Analysis of deformation characteristics of a tunnel in layered soft rocks with considering the effect of bedding

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Abstract. The layered soft rock tunnel is affected by the combination of layering and geostress, and it is easy to cause large deformation disaster. Based on the Weiwu high-speed Minxian tunnel, the influence of bedding on the stress and deformation characteristics of sandstone and carbon slates is studied in this paper. The calculation results show that the influence of bedding on the deformation of sandstone and carbonaceous slates is significant. If the influence of bedding is not considered in the process of tunnel deformation prediction, the deformation of surrounding rock will be seriously underestimated. The influence of bedding on the deformation distribution of surrounding rock is related to the strength of bedrock. For sandstone, the strength of bedrock is high, and the deformation and failure of surrounding rock is mainly caused by shear failure of layer, and its deformation distribution and magnitude is obviously affected by the layered production. When the angle between the bedding and the maximum principal stress direction of the ground stress is 45°, the deformation amount reaches the maximum value. For the layered carbonaceous slates, due to the low strength of the bedrock, the surrounding rock has obvious crushing damage zone after the tunnel excavation, and the layered occurrence has little influence on the deformation value and distribution of the surrounding rock. The maximum deformation orientation of the surrounding rock is basically perpendicular to the direction of the maximum principal stress of the geostress.

1. Introduction

In recent years, with the continuous development of transportation infrastructure construction in western China, numerous highway and railway tunnels have appeared in complex geological environments. Because of the influence of geomorphology and regional tectonics, tunnel wall rocks are deeply buried with large in-situ stresses in Western China. This causes many challenges to the construction of tunnels. In typical tunnels such as Jiazhuqing, Wushaoling, and Muzhailing [1], the tunnel wall rocks are predominantly layered carbonaceous slate and phyllite. These rocks have low strength and bear large structural stresses. The intensities of the stress ratios are all less than 0.2. Significant large deformation disasters occurred during the tunnel excavation [2]. The measured deformation of the tunnel is more than 1 m, and the maximum deformation of the Muzhailing railway tunnel is up to 2 m. The damage and erosion of initial support are serious, resulting in the delay of the construction period and the increase in the construction cost. Through the above observations, it can be concluded that the wall rocks of the tunnels are mainly layered soft rocks such as slate and phyllite. These deformation characteristics are
jointly affected by in-situ stresses, lithology, and bedding mechanical properties. The deformation and failure mechanisms are extremely complex and need to be further studied. Many scholars have studied the deformation characteristics and influencing factors of layered soft rocks. Guo (2017) analyzed the influence of the initial stress field, rock mass structure, groundwater, and other factors on the deformation and failure of layered wall rocks [3]. They believed that the failure modes of layered soft rocks include collapse, sliding slip, tensile crack, bending, and fracture. Sha et al. (2015) and Guo et al. (2017) proved that the deformation and failure modes of layered soft rocks are significantly affected by the dip angle of strata [4-5]. Wu et al. (2018) showed that the interrelation between the tectonic stresses and the dip angle of strata has an important influence on the non-uniform deformation of layered soft rocks. Chen et al. (2018) analyzed the asymmetric deformation and failure characteristics of the layered soft wall rocks of the tunnels [7]. These research attempts have revealed the deformation and failure mechanisms of layered soft rocks, which have important significance for guiding the design and construction of tunnels in layered soft rocks.

Based on the geological exploration of tunnels in layered soft rocks, the layered soft rocks usually exhibit the characteristics of soft-hard interbedding [8]. Taking the Minxian tunnel in the Weiwu Expressway as an example, the interbedded distribution of low strength carbonaceous slate and high strength sandstone results in obvious deformation differences within the wall rocks. This gives rise to great challenges to the design and construction of the tunnel. This research took the Minxian tunnel as an example and studied the influence of the type of bedrock (sandstone, carbonaceous slate) on the deformation and failure modes of wall rocks under the action of bedding cutting. It is believed that the results of this study can provide scientific guidance for the design and construction of the tunnels.

