# Deformation Analysis of Deep Buried Soft Rock Tunnel and Adaptive Control Measure of TBM Construction

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**Abstract.** This study focuses on the deformation mechanism of deep buried soft rock tunnel and adaptive prevention and control measures for TBM construction. For the case of large deformation in deep buried soft rock tunnel, the maximum resistance of support measures such as steel arches, anchor rods, and shotcrete is determined based on the support plan. Based on the determination of surrounding rock types, deformation monitoring data, and support resistance, the convergence constraint method is used to theoretically invert the mechanical parameters of deep buried soft rock, and combined with relevant standard parameter values for verification, reasonable mechanical parameters for deep buried soft rock are obtained. Based on the finite element method, open TBM excavation simulation is conducted for tunnel, and the mechanical response of surrounding rock is studied. The reasons for support structure failure are analyzed, and adaptive prevention and control measures for soft rock deformation are studied.

**Keywords:** Deep Buried Tunnel · Soft Rock · Deformation Analysis · TBM · Control Measure

## 1 Introduction

With the advancement of national water network and transportation power construction, China has become the country with the highest demand and difficulty in tunnel construction in the world [1]. A large number of water diversion tunnels with burial depths of more than 1,000 m and lengths of tens of kilometres have been planned and constructed in China. In the central Yunnan water diversion project, the length of the tunnel reaches 611.99 km, and the maximum burial depth reaches 1450 m [2]. The total length of the Hanjiang to Weihe river water diversion tunnel is 98.26 km, with a maximum burial depth of 2012 m [3]. In the construction of the water diversion project from Three Gorges reservoir to Hanjiang river, the total length of the water diversion tunnel is 194.8 km, and the maximum depth of the tunnel is 1,182 m [4]. Deep buried long tunnels are playing an increasingly important role in major infrastructure projects in China.

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Deep buried long tunnels are subject to alignment constraints, and most of them have to pass through mountainous areas with complex geological and tectonic backgrounds, and face a lot of engineering geological problems such as high ground stress, rock burst, and large deformation of the soft rock, etc., which are extremely risky for engineering construction. Among them, there are more and more engineering examples of large deformation tunnels with soft surrounding rockmass extruded under high ground stress, which seriously restrict the progress of the tunnel construction. During the construction process of the soft rock tunnel section, due to the weak self bearing capacity of the surrounding rock and the short self stabilization time, the surrounding rock during the stress adjustment stage after excavation exhibits characteristics such as fast deformation speed, large deformation amount, and long duration, resulting in a large total deformation amount and a high force on the support structure. In severe cases, it can lead to support failure [5].

In order to study the deformation mechanism of deep buried soft rock, predict the magnitude of soft rock tunnel deformation, and study the adaptive prevention and control measures of TBM construction, a theoretical inversion of mechanical parameters of deep buried soft rock is conducted based on the convergence-confinement method. Then reasonable mechanical parameter values of deep buried soft rock are obtained. Based on the finite element method, the simulation of the tunnel excavation with open TBM is carried out, and the mechanical response of surrounding rock and the magnitude of deep buried soft rock deformation are studied. Through analysis of the causes of support structure failure, study on adaptive prevention and control measures for soft rock tunnel deformation is carried out.

## 2 Theoretical Inversion of Mechanical Parameters for Deep Buried Soft Rock Tunnel

### 2.1 Theoretical Inversion Principles Based on the Convergence-Confinement Method

The Convergence-Confinement method is a theory and method that applies elastic-plastic theory and rock mechanics to underground engineering to explain the interaction between surrounding rock and support. Its principle is shown in Fig. 1. The pressure of surrounding rock decreases with the increase of deformation of the tunnel, and the surrounding rock has been deformed to a certain extent when support measures are taken.

