Stability analysis of surrounding rock of bedding dolomite tunnel with different dip angles

Rao Junying¹, Xie Caijin*¹, Zhao Xia¹, Liu Dengkai¹, Nie Chongxin¹, Liu Ning¹, Song Shuai²

¹ School of Civil Engineering, Guizhou University, Guiyang 550025, China
² Construction engineering college, Guizhou Polytechnic of Construction, Qingzhen 551400, China

Corresponding author’s e-mail: Xie0803@126.com

Abstract: To investigate the stability of surrounding rock of bedding dolomite tunnels with different dip angles, this study considers the diversity of tunnels in different geological conditions. In the case of five different bedding angles, the effects of different dolomite rock thicknesses, contact interlayer thicknesses, contact interlayer elastic moduli, contact interlayer cohesive forces, and contact interlayer friction angles on tunnel stability are analyzed. When the bedding angle is 22.5°, the surrounding rock displacement is the largest, the peeling between layers is obvious. The plastic zone of the surrounding rock is concentrated in the unsupported area of the tunnel. The contact interlayer has a weakening effect on the displacement of the surrounding rock and the expansion of the plastic zone. The thickness of the dolomite and the thickness of the contact interlayer have different effects on the displacement of surrounding rock of different bedding angles. Increasing the elastic modulus of the contact interlayer can reduce the displacement of the surrounding rock, increasing the internal friction angle of the contact interlayer has less influence on the displacement of the surrounding rock, and increasing the cohesive force of the contact interlayer can reduce the displacement of the surrounding rock.

1. Introduction

With the continuous improvement of the transportation system, the number of tunnels has been increasing in recent years, and geological conditions have diversified. Various geological environments greatly impact tunnel structure. In tunnel engineering, the geological body and its supporting structure within a certain range of the tunnel constitute the tunnel bearing system, that is, the rock mass around the tunnel + the tunnel supporting structure = the tunnel structural system. To fully utilize the bearing capacity of surrounding rock and reduce the support pressure during tunnel excavation, detailed investigation on the stability of surrounding rock is needed. At present, the commonly used research methods include model test, numerical analysis, monitoring measurement, and classification of surrounding rock [1-10].

With the upgrade of computing software and the improvement of simulation accuracy, numerical simulation has become a common method to study tunnel surrounding rock stability. The Guiyang City Rail Transit Line 1 Railway Station–Sha Chong Road Station undercut tunnel project from below the railway station is taken as example in this study. The stability of surrounding rock of bedding dolomite tunnels with different dip angles is analyzed through finite element analysis, and the pre-control effect can be achieved before the next construction.
2. Project Overview
This study is based on the underground interval of Guiyang Rail Transit Line 1 Railway Station–ShaChong Road Station (hereinafter referred to as the Huo-Sha tunnel). The Huo-Sha tunnel is a double-hole single-line structure with a total length of 925.411 m. The cores drilled on site are mostly columnar, short columnar, and blocky, and some cores are distributed with honeycomb pores, crystal holes, and joints. The measured RQD value is 30%–75%. The closed joints are more distributed. Only a few joints are open, and the open joints are mostly calcite fine vein cementation. The degree of cementation is good, and the surrounding rock grade belongs to the Class IV surrounding rock. No surface water system is found near the site. After drilling, no groundwater is found in each borehole. The groundwater does not increase, a small amount of upper water is stagnant, and the groundwater level is deep. The resting water level is 1053.00 m. The drilling water test is slightly corrosive to concrete and steel.

3. Numerical Simulation Analysis of Bedding Surrounding Rock Stability of Dolomite Tunnel

3.1 Finite element model establishment
For the finite element simulation of the layer in the surrounding rock, two simulation modes of the sandwich unit and the contact unit are used. Deng Bin et al. [1] studied the weak interlayer in the simulated rock mass of the sandwich unit and the contact unit in 2008. The contact element simulation is higher than the resulting precision sandwich unit simulation. For the simulation of the sandwich unit, the accuracy decreases as the thickness of the interlayer increases. When the thickness of the weak interlayer is 0.1 m, the calculation error is approximately 5.75%. When the thickness of the weak interlayer is 0.05 m, the calculation error is approximately 3.21%. The purpose of this study is only to determine the relative size of the influence of the bedding under different dip angles on the stability of the dolomite tunnel. A 0.05 m interlayer unit is used to simulate the bedding plane.

