Study on Support Optimization of mining roadway in deep steeply dipping coal seam

Sang Fengyu¹ Huang jing², Zhao Baoxiang³

¹Information Institute, Ministry of Emergency Management of People’s Republic of China, Beijing 100029, China
²College of Energy and Mining Engineering, Shandong University of Science and Technology Qingdao Shandong 266590, China
³Shanghai Miao Mining Co., Ltd., Yinchuan, Inner Mongolia 016299, China

Abstract: In order to solve the problem of the failure phenomenon of roof fall and the inward extrusion of two roadsides in main roadway of 31205 working face of Zhubai coal mine, the theoretical analysis, field measurement and numerical simulation were adopted to study the rock breakage and instability of roadway’s and put forward the differential anchor cable and bolt targeted support solution. Industrial tests and the roadway pressure observation were carried out in 31205 main roadway. The field application results showed that the deformation and break of roadway surrounding rock is effectively controlled, the supporting cost was reduced and the supporting effect was remarkable.

1. Introduction

China’s abundant coal resources and long-term strong demand have led to a rapid growth of coal development to a rate of 10~25 m in the depth of mines per year. The mining depth of the main mines in the Middle East has reached 800-1000 m, of which 47 mines are over 1000 m deep. The maximum mining depth of Suncun colliery of Shandong Energy Xinwen Mining Group Co., Ltd. is more than 1500 m[1]. The reserves of steeply dipping coal seam account for 15% - 20% of the total amount of coal in China, widely distributed in major mining areas. Due to the complicated stress environment and weak and water-rich surrounding rock during the mining of deep steeply dipping coal seam, the roadway support cost is high and the support effect is poor, which cannot meet the safe and efficient stoping requirements[2].

Through the comprehensive research on the characteristics of loading and instability of the full-mechanized mining face with large mining height and dip angle, the deformation, failure and migration of the surrounding rock show asymmetric characteristics under the influence of the coal seam dip angle. As the dip angle and mining height increases, the asymmetric characteristics of coal wall abutment pressure become more obvious[3]. After monitoring and analyzing the surrounding rock activities, the data shows that the deformation of the roadway is mainly based on the rise side. Besides, the total load of the anchor cable at the rise side of the roadway is the largest, consequently, the anchor beam net with reinforced anchor cable is proposed[4]. The numerical simulation software is applied to study the deep gob-side entry retaining, and it is proposed to fill the supporting with high pre-stress and intensive bolts and cable support with paste, which can effectively solve the serious deformation of the gob-side entry retaining when working[5]. However, there are few existing studies on roadway support of the deep steeply dipping coal seam, so it is urgent and meaningful to study the roadway support under these
Taking Zhubai colliery as the engineering background, this paper study the stability of the roadway with broken surrounding rock at the by theoretical analysis, numerical simulation and on-site measurement. It is expected to provide research foundation for the roadway support under similar conditions.

2. Introduction of engineering geology

Zhubai colliery mainly includes 3 coal seams, which are located in the middle of Shanxi group, with an average buried depth of about 700 m, a thickness of 2.6-6.6 m and an average thickness of 4.6 m. The Protodyakonov hardness $f$ of the coal seams is 0.5-1.5, the tendency is about 90° and the strike is about 0°. The dip angle of the coal seams is 41° - 59° and the average is 50°. These seams are steeply dipping coal seams, of which the structure is simple and the adhesion is poor. The immediate roof is mainly grey-black sandy shale with coal streaks, which is rich in plant fossils and well bedded with the average thickness of 8.0m and the Protodyakonov hardness $f$ of 4.0-6.5. It belongs to the typical mining of the deep steeply dipping coal seam with broken surrounding rock. The working face adopts the comprehensive mechanical strike longwall retreating mining method with a mining height of 4.6 m and the advance of each working cycle of 0.8 m. And, the roof of goaf is managed by natural caving method. The comprehensive geological column of working face is show in Figure 1:

![Fig. 1 The comprehensive geological column of the 31205 working face](image)