The elastic-plastic analysis method for the deformation and pressure of surrounding rocks in circular tunnels is first proposed by Fenner [6], and then improved by Kastner [7]. The classical pressure theory and bulk pressure theory cannot effectively describe the mechanical behavior of deep buried tunnel after excavation. Currently, elastic-plastic pressure theory is commonly used in engineering. This paper adopts the modified Fenner formula based on elastic-plastic theory to study the interaction between surrounding rock and support [8].

$$u_p = \frac{Mr_0}{4G}\left(\frac{P_i + c\cot\varphi}{(P + c\cot\varphi)(1 - \sin\varphi)}\right)^{\frac{\sin\varphi}{1-\sin\varphi}} \tag{1}$$

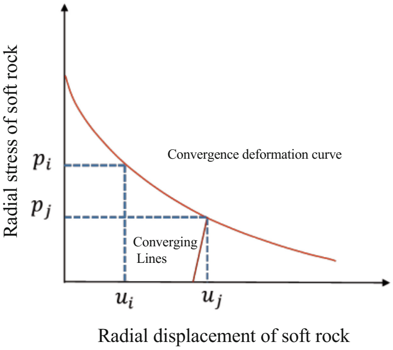


**Fig. 1.** The principle of Convergence Constraint Theory.

where: $u_p$ is the plastic deformation of the tunnel (m), $P_i$ is the support resistance (MPa), $r_0$ is the excavation radius of the tunnel (m), $c$ is the cohesion of the rock mass (MPa), $\varphi$ is the angle of internal friction of the rock mass (°), $G$ is the shear modulus of the rock mass (GPa), and $P$ is the average stress (MPa).

## 2.2 Calculation of Support Resistance

Open TBM excavation tunnels generally use steel arches, shotcrete and anchor rods as support measures. According to Eq. (1), it can be seen that the plastic deformation of the tunnel is closely related to the support resistance, therefore, it is necessary to calculate the support resistance that can be provided by the various support measures, and on this basis, the relevant rock mechanics parameters can be inverted based on the monitoring deformation of the surrounding rock. In soft rock large deformation tunnel, the maximum support force that can be provided by each support measure is calculated by the following formula.

The support force of the anchor:

$$P_{1,max} = \frac{T_b}{S_c S_l} \tag{2}$$

where: $P_{1,max}$ is the maximum support force of the anchor (MPa), $T_b$ is the average pullout force of the pullout test (MN), $S_c$ is the annular spacing of the anchor (m), and $S_l$ is the longitudinal spacing of the anchor (m).

The support force of the steel arches:

$$P_{2,max} = \frac{\sigma_{ys} A_s}{s r_0} \tag{3}$$

where: $P_{2,max}$ is the maximum support force of steel arch, $\sigma_{ys}$ is the yield strength of steel arch, $A_s$ is the cross sectional area of steel arch, $s$ is the spacing of steel arch, and $r_0$ is the radius of tunnel.

Shotcrete support force calculation based on backwall cylinder theory:

$$P_{3,max} = \frac{1}{2} S_c \left[ 1 - \frac{r^2}{(r+t)^2} \right] \tag{4}$$

where: $P_{3,max}$ is the maximum support force of shotcrete, $S_c$ is the compressive strength of shotcrete (MPa), $t$ is the thickness of shotcrete, and $r$ is the inner diameter of shotcrete.

Therefore, the total support resistance of anchor, steel arch and shotcrete is calculated as:

$$P_{max} = P_{1,max} + P_{2,max} + P_{3,max} \tag{5}$$

## 2.3 On-Site Monitoring Information

A deep buried hydraulic tunnel in Southwest China experienced serious soft rock deformation during TBM construction, and the supporting structure was severely damaged due to the tunnel deformation, as shown in Fig. 2. When the tunnel undergoes large deformation of the soft rock, monitoring is carried out on the cross-section and arch deformation, and the monitoring results are shown in Figs. 3 and 4.

