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Deformation characteristics and reinforcement technology for entry subjected to mining-induced stresses

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Abstract: The entry at Zhangcun coal mine in Lu'an coal mining area in Shanxi Province suffered from severe mining-induced stresses with the heading face driven oppositely to an adjacent working face. In this paper, the characteristics of deformation and failure of the entry were investigated in terms of the tempo-spatial relations between heading and working faces through field study and numerical modeling. The three-dimensional (3D) finite difference models were built to investigate stresses, displacements and damages in the surrounding rocks of the entry and the working face. The field study includes selection of reinforcing methods and materials, design parameters, and determination of cable prestress. The monitoring data of entry deformation and stress along the cables during every stage were presented. The state of the reinforced entry was evaluated based on the monitoring data. The results demonstrate that before the heading face of the entry crosses the adjacent working face, the influence of advanced abutment pressure caused by adjacent working face upon the entry is not significant. After they cross each other, however, the lateral abutment pressure will have an evident impact on the entry. The displacement rate of the entry will be greatly increased and reaches a certain value within a certain distance between the heading face and the working face. Then, it will increase again with the presence of secondary mining-induced pressure on the entry when the present working face advances. The fully-grouted cable with short length, high strength and high prestress is an effective way to reinforce the entry suffering from severe mining-induced stresses, which greatly reduces the displacement and failure possibility of the entry. Finally, the principles and recommendations for reinforcing design of entries suffering from severe mining-induced stresses were proposed according to field study, numerical modeling and experiences from other coal mines. Problems encountered in field study and suggestions for reinforcement were also discussed.

Key words: mining engineering; coal mine entry; severe mining-induced stress; stress distribution; field study; reinforcing principle

1 Introduction

It is well known that entries and roadways in underground coal mines suffer from various mining-induced stresses, which result in significant deformation and failure of surrounding rocks. As the mining depth and mining intensity increase, the influence of mining activities on the entries and roadways becomes greater. According to the tempo-spatial relations among working faces, entries and roadways, the entries and roadways can be classified into the categories [1] as follows:

(1) Mining gateways, which include main haulage roadways and tailgates, and entries for withdrawing mining equipments. These entries only suffer from mining-induced stresses caused by current working face. The directions of main haulage roadways and tailgate are parallel to advancing direction of the working face, and they only suffer from advanced abutment pressure of the working face. Entries for withdrawing mining equipments are usually driven before the section is totally mined. The direction of this kind of entries is perpendicular to the advancing direction of the working face. Therefore, the entries suffer from advanced abutment pressure caused by the working face in the whole process. Furthermore, when the working face passes through the entries, its one

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side is the coal pillar, and the other side is the mined-out area.

(2) Retained entries in the section with multi-entry layout, which serve both current and the next working faces. They suffer from not only advanced abutment pressure and mining pressure caused by the current working face, but also front abutment pressure caused by the next working face. Besides, the service period of this kind of entries is usually long.

(3) Gob-side entries, which are located in stress releasing zone and favorable for entry reinforcement. This kind of entries only suffers from the advanced abutment pressure of the current working face. However, as the small pillar at one side of the entry is usually broken, the displacement of surrounding rocks, especially the side-to-side convergence, is considerably large.

(4) Retained gob-side entries. The main haulage roadway of the previous working face is retained and used as the mining gateway for the next working face. The entries suffer from the mining pressures caused by the current working face, and advanced abutment pressure caused by the next working face. Once the sidewall of the entry near the current working face is mined, backfilling needs to be conducted timely to support the roof. The service period of this kind of entries is quite long and significant deformation usually occurs.

(5) Entries supported by pillar. The entries are driven along the gob of the previous working face with a pillar between the gob and the entry. The pillar sizes need to be reasonably selected so that the negative influence of previous working face on the entry can be properly reduced. The entries mainly suffer from the advanced abutment pressure caused by the current working face. If the pillar width is too small, the entry will suffer from the superposition of the residual abutment pressure of the previous working face and the advanced abutment pressure of the current working face.

(6) Entries driven along unstable gob or in the regime affected by mining-induced stresses. The entries suffer from stress superposition caused by the excavation of entry and stoping.

(7) Rise, gathering entries and main roadways suffering from mining-induced stresses.

It is not necessary to address the deformation and damage features of mining gateways affected only by the advanced abutment pressure of current working face, about which many issues have been studied. In view of an entry serving both the current working face and the next working face in the Chengzhuang coal mine in the Jincheng coal mining district, Wang and Li [2] carried out monitoring for chain pillars during mining period. They observed the broken scope in the pillars by a borehole camera, and obtained the deformation characteristics of the entry during each mining phase. Bai [3] built a structural mechanical model for gob-side entries, and investigated the stability of the entries in different mining phases. Lots of studies and practices for retained gob-side entries were carried out in the Huainan coal mining district [4]. The deformation and damage characteristics of entries in different mining phases were identified, and effective support techniques were proposed. Because of unbalance of preparation and winning work, some coal mines have to drive gateways in the area with strong mining-induced stresses caused by adjacent working faces, which are not yet mined. The deformation of gateways of this kind is usually very large. To deal with the supporting problems associated with gateways affected by strong mining-induced stresses and balance preparation and winning work, field entry reinforcement tests were conducted in the Lu’an coal miming area [5]. There were also many achievements on the influence of mining-induced stresses caused by overlying seams on the entries and roadways below them [6, 7], which were mainly related to the effects of rock properties, mining depth, and spatial configuration between entries and working faces in terms of deformation of surrounding rocks.

