Field Tests and research of Large Deformation Control Measures for Soft Rock Tunnel with High Geostress

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Abstract. The Muzhailing highway extra-long tunnel is affected by high geostress, and during the construction, large deformation of soft rock frequently occurred. Taking this as the research background, the high-prestressed constant resistance and large deformation anchor cable support scheme was proposed. In the field test, the indicators of three support schemes were compared, including the convergence deformation of surrounding rock, the deep displacement of surrounding rock, the axial force of anchor cable and bolt, and the stress between primary support and surrounding rock. The field test results show that: under the support of bolts, the cumulative deformation of surrounding rock exceeded 1500 mm, and the primary support damage was serious; In the second scheme, under the support of 4 m and 5 m long constant resistance anchor cables, although the large deformation of surrounding rock was controlled, the cumulative deformation was about 600 mm; In the third scheme, under the support of 5 m and 10 m long constant resistance anchor cables, the cumulative maximum deformation of surrounding rock was reduced to 216 mm, and all the data of the field test were within the controllable range. Therefore, high prestressed constant resistance and large deformation anchor cable support measures can effectively control the large deformation of surrounding rock.

1. Introduction
In recent years, the construction of tunnels in China has developed rapidly. However, under the influence of high geostress, tunnels are prone to large deformation of soft rocks during construction. Researchers have conducted a lot of research on the deformation and support methods of tunnel surrounding rocks. Hoek, E., Marinos et al. [1] studied rock strength and rock mass strength, they considered that rock mass strength and geostress are the key factors affecting the stability of the tunnel surrounding rock. Aydan O. et al. [2] summarized the mechanical mechanism of three kinds of surrounding rock in squeezing phenomenon: complete shear failure, bending failure, and shear sliding failure. Sharan et al. [3] demonstrated that rock failure obeys certain strength criterion, and discussed the relationship between the deformation of circular tunnel and geostress. Tao Z et al. [4] studied the failure mechanism of soft rock roadway in steep layered strata. They analyzed the failure
characteristics of different steeply inclined layered soft rock roadways under the influence of high lithostatic stress and horizontal tectonic stress. He M. C. et al. [5] studied the deformation and failure characteristics of surrounding rock in 45° inclined rock strata and analyzed the temperature characteristics of surrounding rock in the process of roadway failure by using infrared thermography. Brox D et al. [6] studied the deformation characteristics of the Anatolian highway tunnel in Turkey when crossing the fault. Huaning W et al. [7] studied the reinforcement mechanism of bolts through DEM numerical analysis. The research shows that the bolts can effectively control the rock failure and that increasing the number of bolts can improve the reinforcement effect of the surrounding rock. Meng Q et al. [8] considered rock mass and rockbolts as a new homogeneous, isotropic, parameters strengthened equivalent composite material. The research shows that anchor bolt has an important effect on plastic zone size and displacement of surrounding rock. Fei Xu et al. [9] designed a new type supporting system of grid steel frame-core tube for large deformation of tunnel. G Wu et al. [10] studied the performance of foamed concrete and proposed supporting measures for pouring foamed concrete between the primary lining and secondary lining.

This paper introduced the application of constant resistance and large deformation anchor cable support system in the Muzhailing tunnel. Three support schemes were implemented on site, and the monitoring data of the three schemes were compared through field monitoring test research. The test results show that the support method of 5 m and 10 m long constant resistance anchor cable is the best, which ensures the stability of surrounding rock.

2. Engineering background
The Muzhailing tunnel is located in Lanzhou, Gansu Province, China. It is a key control project of the Lanzhou-Haikou national expressway. Figure 1 is the longitudinal section of the Muzhailing tunnel, which has developed strike faults and complicated geological structure. The total length of the tunnel is 15.226 km, the maximum buried depth is 629.1 m, and the excavation section area of the main tunnel is more than 133.8 m². As shown in Figure 2, the lithology is mainly thin layered carbonaceous slate with a dip angle of 0°-30°. Sandstone, limestone, and shale interlayers are localized, and quartzite is scattered in the rock layer. The rock layer is rich in fissure water and has the characteristics of soft rock such as swelling, disintegration, rheology, and engineering disturbance sensitivity.