3. Analysis of deformation and mechanism of roadway

3.1. Deformation of roadway

During the stoping process of the 31205 working face, the roof of the transportation roadway sinks as a whole, and the amount of the subsidence at the working face exceeds 600 mm. The coal in the two sides of the roadway are completely broken and the expansion is obvious with expansion amount of 500 mm. The coal deformation is prominent and the anchor cable fails to meet the design anchorage requirements, resulting in frequent loosening of the anchor cable and insufficient pre-tightening force. The deformation of the transportation roadway is shown in Figure 2. The deformation of the roof and the two sides of the roadway is serious, and mining operation cannot be carried out. As a result, the workers have to repair, which seriously affected the production progress of the coal mine.
3.2. Deformation mechanism of roadway

The transportation roadway of the 31205 working face in Zhubai colliery is deep stoping roadway, which has the characteristics of large buried depth, high geostress and high karst hydraulic pressure compared with the shallow roadway. The horizontal stress of the two sides of the roadway is large and different, resulting in serious and irregular deformation of the two sides, especially in the position of the spandrel and the bottom corner. The surrounding rock of the roadway in the steeply dipping coal seam sinks gradually along the bedding plane. The stress of the surrounding rock of the two sides of the roadway is asymmetric, and there are geostress differences between the sides, resulting in asymmetric deformation of the roadway. In addition, the integrity and strength of the roadway roof in the 31205 working face are poor, and thus the working face is prone to caving during the excavation. The bedding phenomenon of the mudstone roof is obvious, and the cohesion between each stratum is small and the dip angle is large. The vertical stress of the surrounding rock has component along the bedding, and there is a tendency of relative sliding between the strata. For the reason that the thickness of the mudstone roof is 8 m and the shallow coal is relatively broken, it is difficult for the ordinary bolt supporting to work.

The failure of deep steeply dipping roadway usually starts from the stress concentration zone or weak parts. The obtuse angle at the intersection of the roadway and the inclined stratum is prone to stress concentration, thus causing relative dislocation of the strata. Then, shear slip failure of the strata and crack and slide of the surrounding rock occur. Eventually, it forms a fracture zone and compresses the supporting.

The 31205 working face of Zhubai colliery is located in the middle and lower part of Shanxi group, whose roof is sandy shale. The stratum is well bedded and easily permeates the above silty sandstone stratum to form cracks, so that the crack will soften the absorbent roof, resulting in that the anchor cable cannot meet the design anchorage requirements. When the roadway drainage does not function, the long-term soaking of the roadway sidewall caused the decrease of strength and leakage. In addition, the parameters of anchor cable equipment (diameter, length, installation angle, pallet area, pre-stress application, etc.) and support technology do not match the actual geological conditions of the roadway, and the parameters is unreasonably set, which leads to the failure of anchor cable. Besides, the selection of the cross-section shape and support method of the steeply dipping roadway with broken surrounding rocks lack sufficient theoretical study. Therefore, it is very important to select the support parameters reasonably.

4. Numerical analysis

To study the influence of bolt spacing and concrete thickness on the surrounding rock support effect during the stoping process of 31205 working face in Zhubai colliery, Flac3D is used to construct the stoping model of the working face. Meanwhile, according to the elastoplastic theory, considering the
influence of the bearing pressure and the range of filling area, the boundary conditions of the calculation model is set as follows. The upper boundary is applied with uniform load to simplify the model structure, and the thickness of the floor stratum is 40m. The dimension of the model is 200m×100m×240m (Length×width×height). The constitutive relation of Mohr-Coulomb model is adopted for the surrounding rock of the roadway. The horizontal displacement at the boundary is zero, and the bottom is fixed. The whole model is shown in Figure 3. The model is divided into 287,000 quadrilateral elements and 302,978 nodes. The physical parameters of coal and rock are shown in Table 1.

