Stability of Roadway in Upper Seam of Deep Multiple Rich Gas Coal Seams through Ascending Stress-relief Mining

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Stability of Roadway in Upper Seam of Deep Multiple Rich Gas Coal Seams through Ascending Stress-relief Mining

by

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Abstract

The first mining of a protective coal seam through ascending stress-relief mining is one of the most effective techniques for eliminating the risk of coal and gas outburst during the exploitation of multiple coal seams containing high rich gas. However, the difficulty of controlling roadway stability in the upper protected coal seam above the goaf increases greatly after ascending mining. Based on the geological conditions in Guqiao Coal Mine in China, a numerical simulation model is established by means of Itasca's Fast Lagrangian Analysis of Continua (FLAC) software in order to analyze the influence of the ascending mining on the stress distribution of the overlying rock strata and the stability of the roadway with different support parameters in the upper protected coal seam. The results show the impact scopes of stress relief and concentration zones in the overlying rock strata are up to approximately 100m and 90m above the goaf. The vertical stress, plastic zone and displacements in one sidewall of the roadway in the upper protected coal seam are bigger than that of the other sidewall close to the underlying goaf side. However, the stability of the roadways can be improved efficiently by using the appropriate support scheme including high strength and pre-stressed thread steel bolt support combined with pre-stressed cables. Field measurements indicate that the displacements of the surrounding rock could be controlled efficiently in 41 days when the roadway is excavated in the upper protected coal seam above the goaf with a compaction duration of 150 days.

Keywords: Coal and gas outburst, Multiple coal seams, Ascending mining, Roadway, Stability

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1. Introduction

The demand and dependence of China's quick economic development and rapid industrialization process on energy has caused rapid growth of coal production and consumption [1, 2, 3] over the first ten year or so of this century, which accounted for 75.6%, 66.0% of the China's total energy production and consumption in 2013 as shown in **Fig.1** and **Fig. 2** [4], respectively. Coal has accounted for and will continue occupying the dominant position of China's long-term energy mix [5] under the current conditions of rich coal resources and poor oil and natural gas [6].

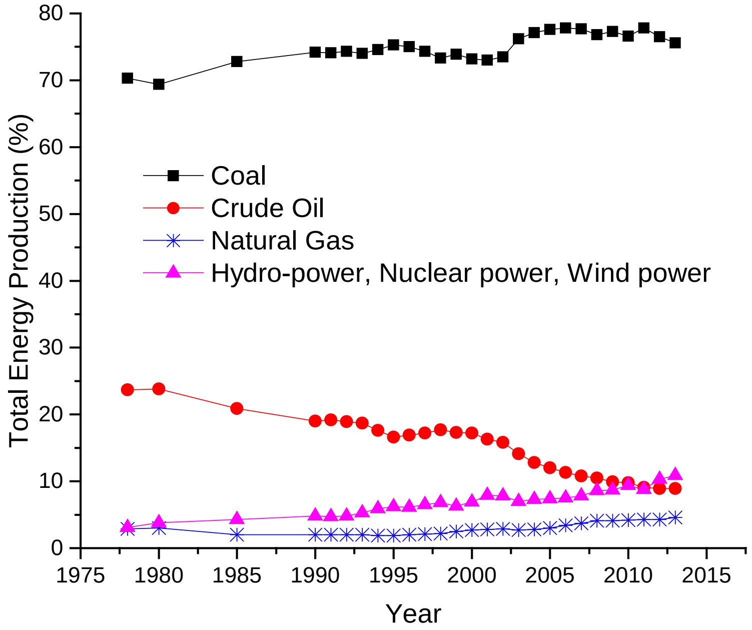


Fig. 1 Composition of total production of energy in China.

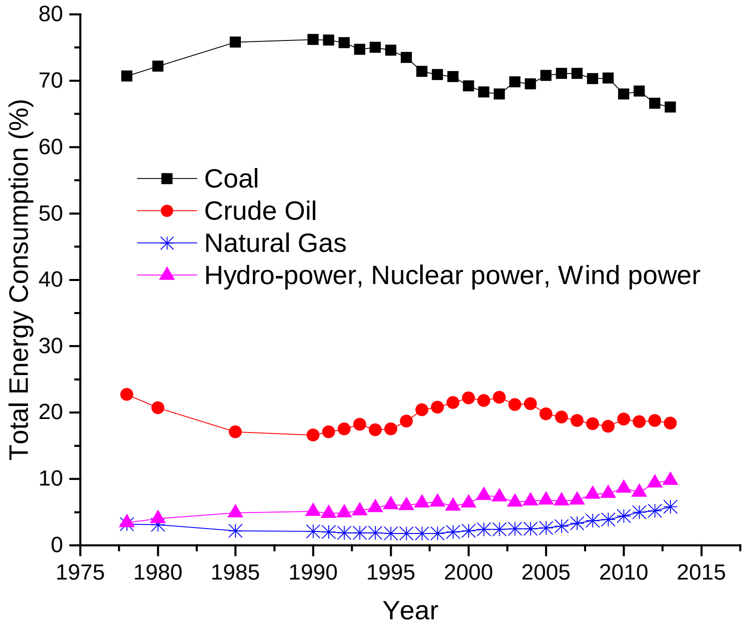


Fig. 2 Composition of total consumption of energy in China.

Currently, the largest share in coal production countries is China, where the raw coal production of 3.87 billion tons [7] constituted about 47% of the total all over the world in 2014 [8]. The coal production of underground mining accounted for around 85% of the total in China.

With diminishing of coal resources at shallow depth, the underground mining depth increases in order to meet the demand for coal. The average mining depth of state-owned key coal mines in China exceeded 700m in 2010. Currently, the mining depth in China increases by 10 ~ 20m per year on average, and the coalbed methane (CBM) pressure increases by 0.1 ~ 0.3 MPa per year [9, 10, 11]. CBM is the catastrophic gas for underground coal mines. When the CBM pressures and content are high in coal seams, gas disasters including coal and gas outburst and gas explosions likely happen during the mining of the rich CBM coal seams, which seriously threats to the production safety of underground coal mines [12, 13, 14, 15, 16]. Geological conditions in Chinese coal mines are becoming more and more complicated as the mining depth increases. The number of coal mines with coal and gas outburst risk is also quickly increasing with the mining depth [17].

China is the coal production country with the most serious gas disasters in the world [11, 18, 19, 20]. Many scholars and researchers have worked on controlling gas disasters by using stress-relief mining method to eliminate or reduce the risk of coal and gas outburst in high rich CBM multiple seams with low permeability. In recent years, research and practice have proved that the mining of the protective coal seam through ascending stress-relief mining is one of the most effective technologies for preventing coal and gas outburst during the extraction of high rich CBM multiple seams with low permeability [21, 22, 23, 24, 25, 26]. However, ascending stress-relief mining inevitably leads to the stress redistribution including stress concentration and stress decreasing zones, and lots of fractures developing in the overlying strata [27]. The deformation of a roadway in the overlying strata may be large such as serious roof subsidence and floor heave due to a large number of fractures even if the roadway is located in stress decreasing zones [28]. Therefore, the control of stability of roadways in the upper protected seam above the goaf becomes more difficult after the extraction of the underlying protective seam in multiple coal seams through ascending mining [29, 30].

Much research has focused on the stability of roadways subject to mining influence. These were though only applied in roadways that had been excavated before mining [31, 32, 33, 34, 35]. However, little work has been conducted on the control of stability of roadways newly excavated in the upper protected seam under the extraction influence of the lower protective coal seam [28]. Thus, the study of the stability control for the roadway in the upper protected coal seam will play an important role in the mining of deep multiple coal seams with high rich CBM through ascending stress-relief mining.

Many underground coal mines in China have multiple coal seams, but they are usually characterized by complicated geological conditions, high rich CBM, low permeability and high adsorption [11, 36]. Huainan mining area is the typical one applying multiple seams mining. The geological conditions are very complicated with characteristics of large overburden depth of 400 ~ 1,500m, 8 ~ 15 layers of coal seams, soft coal, rich CBM with content of 12 ~ 36 m^3 per ton of coal (m^3/t), low permeability of 0.001 mD (1 mD = 10^{-3} μm^2) in coal seams, high CBM pressure (up to 6.2 MPa) and complicated geological structure [24, 37]. Coal Bed Methane Drainage Engineering Design Specification (GB50471-2008) illustrates that CBM in coal seams with permeability less than 1 mD is difficult to be extracted directly with boreholes [10, 11]. Based on ascending stress-relief mining for controlling gas hazards in Guqiao Coal Mine in Huainan mining area, a numerical simulation model was established to research on the issue of the stability of the roadway in the upper protected coal seam of multiple coal seams with high rich CBM.

2. Ascending Stress-relief Mining and Simultaneous Extraction of Coal and Methane

The permeability of coal seams with high gas outburst hazards is generally very low. The traditional direct CBM extraction for the coal seams with high gas outburst hazards needs arranging many intensive CBM drainage boreholes in rock roadways or drilling extraction wells from the ground surface. After CBM extraction is conducted, both the residual CBM content and CBM pressure must meet certain requirements, i.e., the CBM content must be below 8 m^3/t, and the CBM pressure must be less than 0.74 MPa in China [38]. The time of traditional direct CBM extraction is very long and the effect is also very poor due to the low permeability. For example, the traditional direct CBM extraction with boreholes in Huainan mining area needs 10 ~ 20 years [29] when the CBM content is below 8 m^3/t, which cannot meet the requirements of mine safety and efficient production. Furthermore, the cost of traditional CBM extraction is very high because many rock roadways or CBM extraction wells from the surface should be excavated or drilled.