To investigate the surrounding rock stability of dolomite tunnels with different bedding angles, five models with different laminar inclination angles of 0°, 22.5°, 45°, 67.5°, and 90° are established. In establishing the finite element model, the plane model is used to simulate the influence of the size of the analysis on the surrounding rock of the tunnel. The model tunnel size is 3.3 m × 3.6 m, and the plane size is 56 m × 48 m. In the numerical simulation, the dolomite and contact interlayer adopt Mohr–Coulomb criterion and plane strain simulation. The values of the model parameters are listed in Table 1, and the mesh division is shown in Fig. 1.

| Model parameter table |
|------------------------|
| Formation or support structure | Elasticity modulus (GPa) | Poisson’s ratio | Severe (kN/m²) | Cohesion (MPa) | Frictional angle (°) | Remarks |
| Dolomites | 14.5 | 0.22 | 26.0 | 3.52 | 39.1 |
| Weak interlayer | 0.5 | 0.45 | 26.0 | 0.5 | 15.0, 25.0, 35.0 |
| Contact interlayer | 0.5 | 0.45 | 26.0 | 0.5 | 15.0, 25.0, 35.0 |
| Initial support | 15.0 | 0.20 | 25.0 | / | / | Initial support: C25, thickness 350 mm |
| Rock bolt | 200.0 | 0.30 | 78.5 | / | / | 25 mm diameter, circumferential spacing 1 m |

3.2 Analysis of finite element simulation results
Basing on Midas GTS/NX finite element software, two important factors, namely, the displacement of surrounding rock and the plastic zone of surrounding rock under different working conditions, are studied.

(1) Comparison of surrounding rock displacement and plastic zone of dolomite tunnels with different dip angles

The dolomite rock layer is 0.5 m thick, and the interlayer thickness is 0.05 m. The bedding angles are 0°, 22.5°, 45°, 67.5°, and 90°.

① Surrounded rock displacement comparison

The 0° bedding surrounding rock has the largest displacement of the tunnel vault, and the displacement value is 15.5 mm (Fig. 1). In the 22.5°, 45°, and 67.5° bedding surrounding rock, the maximum displacement occurs at the junction of the upper tunnel and the bedding boundary, and the
displacement values are 29.7, 4.9, and 7.3 mm, respectively. However, no obvious displacement is noted at the boundary between the bottom wall and the bedding of the right side wall of the 45° bedding surrounding rock. Displacement also occurs at the boundary between the bottom wall and the bedding of the right side wall of the 67.5° bedding surrounding rock tunnel, which is more obvious than the 45° bedding. Under the 90° bedding condition, the maximum displacement occurs at the boundary between the side walls and the bedding at both sides of the tunnel, and the displacement value is 5.2 mm.

Fig. 1 Surrounding rock at different dip angles

Two Comparison of surrounding rock plastic zone

The size of the plastic zone of the surrounding rock is an effective indicator for the stability of the surrounding rock. In the 0° bedding surrounding rock, the plastic zone is concentrated at the tunnel vault, and the plastic zone of the surrounding rock is greatly affected by the layering and stratification. When crossing the bedding plane, the plastic zone of the surrounding rock is weakened more obviously. In the 22.5° bedding surrounding rock, the plastic zone is concentrated at the junction of the upper surface of the tunnel and the layering boundary. The article defines this junction as the unsupported area of the bedding dolomite tunnel. In the 45°, 67.5°, and 90° bedding surrounding rock, the surrounding plastic zone is also concentrated in the unsupported area of the tunnel (Fig. 2).

Fig. 2 Plastic zones in different dip angles

(2) Surrounding rock displacement and plastic zone comparison of bedding dolomite tunnels with different thicknesses

The dolomite rock layers are 0.5, 1.0, and 1.5 m thick; the interlayer thickness is 0.05 m; and the bedding angles are 0°, 22.5°, 45°, 67.5°, and 90°.