Table 1 Physical parameters of coal and rock

| Layer         | Rock types               | Natural density kg/m³ | Shear modulus/Pa  | Bulk modulus/Pa  | Cohesive force/Pa | Internal friction Angle/(°) | Tensile strength/Pa |
|---------------|--------------------------|-----------------------|-------------------|------------------|-------------------|-----------------------------|---------------------|
| Roof 5        | tuff                     | 2450                  | 7.9e+9            | 3e+9             | 6.06e+6           | 32                          | 4.972e+6            |
| Roof 4        | charcoal mudstone        | 2450                  | 7.9e+9            | 3e+9             | 6.06e+6           | 32                          | 4.972e+6            |
| Roof 3        | sandy mudstone           | 2450                  | 7.9e+9            | 3e+9             | 6.06e+6           | 32                          | 4.972e+6            |
| Roof 2        | Silty sand rock          | 2020                  | 9.3e+9            | 2.5e+9           | 2.83e+6           | 46.91                       | 3.972e+6            |
| Roof 1        | Sandy clay               | 1998                  | 8e+9              | 2.4e+9           | 0.6e+6            | 46.91                       | 0.972e+6            |
| 3rd seam      | 3rd seam                 | 1118                  | 5e+8              | 2e+9             | 2.6e+6            | 40.65                       | 1.076e+6            |
| Floor 5       | charcoal mudstone        | 1998                  | 9.1e+9            | 2e+10            | 0.6e+6            | 46.91                       | 0.972e+6            |
| Floor 4       | sandstone                | 1998                  | 9.1e+9            | 2e+10            | 0.6e+6            | 46.91                       | 0.972e+6            |
| Floor 3       | medium sandstone         | 2032                  | 2.7e+9            | 1.3e+7           | 1.34e+6           | 36.98                       | 3.572e+6            |
| Floor 2       | sandy mudstone           | 1998                  | 9.1e+9            | 2e+10            | 0.6e+6            | 46.91                       | 0.972e+6            |
| Floor 2       | mudstone                 | 1998                  | 9.1e+9            | 2e+10            | 0.6e+6            | 46.91                       | 0.972e+6            |

Figure 3 The numerical calculation model of the 31205 working face

The original support model of the working face is simulated for 100m stoping. After the calculation operation reaches equilibrium, the stress and displacement are analyzed. With the mining of the coal
seam in the working face, the distribution of vertical stress in the roof strata on both sides of the coal seam is clear, which shows the stress increasing area, stress peak area and stress relaxed area in front of the working face. From the stress contour in Figure 4, it can be seen that the depth of the distressed zone in the footwall is about 5 m, and the stress is 0.5 ~ 1.5 MPa. Similar to the footwall, as the pressure of the overlying strata of the stoping seam on in the working face is released, a certain depth of the distressed zone is generated in the roof, and the stress of the zone is only 0.5 MPa. With the decrease of the distressed area of the roof, the stress value increases gradually, and the value is about 24 MPa at about a 15 m depth of the roof.

![Figure 4 The stress contour of the working face for 100m stoping](image)

With the continuous mining of coal in the working face, the roadway footwall swells upwards, and the uplifting speed in the middle is faster than that of the two sides. Moreover, the uplifting speed from the surface to the depth of the footwall gradually decreases, which is consistent with the actual deformation. Apart from that, the roof strata also subside during the mining process. The subsidence speed of the strata in the horizontal direction is that the overlying strata in the middle of the goaf subsides fast, while the subsidence speed of the overlying strata at the side of working face and both ends of the goaf, which is closed to the open-off cut, is slow. In the vertical direction, the overlying strata near the bottom of the roof subsides fast, and the subsidence speed the strata at the top of the roof is slow.

4.1. Analysis of bolt spacing in roadway

Three sets of bolt spacing and thickness of concrete spray layer were selected for simulation. Considering the actual broken surrounding rock and construction conditions of the roadway of deep steeply dipping coal seam, the bolt spacing was set at 400, 600 and 800 mm respectively, and the thickness of concrete spray layer was set at 150, 200 and 280 mm. The support effect of different bolt spacing and layer thickness on the roadway was studied. The basic parameters of anchor are shown in Table 2. According to displacement boundary constraints, the displacement velocity of each boundary of the model is 0. It mainly analyzes the effect of the bolt spacing on the pressure arch during the simulation.

![Table 2 The mechanical parameters of high-strength bolt](image)

The stress field of the surrounding rock under different bolt spacing is shown in Figure 5, and the characteristic parameters of bearing arch under different bolt spacing are shown in Table 3. It can be seen that with the decrease of anchor spacing, the minimum thickness of low stress bearing arch (< 16KPa) increases, and the thickness of 10KPa bearing arch increases from 1.4 m to 2.1 m. High stress
arch lines begin to overlap to form high-pressure arch (26KPa, 28KPa), and the thickness of high stress bearing arch increases gradually. The relationship between the ultimate strength of the bearing arch and the bolt spacing is approximately linear, while the minimum thickness of the bearing arch decreases approximately as a power function. When the bolt spacing is reduced from 800 mm to 300 mm, the minimum thickness decreases from 0.39 m to 0.25 m. When the spacing reaches 400 mm ~ 300 mm, a large area and high strength compressive stress zone is formed in the anchorage range. In the surrounding rock, the maximum strength of bearing arch is 28KPa and the thickness is 0.25 m. While the minimum strength of the compressive stress arch is 10KPa and the thickness is 2.1 m. The surrounding rock in the anchoring area is almost under high compressive stress.