2. Overview of supporting projects

The Minxian tunnel in the Weiwu Expressway runs through the Min Mountain in an N-S direction. The starting and ending stake numbers of the left and right lines are ZK234+610~237+400 and K234+570~237+418, respectively. The length of the tunnel is 2848 m, and the maximum buried depth of the tunnel is 286.9 m. The tunnel is located in the Qinling-Kunlun latitudinal structural system, which belongs to the middle branch of the Geosynclinal fold system of the West Qinling (i.e the Hercynian Indosinian fold belt). The structural line is generally in the E-W direction. There are strong fold belt activities, strike faults, complex geological structures, and strong neotectonic movement near the tunnel. The in-situ stress test in the tunnel site demonstrates that the stress in this area is primarily tectonic stress and the horizontal lateral earth pressure coefficient is in the range of 1.6 to 2.0.

The wall rocks of the tunnel are dominated by layered carbonaceous slate and sandstone, which are distributed in soft-hard interbedding. According to the observations made on the metacarpal surface, the bedding of the wall rocks is extensive. The bedding thickness of the sandstone and carbonaceous slate is between 5 to 30 cm, leading to extremely broken wall rocks. To obtain the strength of carbonaceous slate and sandstone, the on-site point load tests were carried out on 86 groups of carbonaceous slate samples and 36 groups of sandstone samples. The test results are shown in Figure 1. The results suggested that the strength of the sandstone is obviously larger than that of the carbonaceous slate. The average point load strength of the carbonaceous slate and sandstone were 2.4 Mpa and 5.6 Mpa, respectively.

Figure 1. Results of the point load tests of the Minxian tunnel in the Weiwu Expressway.
Because of the joint influences of bedding cutting and in-situ stress, the deformation of wall rocks of the Minxian tunnel showed obvious heterogeneous characteristics. The 3D scanning results of the deformation of the wall rocks in the ZK235 + 467 section are shown in Figure 2. It can be observed that the maximum deformation of wall rocks of the tunnel occurred in the right spandrel (a maximum deformation of 900 mm), while the maximum deformation of the left spandrel of the tunnel was about 260 mm. Also, due to the influence of soft-hard interbedding of sandstone and carbonaceous slate, the deformation of wall rocks along the longitudinal direction of the tunnel was significantly heterogeneous. As shown in Figure 3, when the buried depth of the tunnel changes a little, the maximum deformation of the thin-layered carbonaceous slate tunnel can reach 1330 mm, while the deformation of the sandstone with larger strength is just 15 to 40 mm. The heterogeneous deformation of the tunnel leads to the high support parameters in the small deformation sections. This results in a waste of cost. At the same time, the support structures of the large deformation sections suffer serious cracking, steel arch distortion, second lining invasion, and even collapse, which seriously affect the construction progress and construction safety.

![Figure 2. Three-dimensional scanning display of the deformation of the wall rocks in the xx section.](image)

In summary, the layered strata of the Minxian tunnel are not only heterogeneous in the cross-section of the tunnel but also heterogeneous in the longitudinal range of the tunnel. Such heterogeneous deformation is not only related to the cutting action of the in-situ stress and bedding but also related to the soft-hard interbedding of sandstone and carbonaceous slate [9]. Many scholars have studied the influence of the in-situ stress and bedding cutting on the deformation and failure mechanisms of wall rocks, but few researchers have investigated the deformation and failure modes of soft-hard interbedded bedrocks. In this study, the deformations of wall rocks in sandstone and carbonaceous slate sections were compared and analyzed to determine the deformation development regularities.

3. Analysis of the genesis of the heterogeneous deformation of the Minxian tunnel
Considering the characteristics of soft-hard interbedding of the wall rocks in the Minxian tunnel, this study focused on analyzing the deformation and failure modes of different types of bedrocks (sandstone,
carbonaceous slate) under the action of bedding cutting. The objective was to provide a reference for the design and construction of tunnels in layered soft rocks.