Figure 1. Longitudinal section of Muzhailing tunnel

Figure 2. Tunnel exposure of carbonaceous slate.
3. Failure characteristics of tunnel surrounding rock

As shown in Figure 3, the failure form of the surrounding rock was mainly full-circle large deformation failure. The maximum deformation position was mainly concentrated at the left arch waist, and the maximum deformation exceeded 1500 mm. In order to study the influence of the rock layer with non-uniform thickness on the deformation of tunnel, the DFN module in discrete element software 3DEC was used to generate random non-uniform thickness joints with a main dip of 30°. This numerical model adopted the Mohr-Coulomb yield criterion. The vertical stress of the tunnel is 12.5 MPa, the maximum horizontal stress is 21 MPa, and the minimum horizontal stress is 12.5 MPa. The maximum horizontal stress direction is consistent with the tunnel direction, the numerical model is shown in Figure 4, and the specific parameters are shown in Table 1. As shown in Figure 5a, the surrounding rock of the tunnel mainly occurred sliding deformation and compression bending deformation between the rock layers. The deformation at the place of squeezing and bending deformation was large, which was concentrated at the left arch waist, and the maximum deformation was 1508 mm. The range of the plastic zone developed in the direction perpendicular to the stratum and along the direction of the stratum. The maximum depth of plastic zone development is about 11.5m, as shown in Figure 5b.

![Figure 3. Large deformation of tunnel surrounding rock](image1)

![Figure 4. Numerical model](image2)

| Parameter       | Density (Kg/m³) | Bulk modulus (GPa) | Shear modulus (GPa) | Cohesion (MPa) | Frictional angle (°) | Tensile strength (MPa) |
|-----------------|-----------------|--------------------|---------------------|----------------|----------------------|------------------------|
| Rock            | 2500            | 0.44               | 0.25                | 1.7            | 22                   | 0.6                    |
| Rock joint      | /               | 2                  | 1                   | 0.1            | 25                   | 0.05                   |

![Figure 5. Numerical calculation results](image3)

(a) Displacement of surrounding rock (b) Plastic zone of surrounding rock
4. Tunnel support scheme
According to the deformation characteristics of surrounding rock, three support schemes were adopted on site. The first scheme adopts the traditional bolt support measures (Figure 6a). As shown in Figure 6b, in the second scheme, the constant resistance and large deformation anchor cable is used (Figure 7), which is a negative Poisson's ratio anchor cable (NPR anchor cable). This kind of anchor cable can allow the surrounding rock to deform while maintaining high prestress, and has the function of constant resistance to prevent breakage of anchor cable. In this scheme, the constant resistance anchor cables of 4 m and 5 m long are arranged alternately, and the prestress of 350 kN can be applied. The third scheme is to increase the length of the anchor cable based on the second scheme, using 5 m and 10 m long constant resistance anchor cables. (Figure 6c).

![Diagram of tunnel support schemes](image.png)

(a) The first scheme  
(b) The second scheme  
(c) The third scheme

**Figure 6.** Tunnel support scheme

**Figure 7.** The constant resistance and large deformation anchor cable
5. Field test and result analysis

5.1 Test schemes
As shown in Figure 8, four monitoring tests were carried out for each support scheme. The test items include axial force monitoring of anchor cable (anchor bolt), surface deformation measurement of surrounding rock, pressure monitoring of surrounding rock, and deep deformation monitoring of surrounding rock. By comparing the monitoring data of different supporting schemes, the interaction between surrounding rock and supporting structure is studied to select the optimal supporting scheme.

5.2 Axial force analysis of anchor cable and anchor bolt
Due to the use of constant resistance and large deformation anchor cables in the second and third schemes, the anchor cable itself can quickly apply a high prestress (350kN). After the construction was completed, the prestress value was still around 350kN. The first scheme uses bolt support because it cannot apply high prestress itself, and the increase in axial force is due to the increase in deformation of the surrounding rock. After the construction was completed, the maximum axial force was only about 110kN, and the equipment was damaged due to excessive deformation of the surrounding rock. As shown in Figure 9.