Mining practice shows that extracting the first key protective coal seam and conducting CBM extraction in the stress-relief protected coal seam are effective regional measures of production safety for preventing and controlling gas disasters, which improves the safety and reliability of prevention and control measures of coal and gas outburst hazards.

As illustrated in **Fig. 3**, during the extraction of multiple coal seams with rich CBM, the coal seam with relatively lower CBM and without gas outburst hazards is firstly extracted, which is called a protective coal seam or liberated seam (the middle seam) while the others are named protected coal seams [39, 40]. CBM permeability and desorption of the adjacent protected coal seams will be greatly increased by hundreds or even thousands of times [11] after ascending mining and CBM pressure will be decreased. Due to the mining-induced stress-relief in other adjacent coal seams, the high adsorption CBM in other adjacent coal seams will move to the fracture field and can be extracted. Thus, CBM extraction capacities in other adjacent coal seams are improved due to ascending stress-relief mining. The gas outburst risk will be greatly reduced or avoided after CBM extraction.

During ascending stress-relief mining of the protective coal seam, a lot of stress-relief CBM can be extracted with the various forms of CBM extraction techniques as shown in **Fig. 3**. This techniques include long upward and downward CBM extraction boreholes in goaf-side roadway retained (GRR) through the protected coal seams, long boreholes through the roof of the protective coal seam and pre-embedded pipes in GRR through the filling wall connecting the goaf, etc. [18]. The techniques can not only eliminate the risk of coal and gas outburst of the regional coal body in the protected coal seams, but also reduce CBM emissions of the protective and protected coal seams during mining and guarantee the mining safety.

In addition, high concentrations of CBM extracted can be utilized such as power generation and civilian use, which reduces a large amount of greenhouse CBM emissions [41]. This not only promotes the efficient use of clean energy, but also protects the human living environment. Therefore, the ascending stress-relief mining method combined with GRR can achieve underground simultaneous extraction of coal and methane (SECM) [42, 43] which effectively integrates the two previously separate operations of coal mining and methane extraction in multiple coal seams and reduces the number of rock roadways excavation or avoids drilling extraction boreholes from the ground surface.

However, the roadway in the upper protected seam will be excavated in the bending deformation zone, even in the fracture zone above the goaf [44]. Thus, the difficulty of controlling roadway stability in the upper coal seam will increase greatly after ascending stress-relief mining.

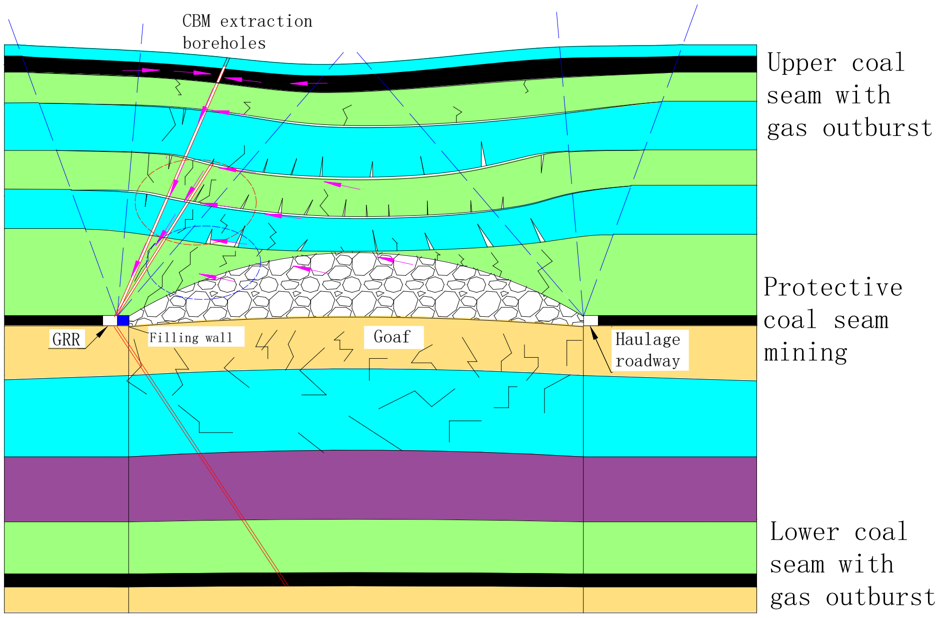


Fig. 3 Schematic diagram of SECM through ascending stress-relief mining.

3. Mining Geological Profiles

Guqiao Coal Mine (**Fig. 4**) is located in Huainan City, Anhui Province, China. The mine operates since April 28, 2007. It is one of the major coal mines of Huainan Mining (Group) Co., Ltd. It has been producing an annual coal output of over 11 million tons (Mt) since 2009 as shown in **Fig. 5**.

There are nine workable coal seams in coal-series strata in Permo-Carboniferous system that is the North China platform type, with the total average thickness of 24.11m, the geological reserves of 2630 Mt, and recoverable reserves of 1297 Mt (760 Mt above -850m) in Guqiao Coal Mine. Based on the reserves of coal and rate of production, it was expected to have a remaining service life up to 85 years in 2013. Moreover, Guqiao Coal Mine is the largest kilometer deep coal mine in Asia [45]. Currently, Guqiao Coal Mine has two mining levels that locate on the level of -780m and -950m.

Seam 11-2 and Seam 13-1 in the first mining level of -780 m are the two main workable coal seams of Guqiao Coal Mine, and they are nearly horizontal. Seam 13-1 with high rich CBM and low permeability has the risk of coal and gas outburst while there is not the risk in Seam 11-2. Therefore, Seam 11-2 is selected as the protective coal seam to conduct CBM extraction and eliminate the risk of coal and gas outburst in the protected coal Seam 13-1 through ascending stress-relief mining as shown in **Fig. 6**. After that, Seam 13-1 is exploited.

Fig. 4 Photo of Guqiao Coal Mine.

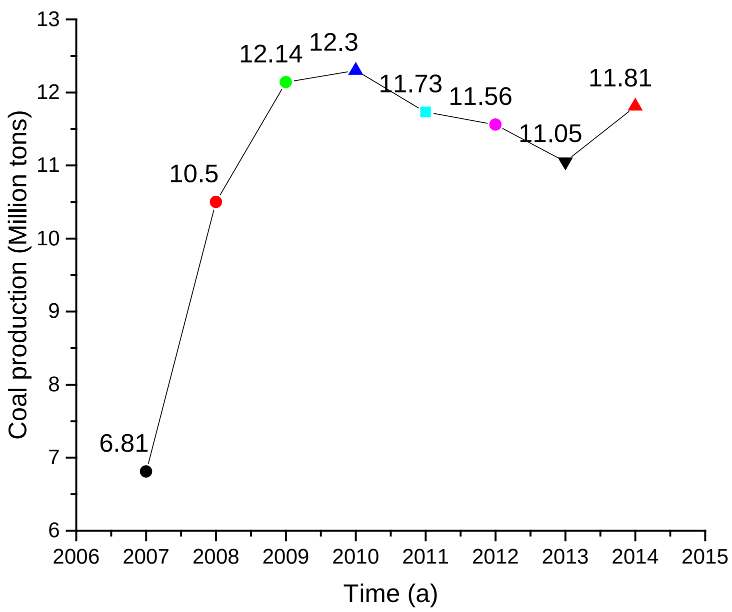


Fig. 5 Coal production of Guqiao Coal Mine.

Longwall coal faces 1115(1) and 1115(3) are located in Seam 11-2 and Seam 13-1, respectively as shown in **Fig. 7**. Longwall coal face 1115(1) is at a depth of 800 m below the surface. Longwall coal face 1115(3) is above the goaf of longwall coal face 1115(1). The vertical distance between seam 11-2 and seam 13-1 is around 75m. The strike length and the dip width of longwall face 1115(3) are about 2,900m and 220m, respectively. The thickness of the coal seam varies from

2.95m to 4.37m with an average thickness of 3.56m according to the geological borehole data. The industrial and recoverable reserves of coal resources in longwall face 1115(3) are 3.21 million tons and 3.05 million tons, respectively. The structure of the coal seams is complex, usually including two or three thin layers of carbonaceous mudstone, and mudstone except coal. The immediate roof strata are usually typical complex structure, which are mainly composed of clay rock, mudstone and siltstone. In addition, sometimes there is a water flow phenomenon in the roof in some places. It is initially large but gradually becomes smaller and finally disappears as time goes on. The geological profiles of coal seams and rock strata are illustrated in **Table 1** in Section 4.