**Fig. 2.** Soft rock tunnel deformation causing distortion of steel arch frames.

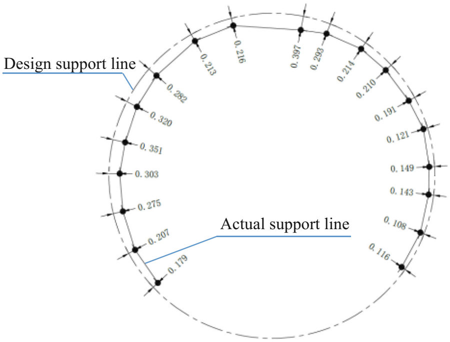


**Fig. 3.** Monitoring deformation of soft rock tunnel section.

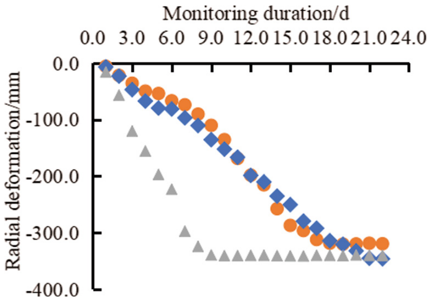


**Fig. 4.** The monitoring deformation of arch displacement.

According to the on-site monitoring data, within a short period of time (3 days) of TBM excavation, the maximum deformation of soft rock increased by 12 cm. After

22 days of adopting support measures for the soft rock tunnel, the surrounding rock deformation became stable, reaching a maximum deformation of 37 cm. The deformation amount and degree of soft rock are relatively high.

### 2.4 Parameter Theory Inversion and Validation

The initial support parameters of the tunnel are listed in Table 1. According to each support parameter, the maximum support force that can be provided by each support measure is calculated by Eqs. (2), (3) and (4), and the total support resistance $P_{max}$ is obtained by Eq. (5), $P_{max} = 1.35$ MPa.

**Table 1.** Support parameter table.

| System anchor spacing(m) | Steel arch frame | | Sprayed concrete layer | |
|---|---|---|---|---|
| | Type | Spacing(m) | Type | Thickness |
| 1.25 | I20b | 0.4 | C25 | 20 |

After determining the relationship between support force and deformation, with monitoring deformation as the target value, the soft rock strength index is inverted. The $\varphi$ value is determined according to class V surrounding rock, and then the c value is back calculated. Finally, the mechanical parameters of soft rock are obtained as shown in Table 2. The short-term strength parameters are the inverse parameters of TBM excavation during shield tail support. As the tunnel deformation increases, the surrounding rock around the tunnel becomes relaxed, and the mechanical parameters of the rock mass gradually deteriorate. The long-term strength parameters are soft rock parameters inverted based on monitoring data.

**Table 2.** The inversion of rock mass mechanical parameters table.

| Inversion stage | Buried depth(m) | Severe(kN/m$^3$) | φ(°) | c(MPa) | E(GPa) |
|---|---|---|---|---|---|
| short-term | 1168 | 22 | 35.0 | 1.3 | 4.0 |
| long-term | 1168 | 22 | 28.0 | 0.54 | 1.4 |

In order to verify the reasonableness of the mechanical parameters of the soft rock, according to the M-C criterion rock equivalent strength can be obtained from Eq. (6), brought into the inversion of c, $\varphi$ value, the equivalent rock strength of the soft rock is calculated to be 1.8 MPa.

$$\sigma_{cm} = \frac{2c\cos\varphi}{1 - \sin\varphi} \tag{6}$$

According to the relevant Chinese regulation [9], the internal friction angle of class V surrounding rock: $21.8 \le \varphi \le 28.8$, $0.05 \le c \le 0.30$, the integrity coefficient of fracture rock mass $K_v \le 0.15$, the saturated uniaxial compressive strength of the tested rock: 10 MPa $\le R_b \le$ 20 MPa. Taking $K_v = 0.15$, then the rock mass equivalent strength is calculated: 1.5 MPa $\le R_c \le$ 3 MPa.

$$R_c = K_v R_b \tag{7}$$

where: $K_v$ is the integrity coefficient of the rock mass and $R_b$ is the saturated uniaxial compressive strength of the rock.