At present, rock bolting technique has been applied as a main reinforcement measure for entries and roadways in underground coal mines around the world [8, 9]. Rock bolting theory and design methods [10–14], bolting material, construction quality control and monitoring instrumentation were extensively investigated [15, 16]. In China, rock bolting technique is also the major reinforcement technique in underground coal mines. The application of high-strength bolts and cables plays a major role in entry reinforcement [17, 18]. However, for the entries suffering from severe mining-induced stresses, such as the entries of categories No.2, 4 and 6, normal bolting is not able to restrain the large deformation and failure of the entries, resulting in failure of bolts and cables and poor reinforcing effect.

In this paper, the entry at the Zhangcun coal mine of the Lu’an coal mining area was studied, which suffered from severe mining-induced stresses with the heading face driven oppositely to the adjacent working face. This entry belongs to the category No.6, and the critical feature is that the heading direction is opposite to the advancing direction of adjacent working face. The deformation and failure features of this entry were investigated. The stress redistribution and evolution around the entry and working face were studied by numerical modeling. The reinforcement technique for the entry was applied, and the reinforcing effect was evaluated. In addition, some principles and recommendations for reinforcing entries affected by severe mining-induced stresses were presented.

2 Deformation and failure features and mechanisms of entries subjected to severe mining-induced stresses

As discussed above, there are several kinds of entries and roadways affected by mining-induced stresses with different deformation characteristics of surrounding rocks. In this paper, the entry affected by severe mining-induced stresses is defined as the one with serious deformation and damage, which experiences two or more times of mining-induced stresses caused by working face advancing, especially the abutment pressure behind the working face.

2.1 Features of entry driven oppositely to adjacent working face

The entry reinforcement of Zhangcun coal mine becomes more difficult with increasing mining depth and complex geological conditions. The excavation velocity cannot meet the need of fast working face advancing, which results in unbalance of preparation and winning work. To ensure normal mining, an entry used for the next working face has to be excavated when the current working face is still being mined. This means that the entry is excavated in the direction opposite to the advancing direction of the current working face, as illustrated in Fig.1. The entry, therefore, will suffer from long-term negative effects of advanced abutment pressure caused by adjacent

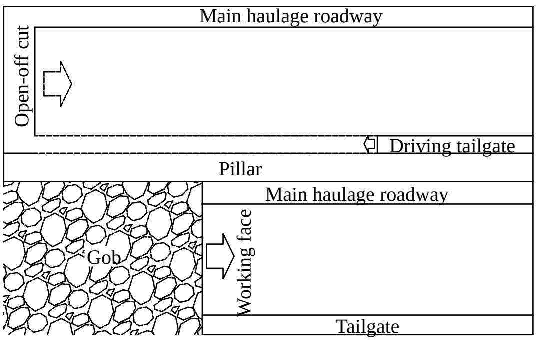


Fig.1 Layout of entries and working faces with heading and working faces in opposite direction.

working face, superposition of excavation and stoping, back abutment pressure caused by adjacent working face, and advanced abutment pressure caused by current working face. These factors result in a significant difficulty for entry reinforcement.

Normal supporting measures fail to effectively restrain the violent deformation of entries of this kind. A combined bolting method, with high-strength bolts, cables and W-shaped steel strap, was applied to the Zhangcun coal mine to reinforce the entries. However, the deformation of the entry was still great. The roof-to-floor convergence reached 1.8 m with the side-to-side convergence up to 2.0 m. Figure 2 shows the deformation and failure state of a tailgate, while Fig.3 shows the deformation and failure state of the tailgate side. The entry deformation was so severe that roof brushing, side extension, floor ripping and re-reinforcement had to be repeated during its service period (Fig.2). The normal mining production was arrested and issue of potential safety was aroused.

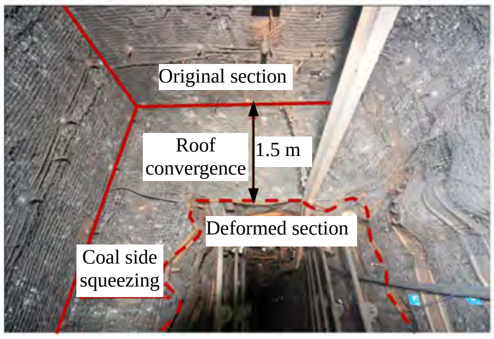


Fig.2 Deformation and failure state of a tailgate.

Fig.3 Deformation and failure state of a tailgate side.

2.2 Deformation characteristics of the entry driven oppositely to adjacent working face in various phases

Deformation and failure features of the entry driven oppositely to adjacent working face are illustrated as follows:

(1) The deformation of the entry can be divided into 5 phases: excavating phase (phase 1), influence of

adjacent heading face (phase 2), heading face crossing oppositely to adjacent working face (phase 3), effect of abutment pressure behind adjacent working face (phase 4), and effect of front abutment pressure caused by current working face (phase 5). The entry shows variable deformation characteristics in different phases.

(2) As the entry suffers from the combination of excavation and advanced abutment pressure caused by the adjacent working face, large deformation and high deformation rate occur during excavation. In this case, relatively stable period does not exist, which is commonly observed in normal entries.

(3) When the entry is influenced by the excavation of the adjacent roadway, its deformation will continue to increase, however, within small extents.

(4) As the heading face approaches the adjacent working face, the entry deformation is further increased. The deformation rate increases faster when the heading face approaches the adjacent working face.

(5) As the heading face is away from the adjacent working face, the entry deformation keeps increasing due to the influence of back abutment pressure caused by the adjacent working face. The deformation rate reaches a maximum value when the distance between the heading face and working face reaches a critical value. This critical distance is dependent on many factors, such as physico-mechanical properties of coal, geological conditions, chain pillar width, mining parameters (mining height, working face length and advancing velocity), and so on. In the Zhangcun coal mine, the critical distance is 100–200 m.