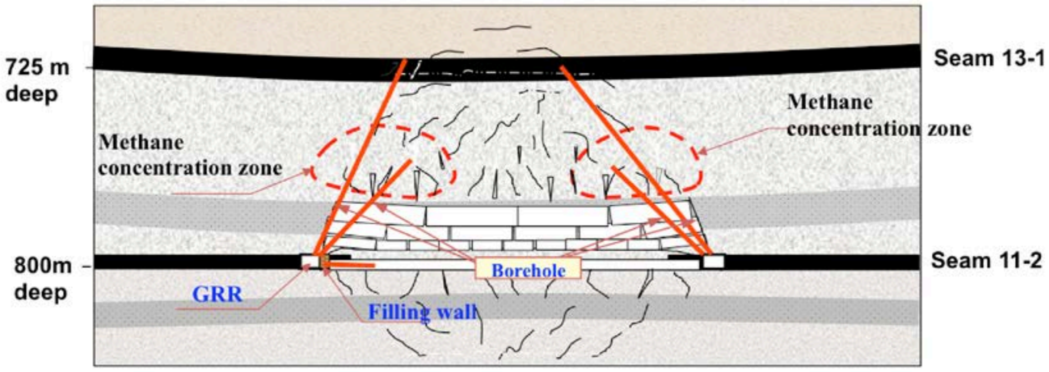


Fig. 6 Simultaneous extraction of coal and methane through ascending mining in Guqiao Coal Mine.

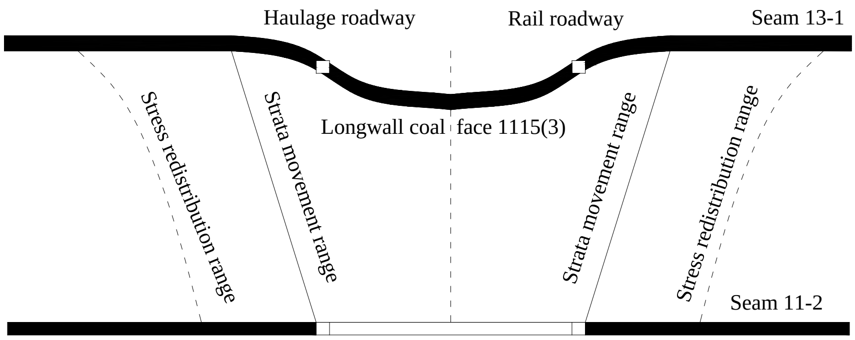


Fig. 7 Section map of longwall coal face 1115(3) and goaf 1115(1) of Guqiao Coal Mine.

4. Numerical Simulation

4.1 Simulation Model

As illustrated in **Fig. 8** and **Table 1**, the numerical model simplified as a plane strain problem was established by means of FLAC software to analyze the influence of the underlying mining on the overlying rock strata and the appropriate support parameters of the roadway in the upper coal seam during ascending stress-relief mining based on the geological condition of Guqiao Coal Mine.

The dimensions of plane model that was composed of seventeen strata layers were 200m wide and 140m high, respectively. The mechanical parameters of the coal seam and rock strata [27] were described in Table 1. The width and height of the underlying longwall face in Seam 11-2 at a depth of 800m below the surface were 220m and 3.5m, respectively. However, considering the symmetry of the model, the width and height of the goaf of the underlying longwall face in this model were 110m and 3.5m, respectively. The cross-sections of the roadway located in the upper coal Seam 13-1 were rectangular shape with dimensions of 5,000mm wide and 3,400mm high.

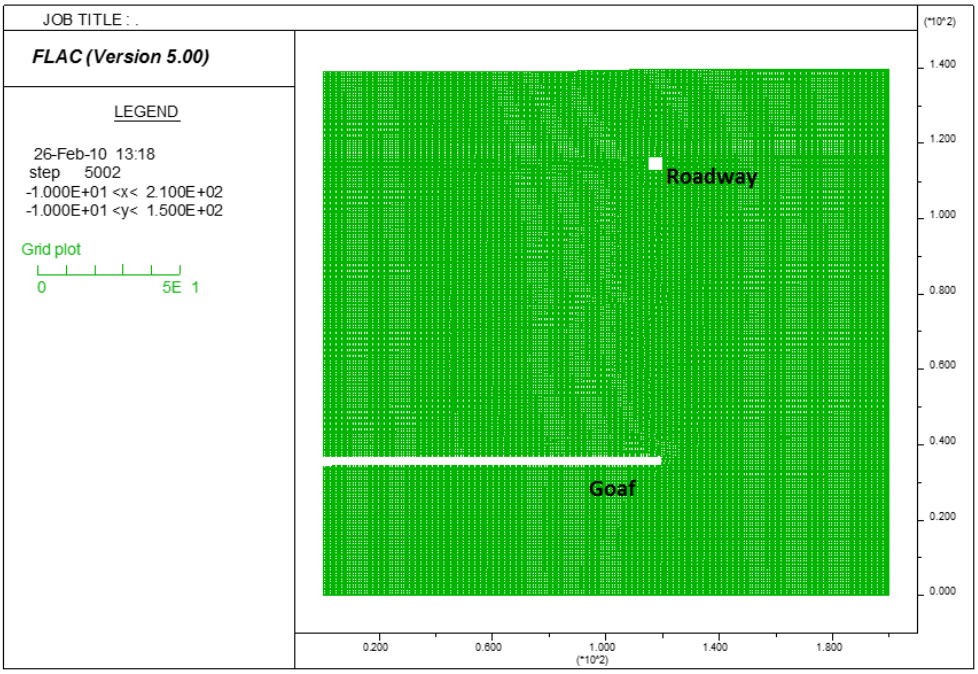


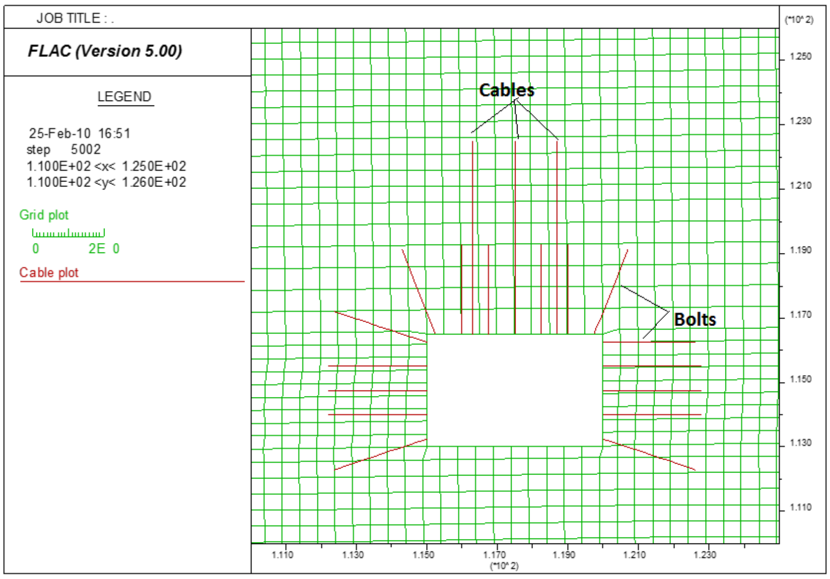
Fig. 8 The numerical simulation model.

Table 1 The mechanical parameters of the coal seam and rock strata.

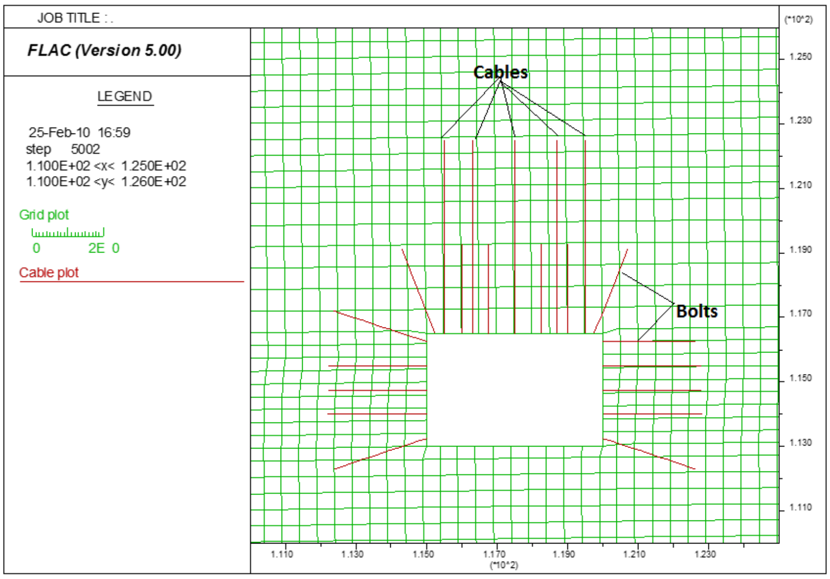
No.	Strata	Density (kg/m^3)	Thickness (m)	Bulk modulus (GPa)	Shear modulus (GPa)	Compressive strength (MPa)	Cohesion (MPa)	Friction (°)
1	Mudstone	2,200	1.5	3.03	1.56	20	1.2	27
2	Siltstone	2,700	16	2.68	1.84	50	2.0	32
3	Mudstone	2,200	4	3.03	1.56	20	1.2	27
4	Clay rock	2,200	2	3.75	1.73	15	1.0	25
5	Seam 13-1	1,400	3.5	1.19	0.37	10	0.8	23
6	Clay rock	2,200	6	3.75	1.73	15	1.0	25
7	Mudstone	2,200	8	3.03	1.56	20	1.2	27
8	Siltstone	2,700	8	2.68	1.84	50	2.0	32
9	Mudstone	2,200	5	3.03	1.56	20	1.2	27
10	Fine sandstone	2,600	12	5.56	4.17	60	2.0	35
11	Mudstone	2,200	6	3.03	1.56	20	1.2	27
12	Fine sandstone	2,600	16	5.56	4.17	60	2.0	35
13	Siltstone	2,700	12	2.68	1.84	50	2.0	32
14	Mudstone	2,000	2	3.75	1.73	15	1.0	25
15	Seam 11-2	1,400	3.5	1.19	0.37	10	0.8	23
16	Clay rock	2,200	4.8	3.75	1.73	15	1.0	25
17	Mudstone	2,200	29.7	3.03	1.56	20	1.2	27