![Figure 5 Stress distribution of the surrounding rock under different bolt spacing](image)

**Table 3 The characteristic parameters of compressive arch under different bolt spacing**

("—" indicates that no compression arch is formed)

| item  | 28 | 26 | 24 | 22 | 20 | 18 | 14 | 12 | 10 |
|-------|----|----|----|----|----|----|----|----|----|
| 800mm | —  | —  | —  | —  | —  | —  | 0.4| 0.8| 1.1| 1.4|
| 600mm | —  | —  | —  | —  | 0.4| 0.5| 0.6| 0.9| 1.2| 1.3| 1.5|
| 400mm | 0.3| 0.4| 0.7| 0.8| 1.1| 1.2| 1.3| 1.4| 1.6| 1.7|

4.2. **Analysis of thickness of concrete spray layer in roadway**

The concrete spray layer with different thicknesses in roadway was simulated, and the results are shown in Figure 6. The main effect of the high-strength spray layer on the surrounding rock is to improve the stress of the unanchored area of the shallow anchor. As the layer thickness increases, the stress of the surrounding rock in the unanchored area gradually changes from the tension to the compression. When the thickness is close to 200 mm, the surrounding rock is almost under compression. It is very important for the stability of the surrounding rock in unanchored areas and improvement of the bolting and shotcreting support. It can be seen from Figure 5 that the stress of the surrounding rock in anchorage area increases rapidly with the increase of the layer thickness, and the thickness raises from 80 mm to 200 mm (1.5 times). The maximum principal stress in the surrounding rock changes from 24KPa to 45KPa nearly 0.875 times. The reason is that the spray layer of high-strength concrete could strengthen the integrity of the surrounding rock. The larger the layer thickness is, the more pre-stress of anchor bolt is converted into uniform load applied to the rock, resulting in a significant increase of the internal stress. When the layer thickness is over 200 mm, the increase rate of surrounding rock stress is reduced with the increase of the layer thickness. Therefore, considering the support strength and cost, the layer thickness is set as 200 mm.
5. **Optimization of support patterns of roadway**

Through the analysis of the above simulation results and the actual conditions, dense bolt holes would indirectly lead to the destruction of surrounding rock when the bolt spacing is too small. The smaller the bolt spacing, the more unstable the surrounding rock, and the worse the bolt support effect, which would affect the construction speed. And, the increase of the layer thickness is beneficial to the control of the deformation of the broken surrounding rock. However, considering the flexible support of the spray layer, displacement requirements and the economic cost of increasing the thickness, the stiffness, strength and toughness of the layer should be increased under the condition of minimizing the thickness as much as possible to achieve the reliability and low cost.

Taking into account all the above factors, it is recommended to adopt left-handed high-strength thread steel anchor, whose pre-tightening force is over 100 kN, the spacing is 800×800mm, and the dimension is φ 20×2400 mm. In addition, the 200 mm concrete spray layer is used to strengthen the support, improve the stress of the shallow surrounding rock and weaken the drilling disturbance. The methods can improve the deformation of the surrounding rock, and realize the stable and regular production of the roadway.

6. **The in-site industrial test**

6.1. *The differential support optimization of the stoping roadway*

After analyzing the support scheme and deformation of the 31201 working face, the optimization of differential support with bolt wire cable and shotcrete is proposed for the transport roadway of the 31205 working face, as shown in Figure 7.

The single anchor cable of φ 19.8×5000mm is used for the side of the arch and the mudstone roof and the exposed length of the anchor cable is 300 mm. Five anchor cables are arranged for each section with a spacing of 2400 mm. The left-hand high-strength thread steel bolts of φ 20×2400mm are applied. The bolts are arranged in a square shape with the row spacing of 800×800mm and each section is provided with 11 bolts. The metal netting is the 60×60mm warp and weft netting woven by 8# hard-drawn wires. The specification of the hard-drawn wire is: length×width = 2000×1300 mm, the overlap amount of anchor netting is 60 mm, and the distance between coupling buckles is less than 120 mm. The single anchor cable of φ 17.8 × 5000 mm and left-hand high-strength thread steel bolt of φ 20 × 2400 mm are selected for support of roadway sides. The I-beam of 2800 mm is utilized between the anchor cables along the roadway. And, the support strength is improved by 200 mm grouting concrete.
Considering the particularity of the coal of the transportation roadway in Zhubai colliery that the integrity of the coal is severely damaged and abnormally broken, especially in the section with complex structure, the grouting concrete with a thickness of 200 mm is adopted to strengthen the support for the abnormally broken section to ensure that the large deformation and damage would not happen during the mining.

