction coefficient of surrounding rock is 3.7), the higher the bench height is, the greater the extrusion deformation of tunnel face is. For example, when the bench height changes from 4.0m to 6.0m, the longitudinal extrusion deformation changes from 283mm to 381mm.
(2) When the grade of surrounding rock further becomes worse (the strength reduction coefficient of surrounding rock is 3.8), the tunnel face is unstable, and the adjustment of bench height cannot significantly improve the stability of tunnel face. The tunnel faces with the bench height of 4.0m (S35), 6.0m (S35) and 8.0m (S39) are unstable when the strength reduction coefficient of surrounding rock is 3.8.

4. Analysis on supporting effect of advanced large pipe shed
The calculation results show that when the strength reduction coefficient of surrounding rock is 3.8, the surrounding rock is stable when the benching tunneling method and advanced large pipe shed construction are adopted, and the maximum displacement of tunnel face is 168mm. Select Y=25m as the research section, and draw the curve of total displacement of monitoring points at key positions of tunnel excavation profile with excavation, as shown in Figure 6.

![Figure 6. Curve of total displacement of key positions of tunnel excavation profile with excavation](image)

As can be seen from Figure 6:
(1) The displacement of each monitoring point gradually increases with the excavation and the deformation gradually develops from arch foot to wall foot. The amount of deformation at arch foot,
side wall, the foot of the wall, arch hance and vault decreases in sequence, while the total displacement is 181.2mm, 175.0mm, 146.5mm, 133.3mm and 127.4mm respectively.

(2) The deformation proportion of the key positions around the tunnel is relatively uniform in each stage. In the advanced deformation stage (before upper bench excavation, 1-24 steps), the total displacement of the surrounding rock at the vault (T5), arch hance (T4), arch foot (T3), side wall (T2), and wall foot (T1) is 50.8mm, 53.1mm, 71.0mm, 51.6mm, and 42.4mm, accounting for 28.9%, 29.5%, 39.2%, 39.9%, and 29.9% of the total displacement; in the upper bench excavation stage (before lower bench excavation, 25-31 steps), the total displacement of the surrounding rock at the vault (T5), arch hance (T4), arch foot (T3), side wall (T2) and wall foot (T1) is 34.9mm, 37.6mm, 59.0mm, 65.7mm and 40.6mm respectively, accounting for 27.4%, 28.2%, 32.6%, 37.5% and 27.7% of the total displacement; in the lower bench excavation stage (26-35 steps), the total displacement of the surrounding rock at the vault (T5), arch hance (T4), arch foot(T3), side wall(T2) and wall foot (T1) is 41.7mm, 42.6mm, 51.2mm, 57.7mm, 63.5mm respectively, accounting for 32.8%, 32.0%, 28.3%, 33.0%, 43.4% of the total displacement.

In order to analyze the process of surrounding rock failure, the cross-section of surrounding rock failure zone with typical construction steps such as S24, S25, S29, S30 and S31 is extracted, as shown in Figure 7.

![Figure 7. Development of surrounding rock failure zone with typical construction steps](image)

As can be seen from Figure 7:

(1) In the whole process of excavation, due to the role of the advanced large pipe shed, the surrounding rock failure zone of the tunnel arch is very small. With the advance of the excavation face, the surrounding rock failure zone mainly develops in the area below the arch.

(2) In the process of cross-section excavation (upper bench and lower bench excavation), the surrounding rock failure zones mainly concentrate in the small depth range of the side wall area, and the failure usually develops from arch foot to side wall to wall foot.

5. Conclusions

This paper analyzed the stability of benching tunneling method construction with various surrounding rock strength reduction coefficients with numerical calculation method, and the main conclusions can be drawn from this paper.

(1) In the benching tunneling method construction of super-large section of soft and broken surrounding rock, the tunnel face is prone to large-scale failure when the surrounding rock grade is very poor. The failure zone of surrounding rock extends from vault to arch hance to arch foot, and the failure zone is about 1.5m above the arch and 4.5m in front of the tunnel face.

(2) When the benching tunneling method is used in the poor surrounding rock stratum, the optimization of the benching tunneling method construction parameters by shortening circulating footage, shortening bench length and reducing the height of upper bench has little effect on improving tunnel stability. The maximum difference between the strength reduction coefficients of the surrounding rock is 0.1 when the tunnel is unstable, and the surrounding rock of the tunnel face will still have large extrusion deformation and eventually lose stability.

(3) Under the pre-support of advanced large pipe shed, the stability of benching tunneling method construction in poor surrounding rock stratum is significantly improved and the tunnel face of upper
bench is hardly extruded by arch surrounding rock. The surrounding rock deformation around the tunnel face mainly concentrates in the side wall area, which gradually develops from the arch foot to the wall foot. The amount of deformation at arch foot, arch hance, side wall, vault and the foot of the wall decreases in sequence. The corresponding surrounding rock failure zone also develops from the arch foot to the wall foot area, with a failure zone with small depth.

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