(6) As the heading face is far away from the adjacent working face, the entry deformation rate gradually decreases until a stable condition is reached.

(7) When the current section is mined, the advanced abutment pressure will act on the entry, and results in an increase in the entry’s deformation. However, the influence of mining is not as severe as that behind the adjacent working face (phase 4).

2.3 Overall deformation and failure characteristics of the entry driven oppositely to adjacent working face

The entry driven oppositely to the adjacent working face shows the following deformation and failure characteristics:

(1) Severe side-to-side convergence, as well as severe roof convergence and floor heave, are the significant features of entry deformation. The side-to-side convergence consists of dilation of fractured rock mass and bulk movement of sidewalls, which suffer from severe abutment pressures. The large side-to-side deformation results in serious floor heave, which in turn accumulates the deformations of sidewall and roof. In this way, the cross-section of the entry is significantly reduced, and the surrounding rocks fail.

(2) Severe entry deformation results in destruction of reinforcement components. Bolts and cables are broken, steel straps are seriously bent, twisted and even torn, and steel meshes significantly deform and are even torn, as shown in Fig.3. Individual hydraulic prop and joist steel have to be adopted to keep entry safe.

2.4 Deformation and failure mechanisms of the entry driven oppositely to adjacent working face

There are two main aspects on the deformation and failure mechanisms of the entry driven oppositely to adjacent working face:

(1) The entry experiences the superposed effects of excavation and mining, and the abutment pressures from adjacent and current working faces, which will last for a long period of time.

(2) The strengths of coal seam are relatively low, and the joints and fractures of surrounding rocks are fully developed in some regions. The surrounding rocks cannot bear the intense mining-induced stresses, and thus serious deformation and failure will happen.

Rock bolting can effectively restrain the entry deformation during the initial heading phase. However, with the increasing abutment stresses, the dilatant deformation, such as separation between rock units, and slippage along fractures and newly generated cracks, will continue to increase, and failure area in the surrounding rocks will be enlarged. This will lead to decrease of the anchorage capacity of bolts. More likely, the resistant forces of bolts cannot be transferred into the surrounding rocks, and bolts will bear more loads than expected. At last, the bolts will fail and lose bearing capacities. The large entry deformation, even roof collapse and sidewall flaking, cannot be avoided.

3 Numerical modeling

As mentioned in Section 2, the major reason for severe deformation and failure of the entry driven oppositely to adjacent working face is mining-induced stresses from two working faces and their superposition. To understand the deformation and failure mechanisms of the entry, the redistribution and evolution processes of mining-induced stresses around the entry and working faces were investigated. The 3D finite difference code FLAC^{3D} was used.

3.1 Numerical model

A gas drainage gateway in the fully-mechanized caving face 2203 at the Zhangcun coal mine was selected as the study site. The caving face 2203 was located at the north of mining panel 22, and the working face 2202 was located at the south of the caving face 2203. Three entries were located between the two faces, as shown in Fig.4. The haulage roadway of the face 2202 was firstly excavated to serve the face 2202. The gas drainage gateway of the face 2203 was then excavated when the working face of the face 2202 was advanced oppositely to the heading face. The tailgate of the face 2203 was excavated between the haulage roadway of the face 2202 and the gas drainage gateway of the face 2203 after the face 2202 was totally mined. The pillar between the haulage roadway of the face 2202 and the tailgate of the face 2203 had a width of 8 m, and that between the tailgate and the gas drainage gateway of the face 2203 was 10.8 m. The cross-section of gas drainage gateway of the face 2203 was rectangular with a width of 4.2 m and a height of 3.3 m, reinforced with bolts and cables. The coal seam had a thickness of 5.83 m and a uniaxial compressive strength of 8 MPa. The rock of the immediate roof was a 3.62 m-thick mudstone, which was overlaid by a main roof of fine sandstone with a thickness of 3.97 m. The gas drainage gateway of the face 2203 suffered from excavation of the tailgate of the face 2203 and the mining-induced stresses caused by the faces 2202 and 2203.

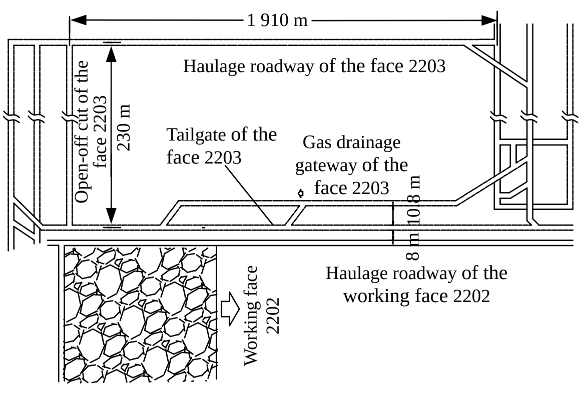


Fig.4 Layout of entries between the faces 2203 and 2202 at the Zhangcun coal mine of the Lu'an coal mining area.

FLAC^{3D} model was built and shown in Fig.5. The 3D model has a length of 271 m, a width of 210 m and a height of 77 m. It consists of 36 750 hexahedral

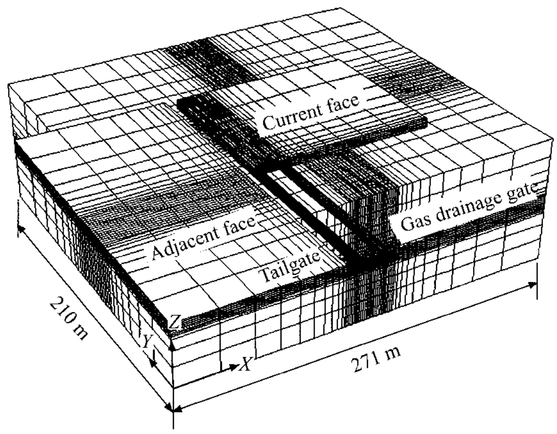


Fig.5 3D numerical model.

elements and 40 392 nodes. The element size of interesting area is 1.0 m × 1.0 m × 2.0 m, which is fine enough to calculate stress and displacement.