According to the results of in situ stress measurements with the stress relief method in the pit bottom located at the -780 m mining level in Guqiao Coal Mine [46], a horizontal stress of 19.76 MPa was applied in a horizontal direction, whilst a vertical stress of 17.57 MPa was applied at the top boundary. The horizontal displacements were fixed at the lateral boundary, and the horizontal and vertical displacements were both fixed at the bottom boundary. The gravity was initialized. The Mohr-Coulomb's criterion was used. In order to simulate the goaf, the corresponding coal seam was excavated and removed from the model, because the natural caving method of the roof in the longwall face mining was used in Guqiao Coal Mine. Then the roof was allowed to fall.

Two steps were conducted to ensure the simulation process was similar to ascending stress-relief mining in Guqiao Coal Mine. At first, the longwall face in the lower protective coal Seam 11-2 was extracted. Afterwards, the roadway with support was excavated in the upper protected coal Seam 13-1.



(a) Scheme 1: roof support with three cables



(b) Scheme 2: roof support with five cables

Fig. 9 The simulation models of the support schemes.

Two simulation support schemes were proposed as shown in **Fig. 9**. The number of cables in the roof in scheme 1 was three while the number was five in scheme 2. Other support parameters were the same. The specifications of bolts in the roof and sidewalls were the diameter of 22mm and length of 2800mm, and the diameter of 20mm and length of 2500mm, respectively. The diameter and length of anchor cables in roof were 21.8mm and 7700mm, respectively. The mechanical parameters of bolts were shown in **Table 2**, respectively.

Table 2 The mechanical parameters of bolts.

Bolt material	Density (kg/m^3)	Diameter (mm)	Yield strength (MPa)	Ultimate strength (MPa)	Shear modulus (GPa)	Elasticity modulus (GPa)
HRB500 steel	7,800	22	500	630	82.3	210

4.2 Results and Discussion

4.2.1 Influence of the Underlying Mining on Stress Distribution of the Overlying Rock Strata

The immediate roof strata bend and move downward under the action of gravity and the overburden strata after the underlying coal seam is mined. When the internal tensile stress exceeds the ultimate tensile strength of the rock, the immediate roof fracture firstly and then fall down. At the same time, the mining results in the stress redistribution of the surrounding rock of the goaf and the overlying strata including the stress decreasing and concentration zones as shown in **Fig. 10**.

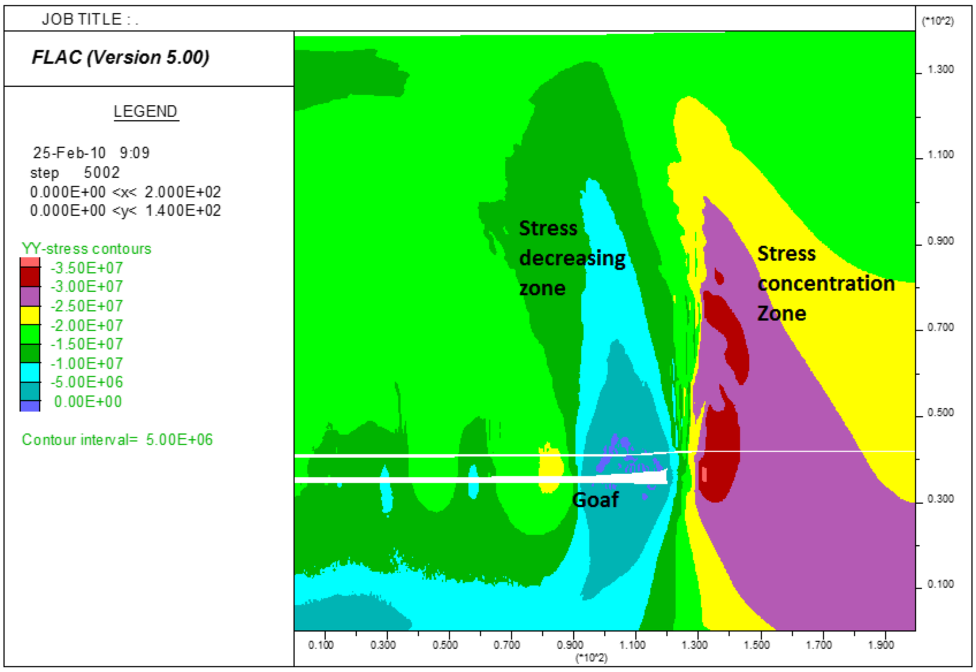
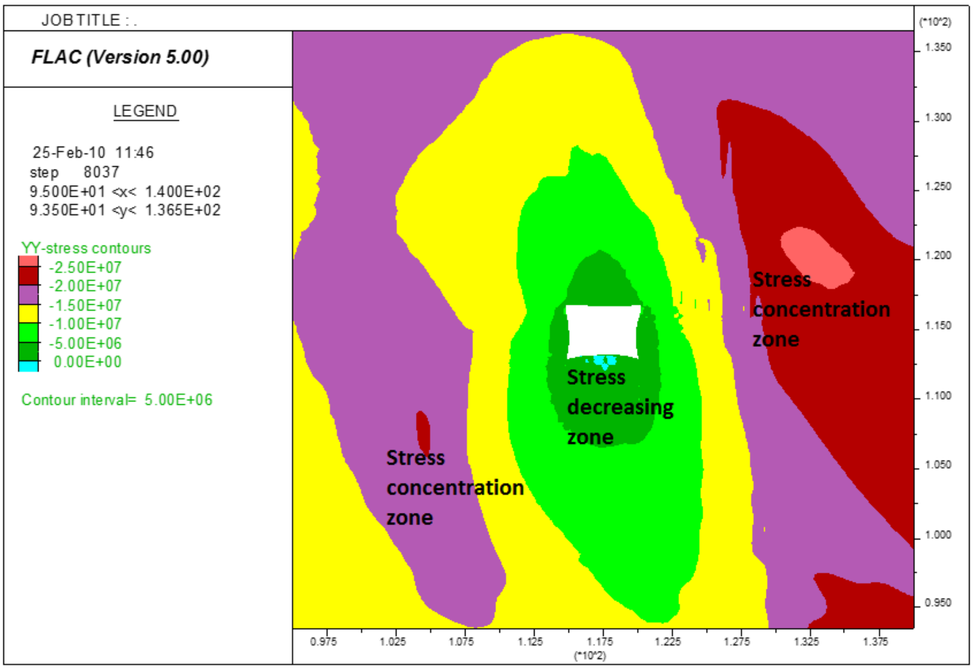


Fig. 10 Vertical stress distribution of the rock strata after the underlying protective coal seam mining before the roadway excavation in the upper coal seam.

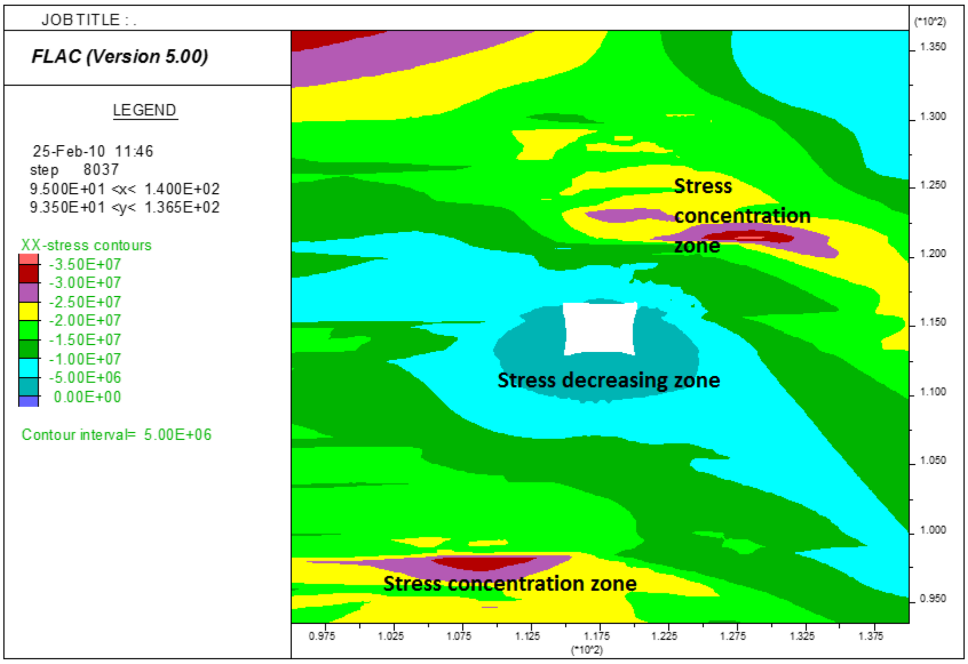
The stress decreasing zone, i.e., stress relief zone in Seam 13-1 above the goaf is beneficial to the CBM extraction. However, the stress concentration is also transmitted to the right lateral deep overlying rock strata. The impact scopes of stress relief and concentration zones in the overlying strata are up to approximately 100m and 90m above the goaf respectively where the stress relief and concentration values are about 15 MPa and 25 MPa, respectively. However, the roadway that will be excavated in the upper Seam 13-1 is located on the edge of the stress concentration zone, which increases the difficulty of the stability control of the roadway in the upper coal seam.