The equivalent compressive strength of the rock mass obtained according to the strength index of the rock mass determined by the inversion is similar to the equivalent rock mass strength obtained by the method suggested by the code, so the mechanical parameters of the theoretical inversion have a high reliability.

## 3 Adaptive Prevention and Control Measures for Open TBM Excavation of Deep Buried Soft Rock Tunnel

### 3.1 The Simulation of the TBM Excavation Based on Finite Element Method

When predicting large deformation of soft rock and determining support measures, it is necessary to compare and analyze multiple schemes. Due to the large calculation amount of three-dimensional models, it is not convenient to the design and comparison of multiple schemes. RS2 is a powerful elastic-plastic finite element analysis software, which is suitable for underground rock excavation calculation. Therefore, this paper relies on deep buried soft rock tunnel and uses two-dimensional finite element software RS2 for modeling and calculation. The load release rate is used as the basic indicator to simulate tunnel TBM excavation, and the deformation response and adaptive prevention and control measures of soft rock tunnel are studied.

When the tunnel is excavated, the surface of the tunnel will not immediately undergo complete deformation. Due to the unloading effect generated by nearby excavation, the rock in front of the excavation face has already deformed before excavation. As the excavation progresses, the face of the tunnel continues to move forward, and the stress in the surrounding rock changes continuously, causing the tunnel wall to continue to deform. Usually, the tunnel does not reach its “two-dimensional” deformation state until the excavation face is moved a few diameters in front of it. As shown in the schematic diagram of Fig. 5.

For tunnels with poor surrounding rock conditions, the influence of the plastic characteristics of the surrounding rock on the deformation of the tunnels should not be ignored, and the Vlachopoulos-Diederichs tunnel deformation curves [10] can be considered in the plastic zone of the surrounding rock (see Fig. 6), therefore, this curve is selected as the reference curve for the longitudinal deformation characteristics of the tunnel in this paper.

The spatial effect of three-dimensional excavation is achieved by controlling the stress release coefficient of the surrounding rock, and different support reactions are provided to the excavation surface at different excavation steps to achieve stress release of the surrounding rock. The displacement ratio method built-in in RS2 software is used to calculate the support reaction coefficient of the surrounding rock when supporting

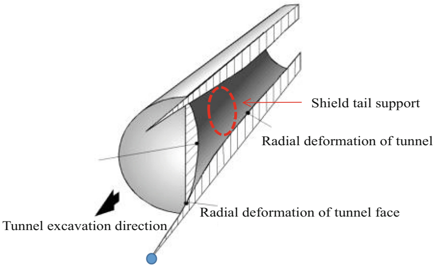


**Fig. 5.** Tunnel excavation deformation diagram.

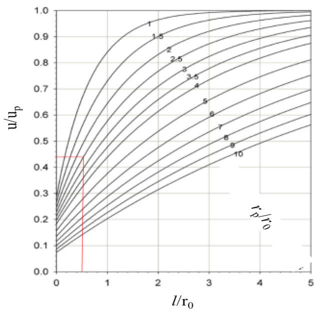


**Fig. 6.** Vlachopoulos-Diederichs characteristic curve of longitudinal deformation of tunnel.

measures are taken. As shown in Fig. 6, the ratio of the distance from the face to the excavation radius of the tunnel during support is taken as the horizontal coordinate (s = $l/r_0$), and the ratio of the radius of the unsupported plastic zone to the radius of the tunnel (t = $r_p/r_0$) is taken as the value of the displacement-dependent curve.

### 3.2 Soft Rock Excavation Unloading Response

The 2D numerical model built using 2D finite element software is shown in Fig. 7. The tunnel deformation before the installation of support measures is calculated using the Vlachopoulos-Diederichs method. The maximum tunnel wall displacement $u_{max}$ away from the tunnel face and the radius of the plastic zone away from the tunnel face are obtained based on finite element analysis.