1) Surrounding rock displacement comparison

In the 0° bedding surrounding rock, the displacement of surrounding rock increases with the increase of dolomite rock thickness. The reason is that the surrounding rock strata are thicker and have larger self-weight, thereby resulting in larger displacement. When the rock thickness is 0.5, 1.0, and 1.5 m, the displacement of the surrounding rock is 15.4, 16.8, and 25.5 mm, respectively.

At 22.5° bedding surrounding rock, when the rock thickness is 0.5, 1.0, and 1.5 m, the displacement of surrounding rock is 29.7, 40.2, and 38.7 mm, respectively. At a thickness of 1.0 m, owing to the special location of the bedding, the residual layering of the unsupported area after tunnel excavation is relatively thin, the displacement of surrounding rock is large, and the displacement of surrounding rock continues to increase with rock thickness.

In the 45° and 67.5° bedding surrounding rock, when the rock thickness is 0.5, 1.0, and 1.5 m, the displacement of the 45° bedding surrounding rock is 4.9, 26.7, and 45.6 mm respectively; the displacement of the 67.5° bedding surrounding rock is 7.3, 13.4, and 3.0 mm, respectively. The displacement of surrounding rock is large with the increase of rock thickness. When the rock is thinner, the displacement of the unsupported area of the tunnel is larger, and the thicker the rock, the interlayer slip of the bedding is more obvious than the interlayer separation. The maximum displacement moves from the unsupported area to the tunnel vault.

In the 90° bedding surrounding rock, when the rock thickness is 0.5, 1.0, and 1.5 m, the displacement of surrounding rock is 5.2, 7.3, and 5.7 mm, respectively. The displacement of the
surrounding rock that occurs at the side walls of both sides of the tunnel is large.

Under different rock thickness conditions, for the bedding dip angle of 22.5° dolomite, the displacement average is the largest and reached 36.2 mm. The bedding angle is 67.5° and 90° dolomite, and the average displacement is small. The displacement values are 7.9 and 6.1 mm, respectively. The 22.5° bedding surrounding rock has a greater degree of interlayer stripping than the 67.5° bedding surrounding rock. During initial support, support is strengthened for the unsupported area of 22.5° bedding surrounding rock. In the 45° bedding surrounding rock, the layer thickness increases, the component force of gravity increases in the vertical direction, and the interlayer slip is more obvious, resulting in linear growth of the surrounding rock displacement (Fig. 3).

Fig. 3 Displacement diagram of surrounding rock thickness in different rock layers

2. Comparison of surrounding rock plastic zone

After the tunnel is excavated, a plastic zone will be formed in the vicinity of the tunnel’s unsupported area. In the 0° bedding surrounding rock, after tunnel excavation is completed, the plastic zone of the surrounding rock is concentrated in the position of the unsupported area of the vault, and the plastic zone is greatly affected by the bedding contact interlayer. Given that the rock strata in the unsupported area of the tunnel form their own beam, the plastic region becomes smaller with each passing contact sandwich.

In the 22.5° bedding surrounding rock, the plastic zone of the surrounding rock is concentrated in the left arch shoulder space where the tunnel intersects the bedding. Similarly, the rock strata in the overhanging zone of the tunnel form their own beams, which can resist the further expansion of the surrounding rock’s plastic zone.

In the 45° bedding surrounding rock, rock thickness is 0.5 and 1.0 m, and the plastic zone of surrounding rock is similar to 22.5° bedding surrounding rock. The rock is also concentrated on the position of the left-shoulder unsupported area where the tunnel intersects the bedding. However, for rock strata with a thickness of 1.5 m, the rock layer is thicker, the self-formed beam has greater stiffness, and the plastic zone is smaller than the first two.

The 67.5° bedding surrounding rock is generally similar to the 45° bedding surrounding rock. In the case of thicker rock layers, the plastic zone of the arch crown is more pronounced than the unsupported area.