4.2.2 Stability Analysis of the Roadway in the Upper Protected Coal Seam above the Goaf

The calculated results from the simulation including vertical and horizontal stresses, plastic zone distribution and displacements of the surrounding rock of the roadway with different support schemes after excavation are presented in **Fig. 11**, **Fig.12**, **Fig.13**, **Fig. 14** and **Table 3**.

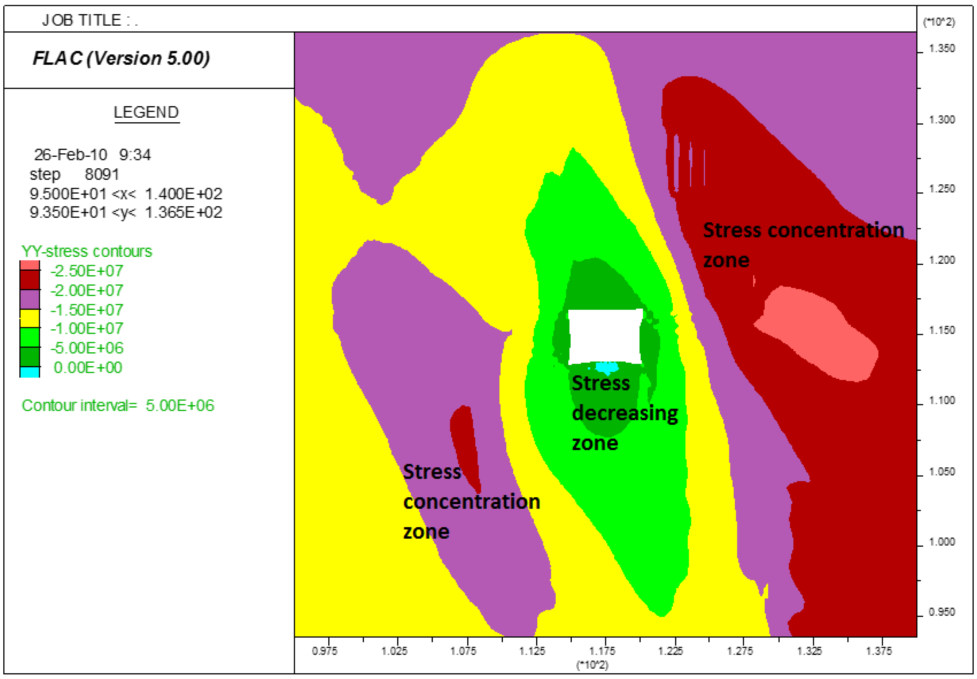


(a) Vertical stress distribution

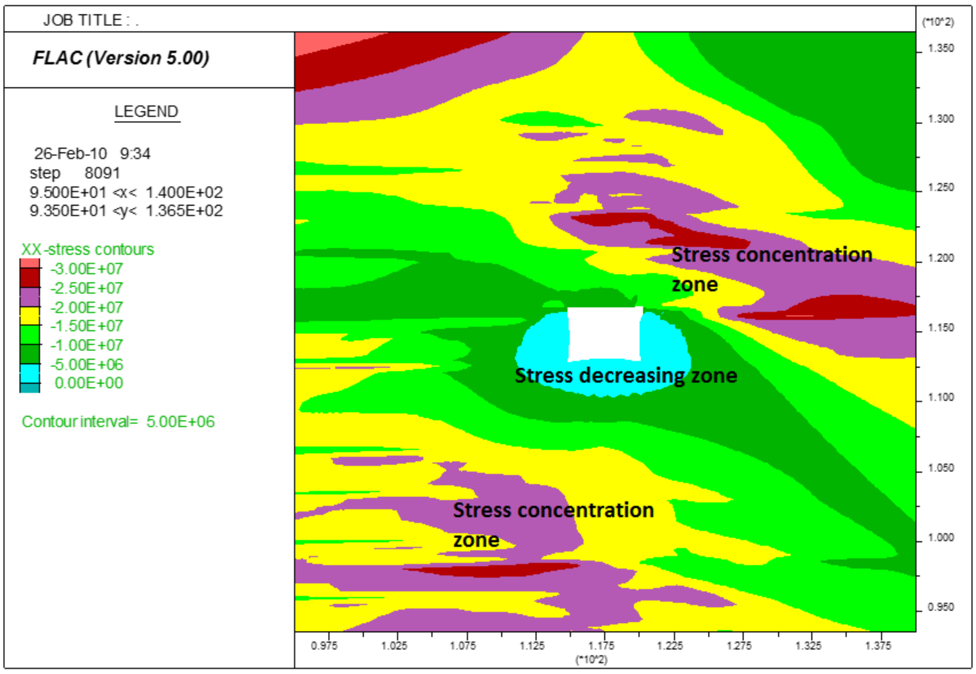


(b) Horizontal stress distribution

Fig. 11 Stress distribution of the surrounding rock of the roadway with support scheme 1.



(a) Vertical stress distribution



(b) Horizontal stress distribution

Fig. 12 Stress distribution of the surrounding rock of the roadway with support scheme 2.

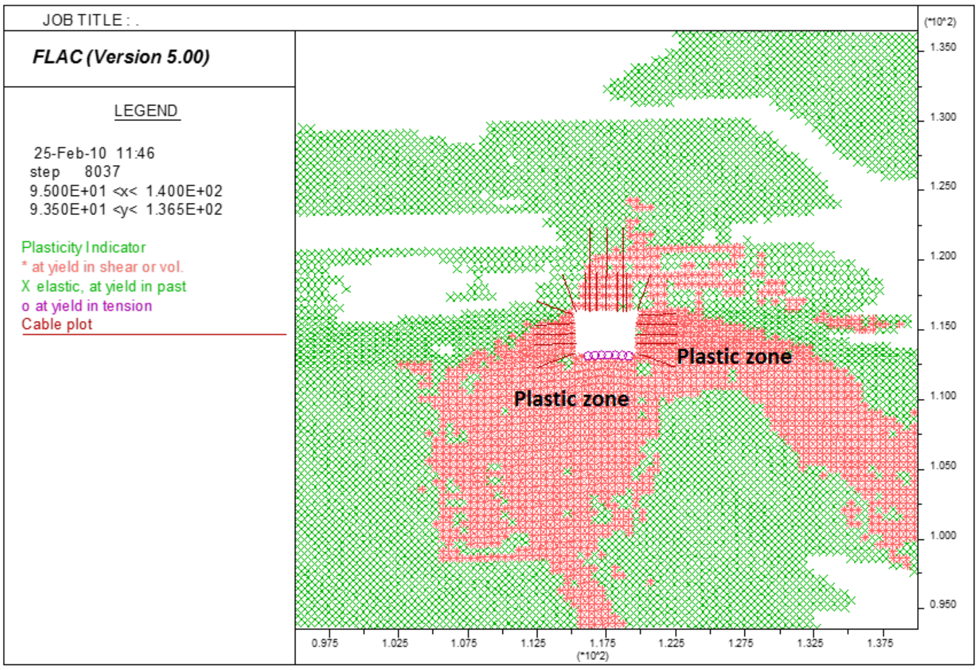


Fig. 13 Plastic zone distribution of the surrounding rock of the roadway with support scheme 1.

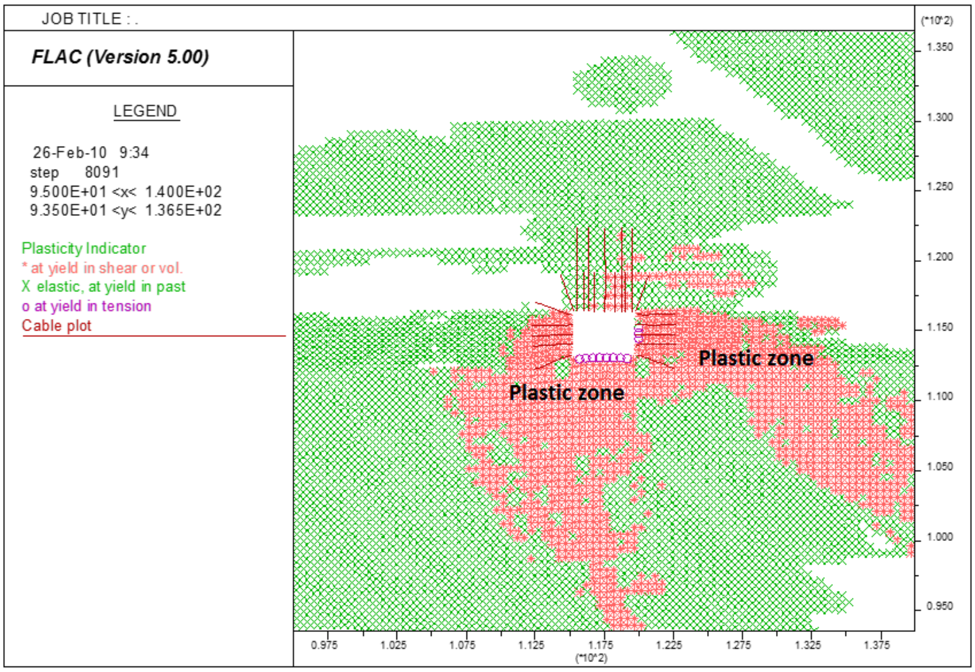


Fig. 14 Plastic zone distribution of the surrounding rock of the roadway with support scheme 2.