3.1. Calculation parameters and models

The sandstone and carbonaceous slate belonged to soft to relatively soft rocks with a good bedding combination. Based on the geological exploration data of the Minxian tunnel, the results of the on-site point load test and their mechanical parameters are shown in Table 1.

| Lithology            | Density (kg/m³) | Young’s modulus (GPa) | Cohesion (MPa) | Friction angle (°) |
|----------------------|-----------------|-----------------------|----------------|-------------------|
| Sandstone            | 2500            | 4.0                   | 1.5            | 45                |
| Carbonaceous slate   | 2500            | 1.3                   | 1.0            | 35                |
| Joint                | -               | -                     | 0.20           | 30                |

At present, there are mainly two methods to simulate the bedding in layered soft rocks. The first one is the discontinuous method, which initially defines the bedding unit and rock block, and then conducts calculation and analysis. Because of the presence of a highly developed bedding in the carbonaceous slate and sandstone around the Minxian tunnel, that was difficult to implement the discontinuous method due to the significant workload required for bedding modeling. The other one is the continuous method in which the failure criterion of the bedding element is embedded into the solid element at the integral point of the continuous element. Since this method assumes that the bedding is distributed throughout the whole model, the calculation result is conservative. This is suitable for engineering calculations [10]. Hence, the continuous method was adopted in this research. Based on the calculations of the finite element software, the bedding calculation model of carbonaceous slate and sandstone was established. In this model, the bedding was assumed to be a group of joint surfaces with a consistent occurrence. The sliding between the joint surfaces followed the Mohr-Coulomb friction criterion. It was expressed as follows:

\[ F = p \tan \varphi + c - \tau \]  

(1)

In the above equation, \( p \) is the normal force acting on the joint surface, \( \varphi \) is the internal friction angle of the joint surface, \( c \) is the cohesion of the joint surface, and \( \tau \) is the shear sliding force. If \( F > 0 \), the joint surface was closed without mutual sliding, and if \( F = 0 \), the interface was sliding.

In addition to defining the mechanical properties of joints, it was also necessary to define the mechanical properties of bedrocks. In this regard, the Drucker-Prager yield criterion was adopted (the yield trajectory on the meridian plane is shown in Figure 4). The following form of the Drucker-Prager yield criterion was applied in this study:

\[ f_b = q - p \tan \varphi_b - c_b = 0 \]  

(2)

In the above equation, \( q = \sqrt{\frac{3}{2} S : S} \) represents the Mises equivalent deviator stress, \( p = -\frac{1}{3} I : \sigma \) stands for the equivalent compressive stress, \( \varphi_b \) is the internal friction angle of rock block material, and \( c_b \) is the cohesion.
Figure 4. Yield surface of a rock block material.

The numerical model established by calculation and analysis is shown in Figure 5 (the model size was 120 × 120 m). In the calculation process, the deformation characteristics of wall rocks during tunnel excavation were mostly analyzed without considering the influence of the support structure.

Figure 5. Finite element model.

Based on the actual situation of the site, the buried depth of the calculated section was considered to be 200 m. Also, according to the in-situ stress test results of the tunnel site, the angle between the maximum principal stress in the plane and the horizontal plane was considered to be 30 °, as shown in Figure 6. The vertical in-situ stress component was taken to be 5 MPa, the horizontal in-situ stress component was taken to be 9 Mpa, and the shear stress component was taken to be 3.46 MPa.
3.2. Calculation conditions

To analyze the influence of lithology and attitudes of layered soft rocks on the deformation and failure modes of the wall rocks, 12 different calculation conditions were considered in this study, as shown in Table 2. The angle $\alpha$ between the dip angle of the stratum and the maximum principal stress was considered to be between $0^\circ$ and $90^\circ$.

| No. | Lithology          | The angle between bedding and maximum principal stress/° | Maximum principal stress direction/° |
|-----|--------------------|----------------------------------------------------------|-------------------------------------|
| 1   | Sandstone          | No bedding                                               | 30                                  |
| 2   |                    | 0.0                                                      | 30                                  |
| 3   |                    | 22.5                                                     | 30                                  |
| 4   |                    | 45.0                                                     | 30                                  |
| 5   |                    | 67.5                                                     | 30                                  |
| 6   |                    | 90.0                                                     | 30                                  |
| 7   | Carbonaceous slate | No bedding                                               | 30                                  |
| 8   |                    | 0.0                                                      | 30                                  |
| 9   |                    | 22.5                                                     | 30                                  |
| 10  |                    | 45.0                                                     | 30                                  |
| 11  |                    | 67.5                                                     | 30                                  |
| 12  |                    | 90.0                                                     | 30                                  |