6.2. Stress analysis of the surrounding rock

The stress of anchor cable and bolt in the transportation roadway of 31205 working face is monitored, and the curve is shown in Figure 8.

![Figure 8 The stress curve of anchor cable and bolt](image)

After the anchor is pre-stressed, the value of stress gauge increases rapidly to 55 kN. Then, the increase rate of the force on the bolt gradually is slow and eventually reaches a stable state of 94 kN. The dynamometers on the anchor cables of the rise side and roof show that the stress rises and falls repeatedly, and the stress of the anchor cable is low, far lower than that of the bolt. Although the length of the anchor cable is longer than that of the bolt, it is difficult to achieve the anchorage effect because of the serious bedding of the roof in the anchorage area with no stable anchor point for the cable.

The force and its law of the anchor able and bolt are closely related to the applied pre-tightening force during installation. High pre-stressed and strength anchor cable and bolt can not only effectively control the abscession of the surrounding rock, but have little change in the stress, which sets the support in a good condition and avoids the failure such as breaking and shearing of the anchor cable and bolt.

6.3. Deformation analysis of the surrounding rock

In order to observe the structural characteristics and fracture development of the surrounding rock accurately and timely, the borehole observation technology is used for monitoring. Considering the geological conditions of Zhubai colliery, the operation of the equipment and the accuracy and reliability of the research methods, YS(B) electronic borehole observation instrument is applied to study the surrounding
rock structure of the 31205 roadway. Three stations are arranged in the roadway with a spacing of 50m. Each station shall strike and observe one borehole in the middle and two sides of the roof with the diameter of 28 mm and the depth of 7 m. The hole on the roof is located in the center and that of two sides are about 1.0 ~ 1.5 m away from the floor. The layout of the boreholes is shown in Figure 9.

![Figure 9 The layout of the boreholes](image)

Table 4 The range of surrounding rock loose circle

| Measure point | Roof Degree of fracture development | Roof Loosen zone | Left wall Degree of fracture development | Left wall Loosen zone | Right wall Degree of fracture development | Right wall Loosen zone |
|---------------|-------------------------------------|------------------|------------------------------------------|-----------------------|-------------------------------------------|-----------------------|
| 1#            | medium                              | 3.09m            | strong                                   | 3.80m                 | strong                                    | 3.11m                 |
| 2#            | low                                 | 1.95m            | medium                                   | 2.98m                 | medium                                    | 2.48m                 |
| 3#            | medium                              | 2.45m            | high                                     | 3.14m                 | medium                                    | 2.58m                 |
| average       | medium                              | 2.46m            | high                                     | 3.31m                 | medium                                    | 2.72m                 |

It can be seen from the range of loosening circle that the shallow surrounding rock of 31205 transport roadway is broken, especially the left side. The reason is that the upper part of the left side of the roadway is rock and the lower part is mudstone. The difference of mechanical properties between coal and mudstone and the particularity of surrounding rock structure make the stress and structure of the left side tend to be complicated, leading to the deformation and failure. While the average depth of the roof loose circle is 2.46m, and the development of the fracture is in the medium level, which indicates that the roof has been well controlled. The range of loose circle of the right side is obviously larger than that of the roof. It is mainly caused by the high degree of stress concentration in the area, which results in the high sensitivity of the area to mining. According to the range of the whole loose circle of the surrounding rock, the support structure has played a certain effect. The development of the crack in the surrounding rock of the two sides of the roadway is far greater than that of the roof, which indicates that the support of the two sides should be strengthened to improve the deformation and damage of the roadway.