Table 3 Displacements of surrounding rock of the roadway.

Displacements	Left sidewall (mm)	Right sidewall (mm)	Roof (mm)	Floor (mm)
Scheme 1	305	339	189	397
Scheme 2	232	254	138	338

As can be seen from **Fig. 11** and **Fig. 12**, the overall stress distributions of the surrounding rock of the roadways with support schemes 1 and 2 have something in common after excavation. The vertical stress concentration appears in the two sidewalls' rock mass of the roadway. And the horizontal stress concentration appears in the rock mass above the right roof and under the left floor. The stress redistribution in those two sidewalls of the roadway is obviously asymmetric. The vertical stress of the rock mass in the right sidewall is bigger than that of the left sidewall close to the underlying goaf side. For example, the maximum vertical stress of the rock mass in the right sidewall is 30 MPa, whilst the maximum value of the rock mass in the left sidewall is 25 MPa. However, the areas of the low vertical and horizontal stress zones of shallow surrounding rock of the roadway with support scheme 2 are much smaller than that of support scheme 1 as shown in **Fig. 11** and **Fig .12**. Because the support strength of scheme 1 is low, the surrounding rock mass is subject to the yield unloading due to the stress concentration from the roadway excavation. The stress in the surrounding rock decreases and the high stress creeps to the deep surrounding rock. However, it seems the bearing capacity of the shallow surrounding rock mass decreases. Thus, the plastic zone and displacements will increase.

According to **Fig. 13** and **Fig. 14**, the plastic zone distributions of the surrounding rock of the roadways with support schemes 1 and 2, also have the similarity. The shear failure happens in the two sidewalls and the roof while the tensile damage appears in the floor. The plastic zone of the rock mass in the right sidewall is much bigger than that of the left sidewall. Whereas, the plastic zone including shear and tensile failure range of the surrounding rock with scheme 2 is much smaller than that of scheme 1.

Compared with scheme 1, the support strength of scheme 2 is more improved. Therefore, the plastic zone and displacements of the surrounding rock with scheme 2 are much smaller as shown in **Fig. 14** and **Table 3**. The displacements of the left sidewall, the right sidewall, the roof and the floor of the surrounding rock with support scheme 2 are 232mm, 254mm, 138mm and 338mm, respectively, which are acceptable. The support parameters of scheme 2 will be applied in the roadway in the upper protected coal seam above the goaf in Guqiao Coal Mine.

5. Engineering Practice

5.1 Support Parameters

The roadways in the upper protected coal Seam 13-1 were excavated in 150 days when the mining was completed in the lower protective coal Seam 11-2. The overlying rock strata and Seam 13-1 above the goaf were within the curve subsidence zone (deformation zone) and still within movement due to short compaction duration of the goaf of longwall coal face 1115(1) in the lower coal Seam 11-2. The excavation in the upper coal Seam 13-1 was carried out under the unstable conditions of the underlying strata movement and mining pressure.

The support of the deep roadways under dynamic pressure has higher requirements of initial support strength and resistance to the deformation of the surrounding rock. The high strength and pre-stressed thread steel bolt support system, i.e., new 'three-high' bolt support (high pre-stress, high strength, high stiffness) [27, 30, 47, 48] could afford high initial support strength with a high resistance to the deformations of the surrounding rock.

The high strength and pre-stressed thread steel bolt support system combined with the pre-stressed anchor cable beam in the roof was carried out in order to control the stability of the rail roadway above the goaf. The cross-section of the rail roadway was 5,000mm wide and 3,400m high. The support scheme and parameters were the same with the scheme 2 in the numerical simulation except steel strips, as shown in **Fig. 15**.

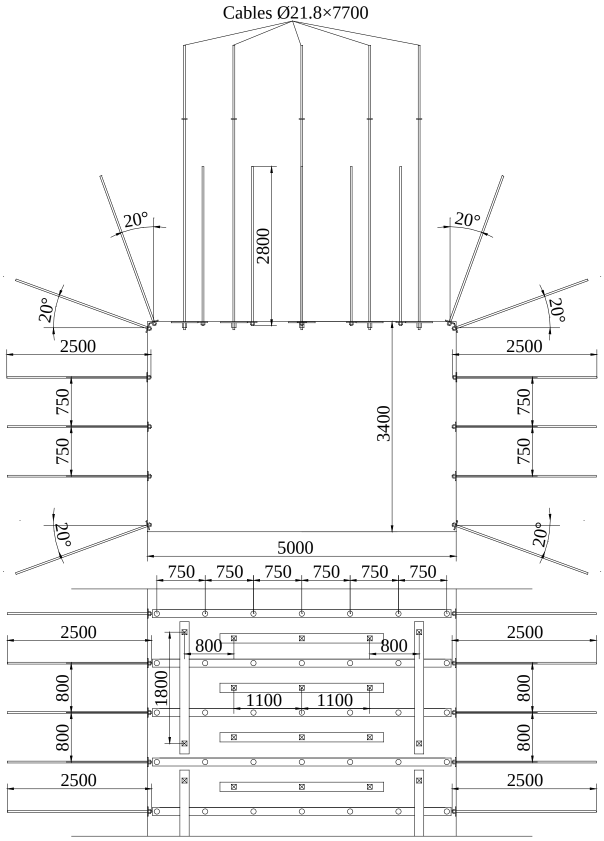


Fig. 15 Section and plan map of the support parameters of the roadway (Unit: mm).

(1) The roof of the roadway was supported by seven high-strength pre-stressed bolts (left-hand twist and IV class thread steel HRB500) combined with 4,800mm long steel strips of Type M5. Each sidewall was reinforced with five high-strength bolts, and 3,200mm long steel belts of Type M5. The diameter of bolts in the roof and sidewalls was 22mm and 20mm, respectively. And the lengths of bolts in the roof and sidewalls were 2,800mm and 2,500mm, respectively. Two resins of Z2380 that were medium-fast resin anchoring agent with the diameter of 23mm and the length of 800mm were used to install one bolt in the roof while one resin of Z2380 was for one bolt in the sidewalls. The interval and array pitch of the bolt layout were 750mm and 800mm, respectively. Besides, the bolts with an approximately 20° angle were installed in the corners.

(2) As illustrated in **Fig. 15**, pre-stressed anchor cable beams were applied perpendicular to the roadway axis between every two rows of the roof bolts after excavation and along the roadway axis direction, respectively. The anchor cable beams consisted of the anchor cables and the channel steel No.14. The diameter and length of anchor cable were 21.8mm and 7,700mm, respectively. Three resins of Z2380 were used to install every cable. A high pretension force of about 80 ~ 100 kN should be preloaded to cables in time to achieve the high pre-stress required to effectively reinforce the roof and control bedding separation during post-excavation installation.

5.2 Field Measurements

In order to analyze the reliability of the support parameters for the roadway above the goaf with a compaction duration of 150 days, field measurements such as surface displacements, bedding separation of roof strata, and axial load monitoring of bolts were carried out during excavation.

5.2.1 Displacements of the roadway

The displacements of the roadway are graphically presented in **Fig. 16** and **Fig. 17**. The maximum displacement velocities of the left sidewall, the right sidewall, the roof and the floor were 36 mm/d, 18 mm/d, 29 mm/d, and 60 mm/d, respectively, on the first day after excavation. The displacements of the surrounding rock tended to be stable in 41 days after roadway excavation. The displacements of the left sidewall, the right sidewall, the roof and the floor were 129mm, 104mm, 83mm and 245mm, respectively for a period of 41 days. The corresponding displacement velocities were 0.78 mm/d, 1.00 mm/d, 0.56 mm/d, 1.72 mm/d, respectively. Afterwards, the displacement velocities were rheological (creep and time-dependent). As a result, the total displacements of 123mm, 167mm, 95mm and 318mm were recorded for the left sidewall, the right sidewall, the roof and the floor, respectively, for a monitoring period of 96 days after excavation. The corresponding creep rates were 0.06 mm/d, 0.69 mm/d, 0.06 mm/d, 1.44 mm/d, respectively.