The built-in Mohr-Coulomb model in FLAC^{3D} was used to simulate the mechanical behaviors of coals and rocks. The properties of coals and rocks are illustrated in Table 1.

Table 1 Physico-mechanical properties of coal and rocks.

Position	Lithology	Density (kg/m^3)	Bulk modulus (GPa)	Shear modulus (GPa)	Cohesion (MPa)	Friction angle (°)
Roof	Sandstone	2 580	8	4.8	2.2	38
	Sandy mudstone	2 460	7.5	3.46	1.4	35
	Siltstone	2 487	6.67	5	1.4	34
	Mudstone	2 483	3.33	1.55	1.2	32
Coal	Coal	1 380	2.67	1.6	0.6	28
Floor	Mudstone	2 483	2.22	1.67	0.8	30
	Siltstone	2 460	8	4.8	1.8	35
	Sandstone	2 580	10	4.61	2.2	36

The normal displacement of the four lateral surfaces and the bottom surface of the model were fixed to be zero. Stress was applied on the top surface to simulate the overburden effects. In-situ stresses, which were obtained from field stress measurements, σ_{XX} = 6.54 MPa, σ_{YY} = 3.91 MPa and σ_{ZZ} = 8.79 MPa, were applied to the model.

One section of the gas drainage gateway of the face 2203, which was 10 m long, was selected as the area of interest. This section was first influenced by the excavation of the tailgate of the face 2203, and then it suffered from the advanced and back abutment pressures of the face 2202, and finally it was subjected to the advanced abutment pressure of the face 2203.

The excavation simulation of the gas drainage gateway of the face 2203 was conducted at first until the stress state in the model was in equilibrium. Then the excavation simulation of the tailgate of the face 2203 was conducted till the stress state in the model was also in equilibrium to analyze the influence of the tailgate of the face 2203 on the gas drainage gateway of the face 2203. The excavation of the first half of the face 2202 was then simulated until equilibrium to calculate the advanced abutment pressure of the working face 2202. After that, the other half of the face 2202 was mined to calculate the back abutment pressure of the working face 2202. Finally, the face 2203 was mined to simulate the effect of the advanced abutment pressure on the gas drainage gateway of the face 2203.

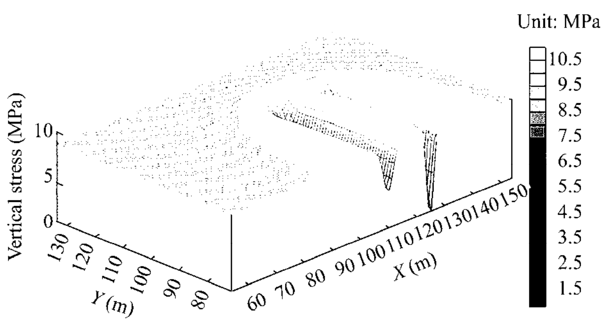
The gas drainage gateway of the face 2203 was reinforced with cables. The built-in cable element in FLAC^{3D} was employed to simulate cables in the underground entries. The mechanical properties of cables and grouting are shown in Table 2. The cable bolting parameters are the same as those applied in underground reinforcement tests (see Section 4.1 for details).

Table 2 Mechanical properties of cables and grout.

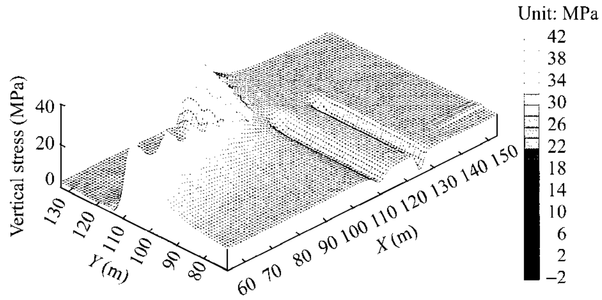
Cable diameter (mm)	Cable ultimate tensile force (MN)	Cable modulus (GPa)	Grout stiffness (10^{10} N·m^{-1}·m^{-1})	Grout cohesive strength (10^5 N·m^{-1})
22	0.6	200	1.28	2.25

3.2 Numerical modeling results

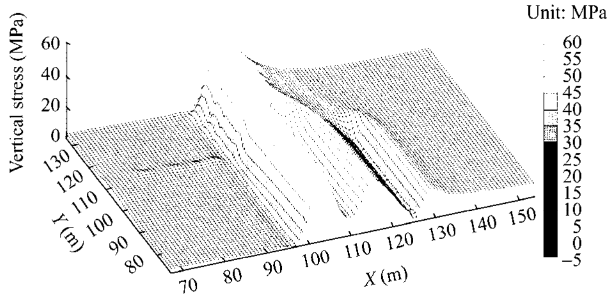
Figure 6 shows development of stress distribution around working faces and entries. The excavation of the gas drainage gateway of the face 2203 caused vertical stress concentration along its two sides and front of heading face. The tailgate of the face 2203 was excavated in the direction parallel to the gas drainage gateway of the face 2203, and the vertical and horizontal stresses were accumulated on the pillar between the two entries, as shown in Fig.6(a). The



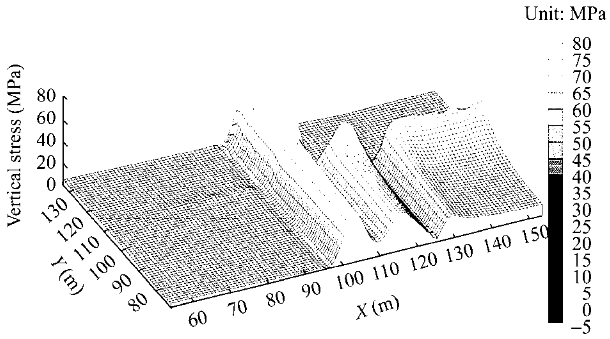
(a) The gas drainage gateway and tailgate of the face 2203 are excavated.