3.3. Analysis of deformation and failure characteristics of layered sandstone

To reveal the influence of bedding on the deformation and failure modes of the wall rocks of the tunnel, the deformations of sandstone with and without bedding were analyzed. The results are shown in Figs. 7 and 8. It can be easily noticed that when the influence of bedding was not considered, the deformation
of sandstone was largely elastic, the maximum deformation was 28 mm, and the direction of maximum deformation was parallel to the direction of the maximum principal in-situ stress. When the influence of bedding was taken into account, the excavation of the tunnel led to a significant increase in the deformation of the wall rocks. The maximum deformation was estimated to be 62 mm (calculation condition 4), which was 121.4% larger than that of the sandstone without bedding (see Figure 8). Moreover, the orientation of the maximum deformation was obviously different from that of the sandstone without bedding. This indicated that for the layered sandstone, the influences of bedding on the deformation and failure modes must be taken into account.

![Figure 7. Deformation of the wall rocks without considering bedding cutting (m).](image)

![Figure 8. Calculation condition 4: Deformation of the wall rocks with considering bedding cutting (m).](image)

To analyze the influence of the bedding angle on sandstone deformation, the distribution of deformation of the wall rocks was plotted under different calculation conditions, as shown in Figure 9. It can be seen from this Figure that the angle of bedding had a strong influence on the deformation distribution of sandstone. In terms of deformation, when the angle between bedding and maximum principal stress direction was 0°, 22.5°, 45°, 67.5°, and 90°, respectively, the maximum deformations of the wall rocks were 50 mm, 54 mm, 62 mm, 41 mm, and 29 mm. These maximum deformations suggested that when the angle between the maximum in-situ stress and bedding changed from 0° to 90°, the deformations of the wall rocks initially increased and then decreased. When the angle between the maximum in-situ stress and bedding was 45°, the deformation of the wall rocks was the largest. This demonstrated that the state of the wall rocks was the most unstable in this condition under the comprehensive influence of the in-situ stresses and bedding.
Figure 9. Variation trend of the displacement around layered sandstone tunnels with different bedding angles.

From the deformation distribution of the tunnel, the influence of bedding was also obvious. Under different bedding angles, the displacement variation trend of sandstone around the tunnel is shown in Figure 9. The maximum convergence deformation direction of the wall rocks when the intersection angle of bedding and the maximum principal stress direction was 0°, 22.5°, 45°, 67.5°, and 90°, is shown in Figure 9. Therefore, the deformation distribution was jointly affected by bedding and in-situ stresses, and the maximum deformation direction changed with the change of the bedding angle.

To analyze the influence of bedding on the deformation and failure of sandstone, the distribution of the plastic zone after tunnel excavation was plotted, as shown in Figure 10. It can be seen from this Figure that the plastic failure zone was dominated by the shear slip failure of bedding. When the local stress was parallel to the bedding, the failure direction of the surrounding rock plastic failure zone was parallel to the bedding distribution. With the increase of the angle between the in-situ stress and the bedding, the angle between the failure direction of the plastic zone and bedding gradually increased and tended to become perpendicular to the direction of bedding. This resulted in the shear failure of the bedding as well as the elastic failure of the rock mass. Consequently, during tunnel excavation, for the layered sandstone with high bedrock strength, there was not only shear failure parallel the bedding direction, but also multi-directional and multi-angle plastic failures. They were caused by the combined effects of the in-situ stress and bedding angle.
3.4. Analysis of deformation and failure characteristics of layered carbonaceous slate