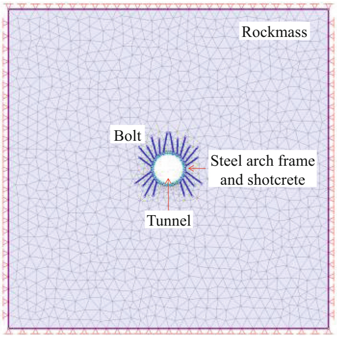


**Fig. 7.** Two-dimensional analysis model of tunnel cross-section.

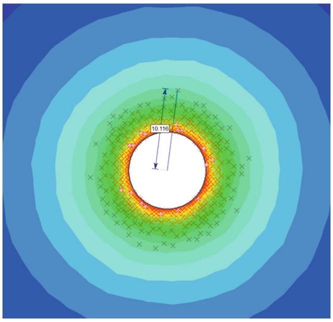


**Fig. 8.** The depth of plastic zone after tunnel excavation.

According to the results of numerical calculation, when TBM excavation and boring, using short-term strength parameters. When the load is completely released, the maximum deformation of the surrounding rock is 13 cm, and the length of the open TBM shield body is taken as 6 m, so the distance from the excavation face to the shield tail installing steel arch and other support measures will be 6 m. The excavation radius of the tunnel is 4.85 m. Thus, the ratio of the distance from the excavation face to the excavation radius of the tunnel during support is calculated as 1.24 (s). The distribution of the plastic zone in the surrounding rock after excavation is shown in Fig. 8. The radius of the unsupported plastic zone is 10.12 m, and the ratio of the radius of the unsupported plastic zone to the radius of the tunnel is calculated to be 2.08 (t).

According to the value of s and t, with reference to the longitudinal deformation characteristic curve of the tunnel (Fig. 6), the ratio of the shield tail rock deformation to the maximum deformation of the surrounding rock is 0.70, from which the deformation of the shield tail rock is calculated to be 9.1 cm. Based on the curve of the relationship between the load release coefficient and the deformation of the arch top in Fig. 9, it is determined that the load release coefficient at the support of the shield tail is 0.04.

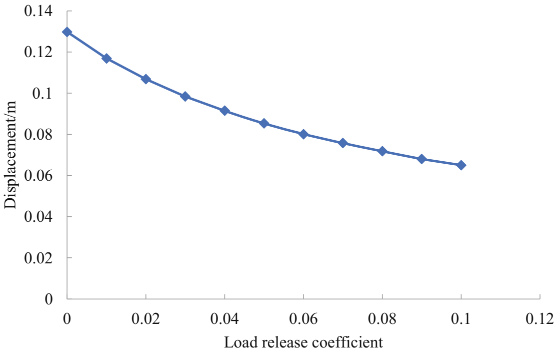


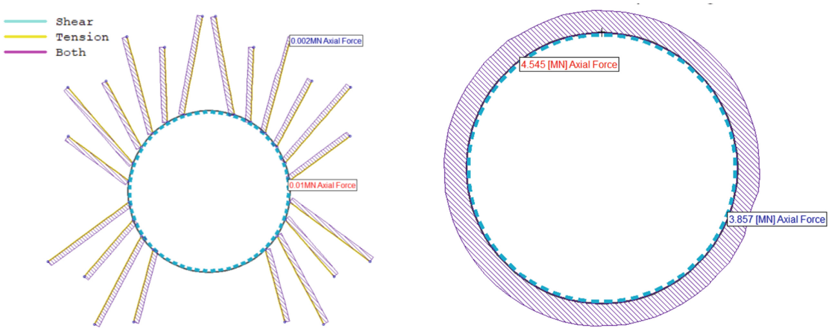
**Fig. 9.** The curve of the relationship between load release coefficient and arch deformation after tunnel excavation.