(b) The face 2202 is mined.



(c) The face 2202 is mined out.



(d) The face 2203 is mined.

Fig.6 Development of stress distribution around working faces and entries.

mining of the face 2202 resulted in significant abutment pressures in the front and at side parts of the working face, as shown in Fig.6(b). The coefficient of stress concentration defined as the ratio of the abutment stress caused by mining to the in-situ stresses, reached 4.8. It can be seen that the influence of the face 2202 on the two entries is greater than that of heading face.

After the face 2202 was totally mined, great lateral abutment pressures occurred in the pillar between the tailgate of the face 2203 and the haulage roadway of the face 2202. The coefficient of stress concentration reached 6.8, as shown in Fig.6(c). The mining of the face 2203 caused great advanced and lateral abutment pressures, which increases stress concentration within the pillar between the two faces, as shown in Fig.6(d).

The evolution process of the stress in the pillar between the gas drainage gateway of the face 2203 and the tailgate of the face 2203 is further discussed. The advanced abutment pressure caused by the face 2202 is confined to a limited area before the working face. This pressure has no evident influence on the pillar 12 m away from the working face, only resulting in a small increase in the vertical stress at the corners near the working face. The lateral abutment pressure behind the working face 2202, however, has a significant impact on the pillar. The vertical stress within the middle part of the pillar is greatly increased, while the vertical stress at the two sides of the pillar decreases, with its magnitudes even smaller than that of in-situ vertical stress. The reason is that the coal pillar fails at the two sides due to high abutment pressure, and it cannot yet bear high vertical stresses. The pillar is ahead of the working face 2203 during stoping, therefore, the advanced abutment pressure caused by the working face of the face 2203 superposes with the lateral abutment pressure behind the face 2202, which results in obvious increase in vertical stress within the pillar.

The displacement curves of the gas drainage gateway of the face 2203 in the whole service period during excavation and mining are shown in Fig.7. The numbers 1 to 5 indicate different displacement stages as mentioned above.

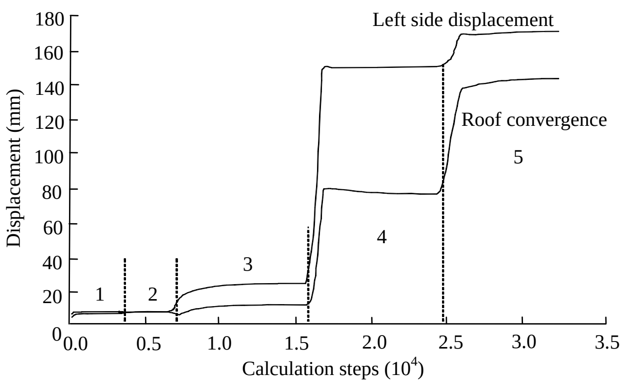


Fig.7 Developing process of displacement of gas drainage gateway of the face 2203.

The roof convergence and side displacement of the gas drainage gateway of the face 2203 during excavation are considerably small. The impact of the tailgate excavation of the face 2203 upon the gas drainage gateway is also not significant only with a slight increase. Under the influence of the advanced abutment pressure caused by the working face 2202, both the roof convergence and side displacement of the gas drainage gateway of the face 2203 increase to some extent, but the advanced abutment pressures within certain areas cannot make the gas drainage gateway of the face 2203 have comparatively large displacements, as shown in the stage 3 in Fig.7. However, the influence of the lateral abutment pressures behind the working face 2202 on the gas drainage gateway and tailgate is significant. The plastic zones around the entries expand, and the roof and side deformations of the gas drainage gateway of the face 2203 drastically increase, as shown in the stage 4 in Fig.7. At the side of the gas drainage gateway near the pillar, the high abutment pressure results in serious coal burst extrusion. Under the influence of the advanced abutment pressure in front of the face 2203, the displacement of the gas drainage gateway continues to increase with expanding plastic zones around the entries.

It is evident that the high stress concentration caused by the advanced and back abutment pressures of the adjacent working face, the advanced abutment pressure of the current working face, and their superposition, is the fundamental reason for significantly large deformation and failure associated with the entry driven oppositely to the adjacent working face.

4 Underground reinforcement tests

Underground reinforcement tests were carried out at the gas drainage gateway of the face 2203 in the Zhangcun coal mine. The geological and production conditions and layout of entries are shown in Section 3.

4.1 Reinforcement design

(1) Reinforcement patterns

Commonly, a so-called two-stage-support method is used for entries with large deformation, which suffer from high rock stresses. It is likely that the entry support should be divided into two stages. In the first stage, the primary support strength should not be too high so that allowable deformation would occur to release stresses around the entry. After a certain period of time, secondary support is applied to keep the entry stable. This method has been widely applied to many entries, and for some cases it is effective. However, for entries with overburden depth more than 1 000 m and those subjected to severe mining-induced stresses, the two-stage-support method is not effective [19]. Although secondary support is applied, large deformation is still observed in the entry. Other support measures are needed to keep the entry stable. This greatly increases the cost of entry maintenance and critically affects mining productivity and safety.