The 90° bedding surrounding rock has a change law similar to that of other bedding dip angles. The unsupported area at this time is on both sides of the wall.

In the plastic zone of dolomite tunnel with different dip stratifications under the working condition of different rock thickness, the plastic zone of surrounding rock is mostly concentrated in the unsupported area of the surrounding rock where the tunnel intersects with the bedding. The contact interlayer of the rock layer can effectively resist the development of the plastic zone of surrounding rock. The bedding surrounding rock layer has the function of forming its own beam, and with the increase of the thickness of the rock layer, the greater the beam stiffness, the more obvious the development of the plastic zone resisting the surrounding rock.

(a) Rock layer thickness 0.5m  (b) Rock layer thickness 1.0m  (c) Rock layer thickness 1.5m

Fig. 4 22.5° bedding plastic zone

3) Correlation between displacement and plastic zone of surrounding rock of bedding dolomite
tunnel with different contact sandwich thicknesses

Different layers of sedimentary materials and thicknesses will form different bedding surrounding rocks, and layers with relatively weak properties (e.g., mechanical properties) are called contact interlayers. In the surrounding rock with different dip angles, the thickness of the contact interlayer also affects the stability of the surrounding rock of the tunnel. The thickness of dolomite rock is 1.5 m, and the thickness of contact interlayer is 0.05, 0.5, and 1.5 m, respectively. The displacement and plastic zone of surrounding rock under different dip angles are compared.

1 Surrounding rock displacement comparison

In the 0° bedding surrounding rock, the maximum displacement of surrounding rock occurred in the unsupported area under the condition of contact interlayer thickness of 0.05 and 0.5 m, and the values were 25.6 and 50.6 mm, respectively. Under a contact interlayer thickness of 0.5 m, the displacement value is relatively large because the tunnel vault cuts more rock layers, which leads to the reduction of the stiffness of the dolomite rock stratum and the increase of the displacement. Under a contact interlayer thickness of 1.5 m, the contact interlayer existing under the tunnel inverting arch is thicker when the model is established, and the larger displacement value appears in the tunnel inverting arch position. The value is 5.9 mm.

In the 22.5° bedding surrounding rock, the maximum displacement of the surrounding rock occurred in the unsupported area with the thickness of the contact interlayer of 0.05 and 0.5 m, and the values were 38.7 and 15.2 mm, respectively. When the contact interlayer thickness is 0.5 m, the displacement value is small mainly because the tunnel arch position is reduced by more rock layers, and the remaining rock layers are thinner, and the initial support can effectively control the displacement. Under a contact interlayer thickness of 1.5 m, the contact interlayer existing under the tunnel inverting arch is thicker owing to the model establishment, and the larger displacement value appears in the tunnel inverting arch position. The value is 5.2 mm. The rock formation is inclined, and the surrounding rock at the inverted arch tends to slide downward.

In the 45° bedding surrounding rock, the maximum displacement of the surrounding rock occurs near the unsupported area under the condition of contact interlayer thicknesses of 0.05 and 0.5 m, and the values are 45.6 and 13.2 mm, respectively. Owing to the location of the tunnel, the rock formation in the unsupported area is not weakened too much under the two working conditions, and the self-stability is better. Under the condition of contact interlayer thickness of 1.5 m, the contact interlayer is weakened too much, and the displacement value is 17.3 mm. The dip angle of the rock formation is large, and the area affected by the weak interlayer is large.

In the 67.5° and 90° bedding surrounding rock, the maximum displacement of the surrounding rock occurs near the unsupported area under the condition of contact interlayer thickness of 0.05 m, and the values are 3.1 and 5.7 mm, respectively. The unsupported area of tunnel does not weaken many rock layers, and the rock layer has good self-stability. Under the condition of contact interlayer thickness of 0.5 m, the maximum displacement of the surrounding rock occurs in the unsupported area with values of 9.7 and 9.8 mm. The unsupported area of the tunnel weakens more rock layers, and the initial support effect is better. Under the condition of contact interlayer thickness of 1.5 m, the displacement value is 9.3 and 7.4 mm, the dip angle of the rock formation is large, and the displacement influence area is large.