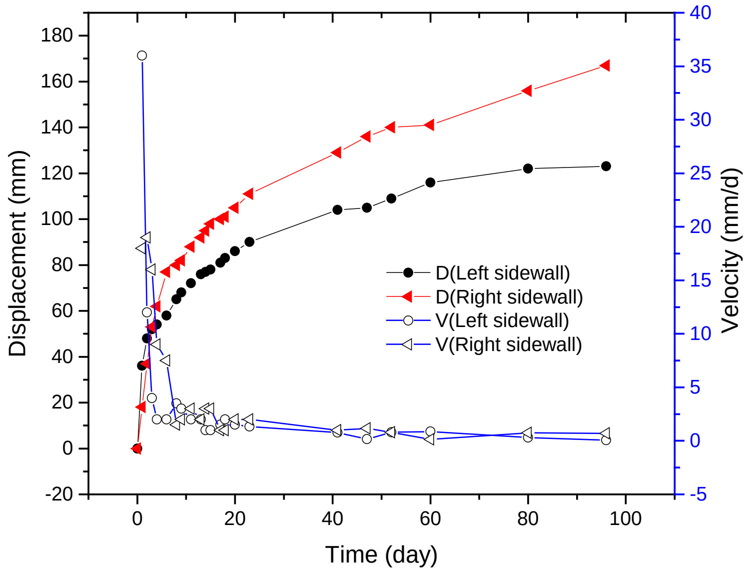


Fig. 16 Displacements and velocities of the left and right sidewalls.

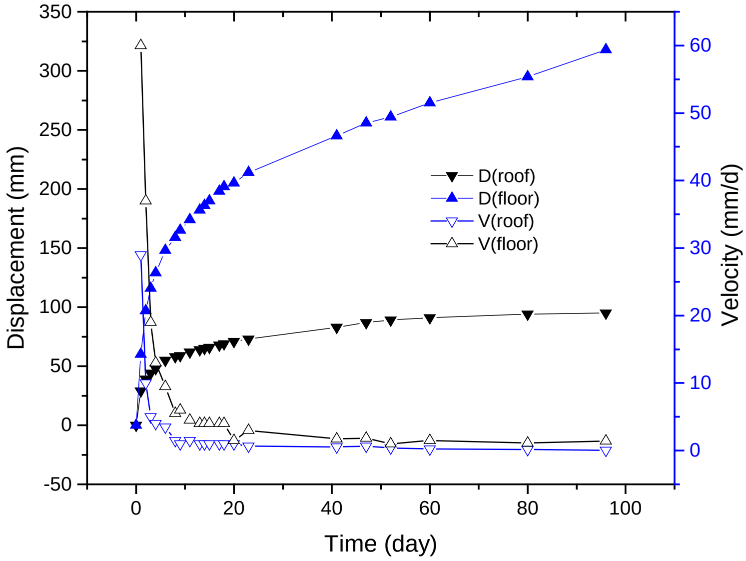


Fig. 17 Displacements and velocities of the roof and the floor.

The low creep rate and time-dependent behavior of displacements of the surrounding rock are accepted considering the 18-month-long service life of the roadway during excavation and mining operation. This finding indicates that ‘three-high’ bolt support system is able to control the stability of the roadway in the upper coal seam above the goaf.

The displacements of field measurements are smaller than that of scheme 2 in the numerical simulation (**Table 3**). For instance, the displacements of the left sidewall, the right sidewall, the roof and the floor are 123mm, 167mm, 95mm and 318mm, respectively, over the monitoring period. Whereas, the corresponding displacements of scheme 2 in the numerical simulation are 232mm, 254mm, 138mm and 338mm, respectively. However, if the creep and time-dependent behavior of the surrounding rock in the deep coal mine was considered, to some extent, the results from field measurements could be in line with that from the numerical simulation. In addition, because the right sidewall was located in the higher stress zone than the left sidewall, and the floor was not supported, the displacements of the roadway showed asymmetry. The displacements of the floor and the right sidewall near the higher stress zone were much larger than that of the roof and the left sidewall close to the underlying goaf side, which represented 77% and 58% of those of the roof-to-floor and sidewall-to-sidewall, respectively.

5.2.2 Roof bedding separation

Deformations of roof bedding separation started to be stable in 40 days when deformations of shallow basis point (3m deep) and deep basis point (8m deep) in the roof were 63mm and 78mm, respectively, as shown in **Fig. 18**.

The maximum deformations of shallow basis point and deep basis point in 96 days after excavation were 79mm and 95mm, respectively. Therefore, the deformation of roof bedding separation outside bolts’ anchorage zone that was between shallow basis point and deep basis point was only 16mm. Moreover, the maximum displacement of deep basis point was the same as the roof displacement that was 95mm in 96 days (**Fig. 17**, **Fig. 18**). The data of roof bedding separation indicates that pre-stressed anchor cable beam structures can effectively control the roof bedding separation and displacement.

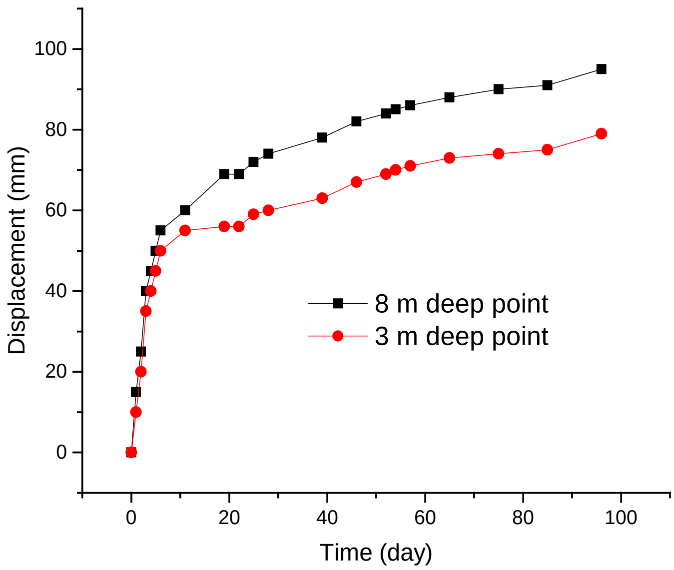


Fig. 18 Displacements of roof bedding separation.

5.2.3 Axial loading of the bolts

The axial loading of the bolts increased quickly during 10 days after the installation of the bolts as shown in **Fig. 19**. Then the axial loading tended to be stable. The maximum value of the axial loading of the bolts was 245 KN in the right roof. The bearing capacity of anchor bolts was excellent, which effectively control the roof displacement. In addition, the ultimate axial loading of bolts in the right sidewall and right roof were larger than that of the left sidewall and the left roof close to the underlying goaf side. It was in line with the results of the numerical simulation, i.e., the high stress was more concentrated in the right sidewall than that of the left sidewall. More precisely, the maximum values of the axial loading of the bolts in the right sidewall and right roof were 239 kN and 245 kN, respectively, whilst the corresponding maximum values in the left sidewall and the left roof were 120 kN and 200 kN, respectively.

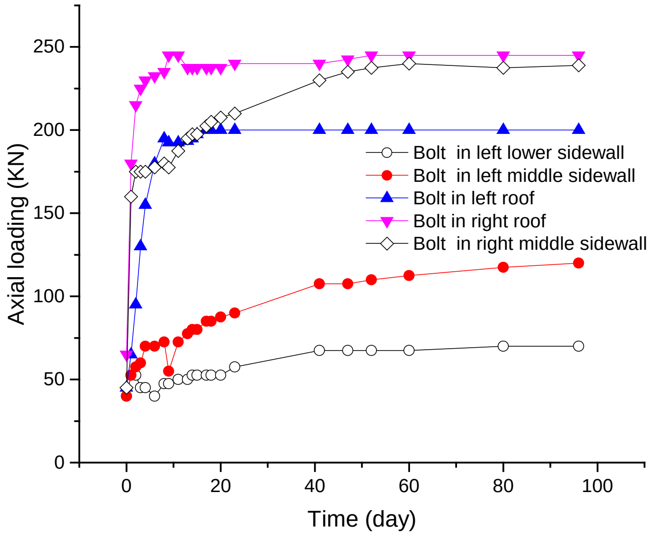


Fig. 19 Axial loading of the bolts.

5.2.4 Borehole image monitoring in the roof strata

The measurement of borehole image monitoring was conducted to detect the fracture condition in the roof strata as shown in **Fig. 20.** According to the borehole image monitoring, there was not any evident bedding separation and fractures in the roof strata reinforced by bolts and cables. Therefore, it can be said that the bolt support system combined with pre-stressed anchor cable beams is appropriate to reinforce the thick complex roof effectively. Support effect of the roadway in the upper protected coal seam is shown in **Fig. 21**.

(a) 2.0 m deep (b) 5.0 m deep

Fig. 20 Pictures from borehole image monitoring in the roof strata.

Fig. 21 Support effect of the roadway.

6. Conclusions

(1) The results from the numerical simulation show the impact scopes of the ascending mining-induced stress relief and concentration zones in the overlying rock strata are up to approximately 100m and 90m distances above the goaf, respectively. The stress relief zone above the goaf is beneficial to the CBM extraction. However, the lateral stress concentration increases the difficulty of the stability control of the roadway in the upper protected coal seam.

(2) Field measurements indicate that the displacements of the roadway tend to stable 41 days after the support scheme is implemented after excavation when the underlying goaf compaction duration is 150 days.