In order to effectively reinforce entries suffering from severe mining-induced stresses, a high-stiffness and high-strength reinforcement method should be implemented at the beginning of entry reinforcement. This kind of reinforcement should be able to effectively restrain deformation and failure of the entry so that secondary support is not needed. High prestress and high stiffness of the reinforcement system are critical [20–23]. Combining with the numerical results and experiences at the Zhangcun coal mine, fully-grouted cables with high prestress and short length were determined to reinforce the gas drainage gateway of the face 2203.

(2) Reinforcement components

The cables with high strength and high elongation capacity were applied. The cables were made of a 19-wire steel strand with a diameter of 22 mm. The cables have a ultimate pulling capacity of more than 550 kN and an elongation capacity of 7% [24, 25]. The domed high strength plates are matched with the cables, 300 mm × 300 mm × 16 mm in size, and meshes made of steels with a diameter of 6.5 mm are installed with the cables.

(3) Reinforcement parameters

The cable parameters were determined based on the combination of parametric study with FLAC^{3D} modeling and field experiences. The cable prestress, a key factor affecting the performance of cables, was determined by the following method.

A numerical model without in-situ stresses was built at first. Cables were installed with different values of prestress in this model, and then the stress in the rock mass caused by the prestressed cable was calculated. The reasonable prestress and cable distribution pattern should be able to form a joined and superposed compressive area. Secondly, the numerical model considering in-situ stresses and mining-induced stresses was built. The effect of mining-induced stresses was estimated through the coefficient of stress concentration obtained from the numerical results in Section 3. The effects of prestress and other parameters on the deformation and failure of surrounding rocks were analyzed by changing their values. The cables with reasonable prestress should restrain obvious separation and tensile failure zones in the surrounding rocks, especially in the roof. The reasonable values of prestress and other parameters of cables should be determined by considering the results of both models.

The cable bolting parameters are evaluated as follows. The diameter of cables is 22 mm with a length of 4.3 m. The diameters of boreholes drilled in the roof and sidewalls are 28 and 42 mm, respectively. When the cables were installed, resin capsules were used to anchor the front part of the cables. Then pretension loads of 200–250 kN were applied to the cables. After that, cement grouting was used for the other part of the cables, so that the cables could be anchored at full length. 5 cables per row were installed in the roof with a row spacing of 1.2 m, and 3 cables per row were installed in each sidewall with a row spacing of 1.2 m. All the cables were perpendicular to the surface of the gas drainage gateway. The layout of the cables is shown in Fig.8.

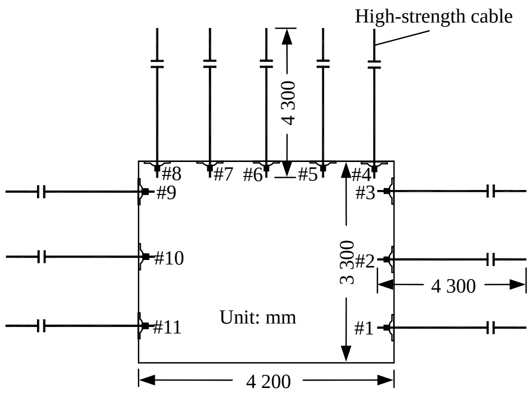


Fig.8 Layout of cables installed in gas drainage gateway.

4.2 Field monitoring and reinforcing performance

Two monitoring stations were set up in the gas drainage gateway of the face 2203 when it was advanced for 42 and 150 m, respectively. The convergence of the gas drainage gateway, roof separation and axial forces of cables were monitored.

(1) Convergence of gas drainage gateway

The side-to-side convergence at the two stations is 220 and 245 mm, respectively. The roof-to-floor convergence at the two stations is 140 and 175 mm, respectively. The deformation curves of the gas drainage gateway at one of the stations are shown in Fig.9. The displacement of surrounding rocks is small during excavation. The convergence speed of the gas drainage gateway increases significantly after the working face 2202 passes through the monitoring station, and there is a larger increase in side-to-side convergence.

Basically, the short fully-grouted cables with high prestress successfully restrained the deformation of the gas drainage gateway. The side-to-side convergence was reduced by 90% compared with that reinforced

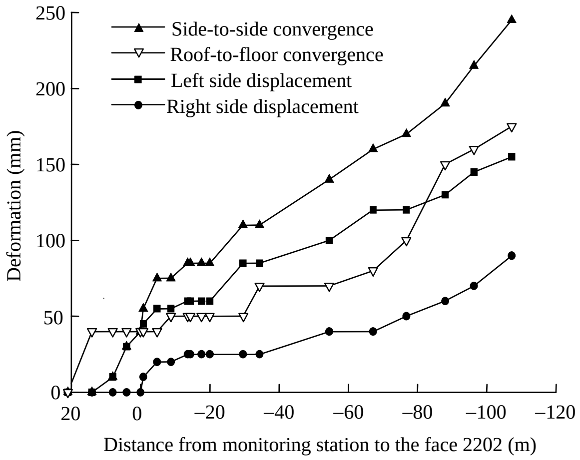


Fig.9 Deformation curves of gas drainage gateway at the Zhangcun coal mine.

with bolts. Almost no separation was observed in the roof. A good reinforcement effect was achieved, and the integrity of surrounding rocks was ensured, as shown in Fig.10.

(a) Global photo of gas drainage gateway profile.

(b) Local photo of gas drainage gateway profile.

Fig.10 Underground photos of gas drainage gateway reinforced with cables at the Zhangcun coal mine.