5.3 Analysis of surface displacement of surrounding rock
Figure 10 shows the displacement curve of the surrounding rock at the maximum deformation under three support schemes. In the first scheme, from the 11th day after the completion of construction, the average daily deformation rate of the surrounding rock increased extremely, and the cumulative deformation exceeded 1500 mm, which eventually led to the destruction of the primary support. Under
the support of 4 m and 5 m long constant resistance anchor cables (the second scheme), although the large deformation of the surrounding rock was controlled, the maximum deformation of the surrounding rock exceeded 600 mm, which failed to meet the design requirements. Supported by 5 m and 10 m long constant resistance anchor cables, the cumulative maximum deformation of the surrounding rock was 216 mm. The scheme may satisfy the requirements of design and construction and can well control the large deformation of surrounding rock.

Figure 10. Surface displacement of surrounding rock

5.4 Analysis of pressure between surrounding rock and primary support

Figure 11 shows the pressure between the surrounding rock and the primary support under three support schemes, with five measurement points for each scheme. The monitoring started with the completion of the primary support construction. The first scheme had been monitored for 20 days, and the second and third schemes had continued for 30 days. Under the support of the anchor bolt, the pressure on the initial support is asymmetric (figure 11a). In the second scheme, the primary support pressure was reduced, and the asymmetry between the left and right sides was also relieved, but the surrounding rock pressure was still very large, and the primary support was prone to instability and damage (figure 11b). As shown in Figure 11c, in the third scheme, the surrounding rock pressure and asymmetry were significantly reduced, which indicates that the constant resistance anchor cable reduces the asymmetric deformation of the surrounding rock and improves the safety of the initial support.

(a) The first scheme  
(b) The second scheme  
(c) The third scheme

Figure 11. surrounding rock pressure (MPa)

5.5 Analysis of deep displacement of surrounding rock

For each monitoring section, the crown of the tunnel is selected for measurement. The measurement depth of the first and the second schemes is 1 m, 2 m, 3 m, 4 m, and 5 m from the surrounding rock surface respectively. The measurement depth of the third scheme is 1 m, 3 m, 5 m, 7 m, and 10 m from the surrounding rock surface respectively. Each section has five measurement points in total. In the first scheme, the maximum relative displacement between the deep measuring points was 729 mm, and the cumulative deformation of the 5 m measuring point exceeded 800 mm, which indicates that the deep layer of the surrounding rock is separated greatly (Figure 12a). Compared with the first scheme, the second scheme reduced delamination in the deep part of the surrounding rock, but the deformation at the 5m measurement point is still very large, indicating that the plastic zone range exceeds the anchor cable coverage (Figure 12b). As shown in Figure 12c in the third scheme, the delamination mainly occurred between 5m-10m in the depth of the surrounding rock. There was no
displacement in the deep surrounding rock at the measuring point of 10m, and the delamination of the surrounding rock was small between 1m-5m. Short anchor cables improve the self-supporting capacity of surrounding rocks. The long and short anchor cables together increase the strength of the surrounding rock within the coverage area of the entire anchor cable and effectively control the large deformation of the surrounding rock.

![Image](image-url)

**Figure 12.** Deep displacement of surrounding rock

6. Conclusion

(1) Through the on-site geological survey and numerical simulation, the characteristics of large deformation of surrounding rock of Muzhailing tunnel were analyzed. The main deformation forms of surrounding rock are interlayer sliding and compression bending, and show asymmetry. The maximum deformation of surrounding rock was more than 1500 mm, and the primary support was seriously damaged. The range of the plastic zone develops in the direction perpendicular to the rock strata and along the layer, and the maximum depth of the plastic zone was about 11.5 m.

(2) The field test results show that the traditional bolt support cannot control the large deformation of the surrounding rock. The 4m and 5m long constant resistance anchor cable support schemes reduce the deformation of the surrounding rock, but cannot meet the requirements of the subsequent tunnel construction. Under the scheme of 5 m and 10 m long constant resistance anchor cable support, the anchor cable maintains high prestress (350 kN), and the deformation of surrounding rock was reduced from 1500 mm to 216 mm. The pressure on the primary support changed from local pressure to uniform pressure, and the pressure value decreased. In the coverage area of short anchor cable, the separation of surrounding rock layer is small, and the rock mass at 10 m depth of surrounding rock does not move, which shows that the long and short anchor cables together increase the strength of the surrounding rock within the coverage area of the entire anchor cable, and effectively control the large deformation of the surrounding rock.

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