For the 0° (horizontal) dip bedding surrounding rock, the thickness of the contact interlayer increases first and then decreases. When the 0.05 m is increased to 0.5 m, the maximum displacement of the surrounding rock increases from 25.6 mm to 50.6 mm; at 0.5 m to 1.5 m, the maximum displacement of the surrounding rock is reduced from 50.6 mm to 5.9 mm. This situation is mainly related to the weakening of the horizontal cross-section rock thickness of the tunnel section. Within a certain range, the maximum displacement of the rock mass increases with the weakening of the thickness, and the rock layer has the function of a self-forming beam. For 22.5° and 45° (low angle dip), the maximum displacement of the surrounding rock decreases as the thickness of the contact layer increases. For 67.5° and 90° (steep angle), the maximum displacement of the surrounding rock increases with the thickness of the contact layer, but the increase is small. The contact interlayer has a
barrier to the expansion of the surrounding rock displacement. In addition, the displacement of the surrounding rock is also related to the distance from the tunnel inverting arch to the underlying contact interlayer and the thickness of the contact interlayer (Fig. 5).

![Fig. 5 Surrounding rock displacement map of different contact interlayer thicknesses](image)

② Comparison of surrounding rock plastic zone

For the dolomite rock thickness of 1.5 m, the thickness of the contact interlayer is 0.05, 0.5, and 1.5 m (soft and hard interbedded rock), and the plastic zone of the surrounding rock is compared and analyzed under different dip angles.

In the 0° and 22.5° bedding surrounding rock. When the contact interlayer thickness is 0.05 and 0.5 m, the surrounding plastic zone is concentrated in the unsupported area of tunnel. The 1.5 m contact interlayer (soft and hard interbedded rock), the plastic zone of the surrounding rock is concentrated in the tunnel inverting arch.

In the 45° bedding surrounding rock, when the contact interlayer is 0.05 m thick, because the tunnel does not weaken much of the surrounding rock, the surrounding rock has good self-stability; thus, the plastic zone of the surrounding rock is concentrated near the unsupported area of the tunnel. When the thickness of the contact interlayer is 0.5 m, the plastic zone of the surrounding rock is concentrated in the vault. The 1.5 m contact interlayer (soft and hard interbedded rock), the plastic zone of the surrounding rock is concentrated in the unsupported area of tunnel, the area where the tunnel inverting arch and the surrounding rock are at the boundary for the same reason as the surrounding rock displacement.

In the 67.5° bedding surrounding rock, when the contact interlayer is 0.05 m thick, the plastic zone of the surrounding rock is concentrated near the unsupported area of the tunnel for the same reason as the surrounding rock displacement. In the 0.5 and 1.5 m contact interlayer, the plastic zone of the surrounding rock is concentrated in the unsupported area of tunnel.

In the 90° bedding surrounding rock, when the contact interlayer is 0.05 m thick, the plastic zone of the surrounding rock is concentrated near the unsupported area of the tunnel (left wall) and partially focused on the vault. In the 0.5 and 1.5 m contact interlayer, the plastic zone of the surrounding rock is concentrated in the unsupported area of tunnel (left wall). The rock layer on the right wall indicates relatively small weakening and no obvious plastic zone.

Under the same condition, the surrounding rock displacement has a one-to-one correspondence with the surrounding rock plastic zone. In general, the range of the surrounding rock plastic zone is larger than the surrounding rock displacement range. The contact interlayer has the ability to weaken the plastic zone of the surrounding rock to extend deeply.

![Fig. 6 67.5° bedding plastic zone](image)

![Fig. 7 90° bedding plastic zone](image)
4 Conclusion

(1) The displacement value is the largest under the condition of 22.5° dip angle, and the displacement changes with the displacement dip angle are gentle.

(2) The 0° bedding surrounding rock plastic zone is concentrated at the tunnel vault, the plastic zone of the surrounding rock is greatly affected by the stratification of the bedding, crossing the bedding plane, the plastic zone of the surrounding rock is weakened more obviously. The 22.5°, 45°, 67.5°, and 90° bedding surrounding rock plastic zones are also concentrated in the unsupported area.