(2) Loads of cables

The axial loads of the cables were monitored using load cells (Fig.11). Generally, the cables installed in the walls suffer from larger loads than those installed

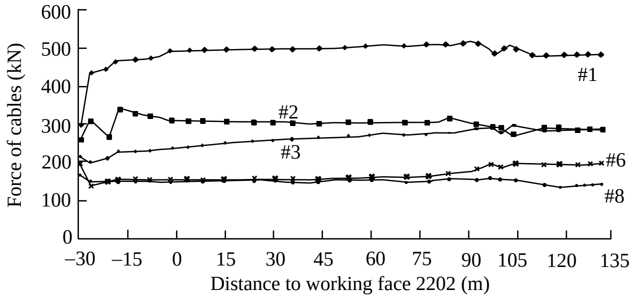


Fig.11 Axial load curves of cables installed in gas drainage gateway at the Zhangcun coal mine.

in the roof. The maximum load, 512 kN, was observed in the cable installed at the wall-floor corner. The reason is that the gas drainage gateway of the face 2203 was excavated along the top of the coal seam with 2.5 m thick coal, which was left in the gateway floor. The weak coal suffered from severe mining-induced stresses and resulted in significant floor heave, as shown in Fig.9. It can be seen that surrounding rocks, including roof, two sidewalls and floor should be reinforced with cables for the entry driven oppositely to the adjacent working face.

It can be observed from Fig.11 that the loads in the majority of cables almost keep constant, and no significant increase in the axial loads can be monitored during excavation of the gas drainage gateway and mining of the adjacent working face 2202 after installation of cables. This indicates that the cables have effectively restrained the dilatant deformation, such as roof separation, opening, sliding of pre-existing bedding and fractures, as well as generation of new fractures. The integrity and strength of surrounding rocks were maintained. The displacement difference in the reinforced zone is small with only a little bulk movement. On the other hand, almost no separation is observed in the reinforced zone; good integrity and bulk movement make the anchoring capacity of cables not being reduced, and the cable loads are not changed drastically. If the cables are installed with low prestress or even zero, they cannot restrain the separation, opening and sliding of pre-existing bedding and fractures in surrounding rocks during excavation. The cable loads will increase rapidly after installation. However, the increasing cable loads cannot be transferred into the surrounding rocks to control further separation and failure, since they are arrested by the existing separation. This situation will cause a further increase in cable loads, and finally, the cables will be broken and lose bearing abilities. It can be concluded that there exists a critical value for cable prestress. Only when the applied prestress load in the cables reaches this critical value, the entry deformation can be effectively restrained. The prestress of 200–250 kN is reasonable for the gas drainage gateway of the face 2203.

In a general sense, good results were observed in the underground tests. However, some defects still existed, e.g. the prestress of a few cables was lower than the design magnitudes, the bulk movement of sidewalls was comparatively large, and serious floor heave occurred in some regions. All these problems should be dealt with and improved.

5 Entry reinforcement principles and recommendations

Some principles and recommendations for reinforcing entries affected by severe mining-induced stresses are presented on the basis of numerical simulations and above-mentioned field study, combined with the cable reinforcement tests and experiences in the Zhangcun coal mine of Lu'an coal mining area, Sihe coal mine and Zhaozhuang coal mine of Jincheng coal mining area.

5.1 Principles for guiding reinforcing entries suffering from severe mining-induced stresses

(1) One-time reinforcement. Large deformation would occur in entries suffering from severe mining-induced stresses. Unreasonable entry reinforcing design will result in large deformation and even failure or collapse. To solve this problem, the initial strength and stiffness of reinforcing system should be increased. The potential deformation of the entries should be considered when designing the cross-sections of the entries, so that the entries can still meet the requirement of production after certain allowable deformation occurs. One-time reinforcement can effectively restrain the deformation of entries to avoid repeated application of reinforcement in the future.

(2) High prestress effectively transferring to surrounding rocks. Both bolts and cables should be installed with high prestress, and the high prestress should be transferred to the surrounding rocks through plates and straps, which are critical to increase the stiffness of reinforcement system. The stress field caused by prestressed bolts and cables is related to prestress, length, spacing, installation angle, and grouted length of bolts and cables. Within the range of cable/bolt length, the reinforcement effectiveness of short bolts and cables with high prestress is much better than that of long bolts and cables with low prestress. The prestressed fully-grouted bolts and cables should also be chosen as proper techniques. The resin capsules are used firstly to anchor the short front part of the bolts and cables (pointed anchor), and then high prestress is applied. Finally, the other parts of the bolts and cables are grouted with cement (full-length anchor). Installation of bolts and cables in this way is beneficial for increasing the extending scope of prestress and stiffness of reinforcement system.

(3) Critical reinforcing strength and stiffness. There exist critical values of strength and stiffness of the reinforcing system. That is, when the strength and stiffness reach these values, no obvious separation and tensile failure zones would occur in reinforced surrounding rocks. Prestressing is the key factor to determine the stiffness of reinforcing system, with which bolts and cables can form a joined and superposed compressive area in the reinforced zone. If not, separation, sliding and opening of beddings and fractures cannot be effectively controlled. The loads on bolts and cables cannot effectively be transferred to surrounding rocks due to the presence of discontinuities in rocks. Therefore, the strength and stiffness of reinforcing system should be designed at their critical values.

(4) Moderate allowable deformability. The deformation of entries subjected to severe mining-induced stresses consists of two parts: (i) discontinuous deformation resulting from the opening, sliding of pre-existing fractures and generation of new fractures; (ii) continuous deformation coming from elastoplastic deformation of rock masses suffering from high stresses. The reinforcing system should be able to restrain the discontinuous deformation. On the other hand, it should have enough ductility to allow for certain continuous deformation to release high stresses. However, the total deformation of reinforced entries should be limited to a certain value for the requirement of production.