**Table 3.** Surrounding rock response after tunnel excavation.

| Tunnel location | Vault | Floor | Left wall | Right wall |
|---|---|---|---|---|
| Deformation(cm) | 79.1 | 81.1 | 77.1 | 79.4 |

During the excavation and support process of the tunnel, the deformation vectors of the surrounding rock around the tunnel all point towards the inside of the tunnel. As shown in Table 3. The deformation displacements of the top arch and bottom plate are 79.1 cm and 81.1 cm respectively. The convergence displacement of the side wall is 77.1–79.4 cm, and the depth of the plastic zone reaches 9.58 m.

Figure 10 shows the stress diagram and yield state of the support structure. It can be seen that the overall axial force of the steel arch and shotcrete combination support is 4545 kN, and yield phenomenon occurs. The system anchor rods have all undergone tensile failure, with a maximum axial tensile force of 10 kN after yielding.



(a)System anchor force cloud diagram and yield state

(b)Stress diagram and yield state of steel arch frame

**Fig. 10.** Stress cloud diagram and yield state of support structure.

### 3.3 Principle of Support and Effect of Retractable Steel Arches

The retractable steel arch support system permits the installation of steel arches with sliding devices near the tunnel surface with minimal deformation of the tunnel. The sliding joints will allow further deformation of the tunnel before the arches are subjected to axial loads. There will be no axial forces in the steel arch until the locking strain is reached, but the steel arch will resist bending moments until the locking strain is reached. This system will prevent extreme deformation in the tunnel, but will also prevent failure of the steel arch by ensuring that the supports are not subjected to very high stresses.

A retractable arch is used, with two retractable locking joints are set around the steel arch frame. The sliding gaps of the steel arch within each retractable joint are $d_1$ and $d_2$, with a total retractable space of $d_1 + d_2$. The schematic diagram of the principle of retractable arch frame is shown in Fig. 11.

For a steel arch with two sliding gaps, the strain calculation during locking is as follows:

$$\frac{\Delta L}{L} = \frac{d_1 + d_2}{2\pi r} \tag{8}$$

where: $\varDelta L$ is the sliding gap of the steel arch, which is composed of sliding gaps $d_1$ and $d_2$, m; $L$ is the circumference of the steel arch, m. The sliding gap of the steel arch is the sliding gap of the steel arch, which is composed of sliding gaps $d_1$ and $d_2$.

The finite element analysis software is used to carry out numerical simulation study on the support of retractable steel arch for the water transfer tunnel through the deep buried soft rock cave section. The calculation model and conditions are the same as those in Fig. 7.

The calculated values of the surrounding rock response of the tunnel excavated with retractable steel arch support are listed in Table 4, and the influence law of the retractable arch frame structure is shown in Figs. 12 and 13.

From Figs. 12 and 13, it can be seen that the tunnel excavation is supported by a retractable steel arch, the deformation displacement of the top and bottom of the tunnel

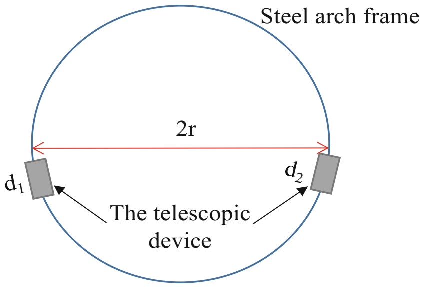
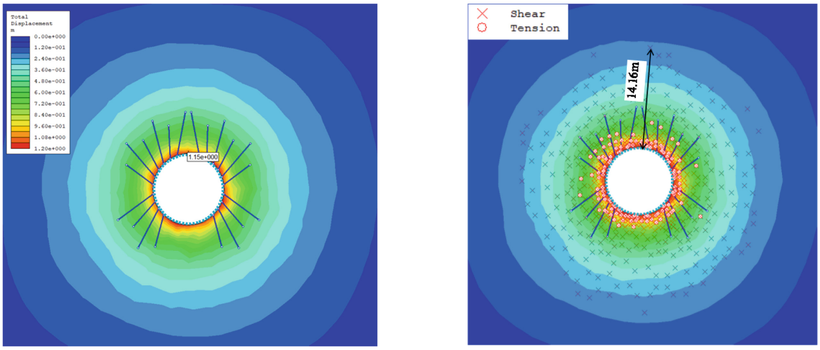