(3) Under different rock thickness conditions, the degree of interlayer peeling of 22.5° bedding is greater than that of 67.5° bedding. During initial support, support should be strengthened for the unsupported area of the 22.5° bedding rock. In the 45° bedding surrounding rock, the layer thickness increases, the component force of gravity increases in the vertical direction, and the interlayer slip is more obvious, resulting in linear growth of the surrounding rock displacement.

(4) The contact interlayer of the rock layer can effectively resist the development of the plastic zone of the surrounding rock. The bedding rock layer has the function of a self-forming beam, and with the increase of the thickness of the rock layer, the rigidity of the beam is greater, and the effect of inhibiting the development of the plastic zone of the surrounding rock is more obvious.

(5) Within a certain range, the maximum displacement of the rock mass increases with the increase in the thickness, and the rock layer has the function of a self-forming beam. The contact interlayer has a barrier effect on the expansion of surrounding rock displacement, the displacement of the surrounding rock is also related to the distance from tunnel inverting arch to underlying contact interlayer and the thickness of the contact interlayer. The contact interlayer has a good effect on preventing the development of the plastic zone.

Acknowledgments

We are grateful to the Chinese Fund of Natural Science (Grant No. 51608141), the Introduction of Talents Scientific Research Fund of Guizhou University (Grant No. (2015)16), the Guizhou Science and Technology Plan Project (QKJ [2016] 1041) and the Guizhou Province Civil Engineering First Class (QYNYL [2017] 0013) for sponsoring this paper.

References

[1] B A. Importance of Anisotropy When Estimating and Measuring in Situ Stress in Rock[J]. Int J Rock Mech Min Sci Geomech Abstr, 1996,33(3):293-325.

[2] Homand F M E H J. Characterization of the Moduli of Elasticity of an Anisotropic Rock Using Dynamic and Static Methods[J]. Int J Rock Mech Min Sci & Geomech Abstr, 1993,30(5):527-535.

[3] Xing Xinkui, Zhang Kumpeng, Yan Maolong, et al. Model Test Research on Influence of Earth Tunnel Support Patterns on Stability of Surrounding Rock[J]. Rock and Soil Mechanics, 2014,35(08): 2157-2162.

[4] Wu Mengjun, Chen Zhanggui, Xu Xibin, et al. The Present and Prospect of Highway Tunnel Surrounding Rock Stability[J]. Journal of Chongqing Jiaotong University, 2003,22(2): 24-28.

[5] Li Diyuan, Li Xibing, Zhang Wei, et al. Stability Analysis of Surrounding Rock of Multi-arch Tunnel Based on Coupled Fluid-solid Theorem[J]. Chinese Journal of Rock Mechanics and Engineering, 2007,26(5): 1056-1064.

[6] Zheng Yingren, Wang Yongzhen, Wang Cheng, et al. Stability Analysis and Exploration of Failure Law of Jointed Rock Tunnel—Seminor on Tunnel Stability Analysis[J]. Chinese Journal of Underground Space and Engineering, 2011,7(4): 649-656.

[7] Lee C, Shou K, Chen S, et al. Numerical analysis of tunneling in slates with anisotropic time-dependent behavior[J]. Tunnelling and Underground Space Technology, 2019,84:281-294.

[8] Song Lixia, Tao Ganqiang, Wang Qingliang. Present Situation and Development Trend of Numerical Simulation of Stability of Surrounding Rocks in Tunnel[J]. Express Information of
Mining Industry, 2007, 6: 16-20.
[9] Huang Chenxi. Stability Analysis on River-crossing Shield Tunnel Nanchang Metro Line one[D]. Nanchang University, 2016:8-14.
[10] Fan Weihua. Study on Surrounding Rock Stability and Lining Reliability of Gonghe Tunnel Construction [D]. Chongqing University, 2009:1-9.
[11] Wang Xiaolei. Experimental Study on Bedding Structure Effect of Soft Rock[D]. China University of Mining and Technology (Beijing), 2013:19-41.