7. Conclusion

(1) Analyses above show that the roof and two sides of the roadway with steep and broken surrounding rock have significant deformation and stress concentration, and the deformation focuses on the mudstone roof and the middle of the roof. The deformation could be improved by increasing the thickness of the spray layer. When the layer thickness is minimized, the stiffness, strength and toughness of the layer should be increased to realize reliability and economy, which provides certain reference value for the selection and parameters of support equipment for stoping in other similar geological conditions.

(2) According to the physical and mechanical properties and stress characteristics of the broken
surrounding rock of the steep seam roadway in Zhubai colliery, the support with bolt wire cable and shotcrete is adopted and the difference support of the roadway is carried out with anchor bolt spacing of 800 mm, concrete thickness of 200 mm and two specifications of anchor cable, which improves the quality and efficiency of the support and greatly reduces the cost under the condition of the broken surrounding rock of the steep seam roadway.

(3) The results of the in-site industrial test of Zhubai colliery show that according to the conditions of roadway roof, floor and the degree of fracture, the reasonable differential support scheme is proposed to improve the integrity and continuity of surrounding rock support in the surrounding roadway of deep steeply dipping coal seam, which could provide good support for the roadway and guidance for development of safe, reasonable and economical roadway support in coal mines. The conclusion can provide some technical support for selection of support parameters for development of stoping roadways.

Acknowledgement
Fund Project: National Natural Science Foundation of China (51704086)

References
[1] Wu Yongping, Liu Kongzhi, Yun Dongfeng, et al. Research progress on the safe and efficient mining technology of steeply dipping seam [J]. Journal of China Coal Society, 2014, 39(8): 1611-1618.
[2] Yuan Liang. Strategic thinking of simultaneous exploitation of coal and gas in deep mining [J]. Journal of China Coal Society, 2016, 41(1): 1-6.
[3] LUO Shenghu, WU Yongping, LIU Kongzhi, et al. Asymmetric load and instability characteristics of coal wall at large mining height fully-mechanized face in steeply dipping seam [J]. Journal of China Coal Society, 2018, 43(7): 1829-1836.
[4] ZHA Wenhua, Xie Guangxiang, Luo Yong. Moving Rule of Surrounding Rock of Steep Seam Roadway Supported by Bolt-Mesh-Anchor [J]. Journal of Mining and Safety Engineering, 2006, 23(1): 90-102.
[5] KANG Hongpu, NIU Duolong, ZHANG Zhen, et al. Deformation Characteristics of Surrounding Rock and Supporting Technology of Gob-side Entry Retaining in Deep Coal Mine [J]. Chinese Journal of Rock Mechanics and Engineering, 2010, 29(10): 1977-1987.
[6] HUANG Qingxiang, DONG Bolin, CHEN Guohong, et al. Failure Mechanism of Entry in Steep Soft Seam and Bolting Design [J]. Journal of Mining and Safety Engineering, 2006, 23(3): 333-336.
[7] Li S, Dun LI. Numerical simulation analysis of covering rock strata as mining steep inclined coal seam under fault movement. T Nonferr Metal Soc. 2011;21;556-561.
[8] Yang ZL. Stability of nearly horizontal roof strata in shallow seam longwall mining. Int J Min Sci Tech. 2010;47;672-677.
[9] WEN Zhijie, LU Jianyu, XIAO Qinghua, et al. Failure mechanism of floor heave and supporting technology of soft rock roadway [J]. Journal of China Coal Society, 2019, 44(7): 1991-1999.
[10] WANG Ningbo, ZHANG Nong, CUI Feng, et al. Characteristics of stope migration and roadway surrounding rock fracture for fully-mechanized top-coal caving face in steeply dipping and extra-thick coal seam [J]. Journal of China Coal Society, 2013, 38(8): 1312-1318.
[11] CHEN Jianqiang, YAN Ruibing, LIU Kunlun. Asymmetric seformation mechanism of roadway at steeply inclined thick coal seam [J]. Journal of China Coal Society, 2018, 43(11): 3007-3015.
[12] WANG Jiong, GUO zhaoxiao, Cai Feng, et al. Study on the asymmetric deformation mechanism and control countermeasures of deep layers roadway [J]. Journal of Mining and Safety Engineering, 2014, 31(1): 28-33.
[13] SUN Xiaoqing, ZHANG Guofeng, Cai Feng, et al. Asymmetric deformation mechanism within inclined rock strata induced by excavation in deep roadway and its controlling countermeasures [J]. Chinese Journal of Rock Mechanics and Engineering, 2010, 29(10): 1977-1987.