**Fig. 11.** Schematic diagram of the principle of retractable arch frame

**Table 4.** The response of surrounding rock supported by retractable steel arch frame after tunnel excavation.

| Tunnel location | Vault | Floor | Left wall | Right wall |
|---|---|---|---|---|
| Deformation(cm) | 115.0 | 117.0 | 112.0 | 115.0 |



(a)The cloud map of tunnel surrounding rock deformation

(b)The cloud diagram for plastic differentiation of tunnel surrounding rock

**Fig. 12.** The response of soft rock excavation using scalable steel arch support.

is 115 cm and 117 cm respectively, and the convergence displacement of the side wall is 112–115 cm, and the depth of the plastic zone reaches 14.16 m.

In the short-term parameter working condition, the force of steel arch is 0, which indicates that the reserved deformation gap has not been used up, and there is still space for expansion and contraction of steel arch. After the use of retractable steel arch support, the maximum displacement of soft rock tunnel arch in the long-term parameter working condition is 115 cm, which is higher than that observed in the case of no sliding gap displacement of 79.1 cm, but much smaller than that in the case of no liner displacement of 163 cm. Compared with the maximum axial force of 4545 kN for the steel arch without sliding gap, the maximum axial force of the retractable steel arch with sliding gap is only

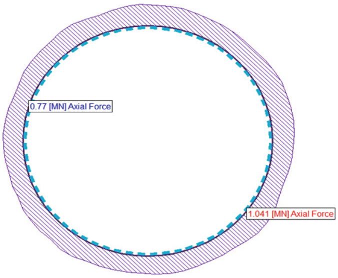


**Fig. 13.** Support structure stress.

1041 kN, and the maximum stress is 202.45 MPa, which is less than the yield strength of the steel arch, so the structural safety can be ensured.

# 4 Conclusion

For the case of large deformation in deep buried soft rock tunnel, theoretical inversion of mechanical parameters of deep buried soft rock is carried out based on the convergence-confinement method. The simulation of the open TBM excavation is carried out based on finite element method. The mechanical response of the surrounding rock and research of adaptive preventive and control measures are investigated. The following conclusions can be obtained:

(1) Through the analysis of monitoring data on the deformation section of soft rock tunnel, it can be concluded that deep buried soft rock is prone to large deformation due to its low strength and high stress environment. With the excavation of the tunnel, at a lower strength stress ratio, the soft rock is prone to large deformation, and the magnitude and scale of deformation are relatively high. There are obvious temporal and spatial effects on the deformation of soft rock tunnel. As TBM is excavated forward, the stress on the support continues to increase, ultimately leading to failure.
(2) The Convergence-Confinement method based on elastic-plastic theory can quickly deduce the mechanical parameters of deep buried soft rock based on the maximum resistance provided by the support structure, combined with the classification of surrounding rock and deformation monitoring data. The rationality of parameter values has been verified by relevant specifications.
(3) In the soft rock tunnel section excavated with open TBM, when the support structures are used at the shield tail, the deformation of the surrounding rock is relatively small, and the depth of the plastic zone is not large. As TBM continues to excavate, the support time and the distance from the excavation face increase, the deformation of the soft rock increases, the depth of the plastic zone deepens, and the mechanical properties of the rock mass continue to deteriorate. The stress on the support structure continues to increase until it is destroyed.
(4) The use of retractable steel arch can effectively ensure the safety of the support structure by dissipating the plastic energy of the surrounding rock and releasing the deformation of the surrounding rock through sliding gaps, thereby reducing the

surrounding rock pressure acting on the support structure. This measure has reliable connection performance and good energy consumption ability, and can be applied in open TBM excavation of soft rock tunnels.

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