The strength of layered carbonaceous slate was lower, and its deformation and failure characteristics were obviously different from those of sandstone after tunnel excavation. To analyze the influence of bedding on the deformation of carbonaceous slate, the tunnel conditions with and without bedding were
plotted, as shown in Figure 11. It can be noticed from this Figure, that when the influence of bedding was not considered, the maximum deformation of carbonaceous slate was 86 mm. When the bedding influence was taken into account, the deformation was up to 860 mm. These showed that the convergence deformation value of carbonaceous slate increased significantly due to the influence of bedding cutting. Therefore, for layered carbonaceous slate, the influence of bedding must be considered during the prediction of the deformation, otherwise, the calculated deformation would be significantly lower.

![Figure 11. Displacement-deformation diagram for carbonaceous slate (m).](image)

To analyze the influence of the bedding angle on the deformation of carbonaceous slate, the deformation distributions of carbonaceous slate under different bedding angles were plotted, as shown in Figure 12. It can be observed that when the angle between the bedding and the maximum principal stress was 0°, 22.5°, 45°, 67.5°, and 90°, the maximum convergence deformation of the wall rocks was 856 mm, 881 mm, 865 mm, 854 mm, and 865 mm, respectively. These demonstrated that the bedding angle had little influence on the deformation distribution, and the orientation of the maximum deformation was perpendicular to the direction of the maximum principal stress.
Figure 12. Variation trend of the displacement around layered slate tunnels with different bedding angles.

To further analyze the mechanism of deformation distribution of layered carbonaceous slate, the plastic failure zones of the wall rocks under different bedding angles were plotted, as shown in Figure 13. It can be observed that, because of the low strength of the carbonaceous slate, the compression failure was the main failure mode after tunnel excavation, and the distribution of the largest plastic zone was parallel to the minimum principal stress. When the wall rocks were crushed, the bedding slips had little influence on the failure range. Hence, the change of the bedding angle had little influence on the plastic failure of the wall rocks.
Figure 13. Distribution of plastic failure zones under different angles of layered sandstone.

In summary, for sandstone and carbonaceous slate, bedding had an obvious influence on the deformation of the wall rocks. When the influence of bedding was not considered in the calculation process, the calculated values were significantly lower. Due to a significant difference between the strength of sandstone and that of carbonaceous slate, the effect of the bedding angle on the deformation distribution and failure mechanism was quite different. Because of the high strength of sandstone bedrock, the deformation and failure of the wall rocks were chiefly caused by the shear failure of bedding, and its deformation distribution was strongly affected by the attitude of bedding. When the angle between bedding and the maximum principal stress direction was 45°, the deformation reached the maximum value. Due to the low strength of the bedrock of layered carbonaceous slate, the wall rocks were obviously crushed after the excavation of the tunnel. The attitude of bedding had a little influence on the amount and distribution of deformation of the wall rocks. Also, the direction of maximum deformation was perpendicular to the direction of the maximum principal stress of the in-situ stress.
4. Conclusion
Considering the Minxian tunnel in the Weiwu Expressway, the deformation and failure characteristics of interbedded carbonaceous slate and sandstone were analyzed under the action of bedding. The following conclusions were drawn from this research:

(1) For layered strata, bedding had a great influence on the deformation of both sandstone and carbonaceous slate. Hence, during the prediction of the tunnel deformation, the influence of bedding must be taken into account, otherwise, the calculated results would be significantly lower.

(2) Because of the difference in strength between the sandstone and carbonaceous slate, the effect of the bedding attitude on its deformation distribution and failure mechanism is significant different. For the sandstone, the deformation mechanism and failure mode of the surrounding rocks are mainly caused by the shear failure of bedding, and its deformation distribution is strongly affected by the angles of bedding. The deformation of sandstone has the maximum value when the angle between bedding and the maximum principal stress direction is 45°. As regard to the tunnel with layered carbonaceous slate, the bedding has a little influence on the deformation and distribution of the surrounding rock because an obvious compression failure zone was formed after the excavation of tunnel. And the direction of the maximum deformation of the layered carbonaceous slate is perpendicular to the direction of the maximum principal in-situ stress.

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