(5) Matching the reinforcing components with each other. High-prestressed reinforcing system makes more demands on reinforcing components. The geometric and mechanical performances of various

components, such as bolt bars and cable strands, plates, straps and meshes, should be matched with each other, so that the integrated effectiveness of the reinforcement system can be ensured. Weakness of any component would result in a significant decrease in reinforcement effectiveness, even failure of reinforcing system.

(6) Reinforcing full cross-section of entries. The deformation of entries affected by severe mining-induced stresses occurs in all directions. Large roof convergence always occurs with severe side-to-side convergence and floor heave. Roof, sides and floor are connected and influence each other, and failure in any part can lead to instability of the entries. Therefore, the full cross-section of entries should be reinforced to form a bearing structure around the entries, and the intense deformation of entries can be restrained to an allowable value.

(7) Economic rationality. Economic rationality should be considered when reinforcement pattern for entries affected by severe mining-induced stresses is adopted. Firstly, the reinforcement effectiveness and safety of entries should be guaranteed, and then the cost of reinforcement system should be kept as low as possible. In addition, the reinforcing components should be installed without difficulty.

5.2 Existing problems and recommendations for improvement

Though the cables with high prestress successfully restrained the intensive deformation of the gas drainage gateway of the face 2203 at the Zhangcun coal mine, some problems still exist and need to be solved.

(1) The loss of prestress for a few of cables is considerably large during installation. The function of these cables is significantly reduced since prestress does not reach the designed value. The structure of pulling equipment for cables needs to be improved, and the matching of steel strands with wedged barrels should be further optimized to decrease prestress loss during installation.

(2) Though the integrity and stability of two sides of the gas drainage gateway of the face 2203 were well retained, comparatively large bulk movement and side-to-side convergence were observed during later service period of the gateway. Modification of the reinforcement design needs to be carried out to effectively control side displacement when the cable reinforcing system is applied to other entries similar to the gas drainage gateway of the face 2203.

(3) The floor of the gas drainage gateway of the face 2203 was not reinforced due to the difficulty in installing cables in the floor and the short service period of the gas drainage gateway. Significant floor heave took place in some parts of the gas drainage gateway after the adjacent working face 2202 passed through it. Floor ripping had to be carried out, resulting in a further increase in side-to-side convergence. Equipments specially designed for installing cables in floor need to be developed so that cables can be easily installed in the floor.

(4) The designed reinforcement scheme of cables was the combination of resin capsules anchoring the front short part of cables with cement anchoring the other part of cables. When this installing method was employed in field, it was observed that some boreholes collapsed before grouting, especially the boreholes drilled in the coal sidewalls. The effectiveness of grouting was significantly reduced. More robust method needs to be developed to deal with this problem.

(5) Only the spatial configuration between entries and working faces was considered in numerical simulations in this paper, and time-dependent effects were not considered. As a matter of fact, the service period of the gas drainage gateway of the face 2203 is much longer than that of normal gateways. Rheological characteristics of surrounding rocks of the gas drainage gateway are considerably evident. The mining-induced stresses experience 5 phases with time, and reach peak values at some distance behind the adjacent working face. The displacements also experience 5 phases with the peak displacement rate at some distance behind the adjacent working face. Side displacements and floor heave are pretty large, and the floor and sides cannot keep stable in a very long time. Therefore, the variation characteristics of stresses and displacements and the time-dependent properties of surrounding rocks in different mining phases should be further investigated. At the same time, the time-dependent properties of bolts and cables suffering from high stresses need to be studied.

6 Conclusions

(1) The entries driven oppositely to the adjacent working face will suffer from advanced abutment pressures induced by the adjacent working face, stress

superposition effects by excavating and mining, back abutment pressures of the adjacent working face, and advanced abutment pressures caused by current working face. The service life of entries of this kind is much longer than that of normal gateways with severe deformation and great difficulty in reinforcement.

(2) Before the entry heading face and adjacent working face cross each other, the entry suffers from advanced abutment pressures caused by the adjacent working face, which have no evident influence on the entry. After they cross each other, the entry suffers from lateral abutment pressures caused by the adjacent working face, which have a significant influence on the entry and result in a rapid increase in entry deformation and failure zones. When the entry is influenced by current working face, the superposition of back abutment pressures from the adjacent face and advanced abutment pressures from the current working face will cause the entry deformation to further increase.

(3) Conventional bolts and cables cannot effectively restrain severe deformation of entries driven oppositely to the adjacent working face. It is an effective way for reinforcement of entries, affected by severe mining-induced stresses, to restrain discontinuous deformation and release continuous deformation of surrounding rocks by increasing the initial reinforcing strength and stiffness of the bolting system.

(4) The fully-grouted cable reinforcing method with high prestress and short length is an effective method to reinforce entries suffering from severe mining-induced stresses. Principles of one-time reinforcement, high prestress, critical strength and stiffness of reinforcing system, moderate deformability, matching of reinforcing components, global cross-section reinforcement and economic rationality should be fully considered reinforcement designing.

(5) By applying intensive cables with high prestress to the gas drainage gateway of the caving face 2203 driven oppositely to the adjacent working face in the Zhangcun coal mine of the Lu’an coal mining area, the deformations of the entry, roof convergence and side-to-side convergence were significantly decreased, and roof separation was effectively restrained. More researches are needed for the effectiveness of applied prestress and grouting, control of bulk movement of walls and floor heave, time-dependent features of surrounding rocks, and rheological characteristics of bolts and cables.

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