(3) The numerical simulation and field measurements both illustrate the displacements of the roadway are asymmetrical. The displacement of the right sidewall is much larger than that of the other sidewall close to the underlying goaf side, because the right sidewall is near stress concentration zone due to the ascending mining of the underlying protective coal seam.

(4) The new ‘three-high’ bolt support system combined with pre-stressed anchor cables that is successfully applied in Guqiao Coal Mine can control the stability of the roadway in the upper protected seam, which plays an important role in the application of multiple coal seams extraction with rich CBM and low permeability through ascending stress-relief mining.

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References

1) F. Fu, H. Liu, et al.; Measuring the Energy Consumption of China’s Domestic Investment from 1992 to 2007, Appl. Energy, Vol.102, pp.1267-74 (2013).
2) S. Kong, Y. Cheng, et al.; A Sequential Approach to Control Gas for the Extraction of

Multi-gassy Coal Seams from Traditional Gas Well Drainage to Mining-induced Stress Relief, Appl. Energy, Vol.131, pp.67-78 (2014).

3) K. Wang, Y. Wei, et al.; Energy and Emissions Efficiency Patterns of Chinese Regions: a Multi-directional Efficiency Analysis, Appl. Energy, Vol.104, pp.105-116 (2013).
4) National Bureau of Statistics of China; http://www.stats.gov.cn (2014.)
5) L. Wang, Y. Cheng; Drainage and Utilization of Chinese Coal Mine Methane with a Coal-methane Co-exploitation Model: Analysis and Projections, Resources Policy, Vol.37, No.3, pp.315-321 (2012).
6) W. Yang, B. Lin, et al.; Stress Evolution with Time and Space during Mining of a Coal Seam, Int. J. Rock Mech. Min. Sci., Vol.48, No.7, pp.1145-1152 (2011).
7) National Bureau of Statistics of China; http://www.stats.gov.cn (2015).
8) BP Statistical Review of World Energy; http://www.bp.com/statisticalreview (2015).
9) L. Yuan; Theory and Technology of Gas Drainage and Capture in Soft Multiple Coal Seams of Low Permeability, China Coal Industry Press, Beijing (2004), [in Chinese].
10) L. Yuan; Theory and Practice of Integrated Pillarless Coal Production and Methane Extraction in Multi-seam of Low Permeability, China Coal Industry Press, Beijing (2008), [in Chinese].
11) L. Yuan; Theories and Techniques of Coal bed Methane Control in China, J. Rock Mech. Geotech. Eng., Vol.3, No.4, pp.343-351 (2011).
12) X. Chen, Y. Cheng; Influence of the Injected Water on Gas Outburst Disasters in Coal Mine, Nat. Hazards, Vol.76, pp.1093-1109 (2015).
13) H. Guo, D. Adhikary, et al.; Simulation of Mine Water inflow and Gas Emission during Longwall Mining, Rock Mech. Rock Eng., Vol.42, No.1, pp.25-52 (2009).
14) C. O. Karacan, E. Okandan; Fracture/Cleat Analysis of Coals from Zonguldak Basin (northwestern Turkey) Relative to the Potential of Coalbed Methane Production, Int. J. Coal Geol. Vol.44, No.2, pp.109-125 (2000).
15) C. O. Karacan, F. A. Ruiz, et al.; Coal Mine Methane: a Review of Capture and Utilization Practices with Benefits to Mining Safety and to Greenhouse Gas Reduction, Int. J. Coal Geol., Vol.86, pp.121-156 (2011).
16) Y. Qin, L. Wang, et al.; Experimental Study of Different Granularity on the Gas Absorption of Coal, Procedia Eng., Vol.26, pp.93-100 (2011).
17) H. Wang, Y. Cheng, et al.; Gas Outburst Disasters and the Mining Technology of Key Protective Seam in Coal Seam Group in the Huainan Coalfield, Nat Hazards, Vol.67, pp.763-782 (2013).
18) D. Qian, H. Shimada, et al.; Application of Goaf-side Roadway Retained and New Type Ventilation System in Deep Longwall Face, Memoirs. Fac. Eng. Kyushu Univ., Vol.74, No.3, pp.99-116 (2015).
19) H. Wang, Y. Cheng, et al.; Gas Outburst Disasters and the Mining Technology of Key Protective Seam in Coal Seam Group in the Huainan Coalfield, Nat., Hazards, Vol.67: pp.763-782 (2013b).
20) L. Wang, Y. Cheng, et al.; The Controlling Effect of Thick-hard Igneous Rock on Pressure Relief Gas Drainage and Dynamic Disasters in Outburst Coal Seams, Nat Hazards, Vol.66, pp.1221-1241 (2013c).
21) G. Hu, H. Wang, et al.; Numerical Simulation of Protection Range in Exploiting the Upper Protective Layer with a Bow Pseudo-incline Technique, Min. Sci. Tech. (China), Vol.19, No.1, pp.58-64 (2009).
22) H. Liu, Y. Cheng, et al.; Pressure Relief, Gas Drainage and Deformation Effects on an Overlying Coal Seam Induced by Drilling an Extra-thin Protective Coal Seam, Min. Sci. Tech. (China), Vol.19, No.6, pp.724-729 (2009).
23) H. Liu, Y. Cheng, et al.; Fissure Evolution and Evaluation of Pressure-relief Gas Drainage in

the Exploitation of Super-remote Protected Seams, Min. Sci. Tech. (China), Vol.20, No.2, pp.178-782 (2010).
24) L. Yuan; Study on Critical Modern Technology for Mining in Gassy Deep Mines, J. China Uni. Min. Tech., Vol.17, No.2, pp.226-231 (2007), [in Chinese].
25) L. Yuan; Technique of Coal Mining and Gas Extraction without Coal Pillar in Multi-seam with Low Permeability, Journal of Coal Science and Engineering (China), Vol.25, No.2, pp.120-128 (2009).
26) C. Wang, N. Zhang, et al.; Experiment Research on Overburden Mining-induced Fracture Evolution and Its Fractal Characteristics in Ascending Mining, Arab. J. Geosci., Vol.8, No.1, pp.13-21 (2015).
27) C. Wang, N. Zhang, et al.; De-stressed Mining of Multi-seams: Surrounding Rock Control for Mining Influenced Roadway in the Overlying Protected Seam, Min. Sci. Tech. (China), Vol.21, pp.159-164 (2011).
28) C. Wang, N. Zhang, et al.; Control Principles for Roadway Roof Stabilization in Different Zones during Ascending Mining, J. China Uni. Min. Tech., Vol.41, No.4, pp.543-550 (2012), [in Chinese].
29) D. Qian, C. Wang, et al.; Surrounding Rock Control Technology and Application of Coal Roadway with Thick and Combined Roof Above Gob in Deep Mine. Coal Min. Tech. Vol.15, No.5, pp.51-54 (2010), [in Chinese].
30) D. Qian, T. Sasaoka, et al.; Stability Control of Roadway in Protected Seam of Deep High-gas Multi-seams through Ascending Mining in China, Pro. Int. Symposium on Earth Science and Technology 2013, Fukuoka, Japan, Dec. 3-4, 2013, pp.154-160 (2013).
31) X. Fang, J. He, et al.; Research on Reinforced Technology for Deep Soft Rock and Dynamic Pressurized Roadway Under High Stress, Rock and Soil Mechanics, Vol.30, No.6, pp.1693-1697 (2009).
32) X. Li, Q. Yao, et al.; Numerical Simulation of Stability of Surrounding Rock in High Horizontal Stress Roadway Under Overhead Mining, J. Min. Safe Eng., Vol.25, No.4, pp.420-425 (2008), [in Chinese].
33) S. Peng, B. Ling, et al.; Study on Over Rock Moving and Roadway Deformation within the Curve Subsidence Zone, J. China Coal Society, Vol.27, No.1, pp.21-25 (2002), [in Chinese].
34) L. Wang, X. Miao, et al.; Numerical Simulation of Bolt-grouting Support in Soft Roadway Affected by Mining, J. Min. Safe Eng., Vol.23, No.1, pp.39-42 (2006), [in Chinese].
35) W. Xie, A. Shi, et al.; Stability Analysis of Surrounding Rock Masses of Roadway under Overhead Mining, Chinese J. Rock Mech. Eng., Vol.23, No.12, pp.1986-1991 (2004), [in Chinese].
36) Y. Cheng, Q. Yu; Application of Safe and High-efficient Exploitation System of Coal and Gas in Coal Seams, J. China Uni. Min. Tech., Vol.32, No.5, pp.471-475 (2003), [in Chinese].
37) L. Yuan; Theory and Practice of Integrated Coal Production and Gas Extraction, Int. J. Coal. Sci. Technol., Vol.2, No.1, pp.3-11 (2015).
38) S. Lu, Y. Cheng, et al.; Application of In-seam Directional Drilling Technology for Gas Drainage with Benefits to Gas Outburst Control and Greenhouse Gas Reductions in Daning Coal Mine, China, Nat Hazards, Vol.73, pp.1419-1437 (2014).
39) D. Li; Mining Thin Sub-layer as Self-protective Coal Seam to Reduce the Danger of Coal and Gas Outburst, Nat Hazards, Vol.71, 41-52 (2014).
40) W. Yang, B. Lin, et al.; Mechanism of Strata Deformation under Protective Seam and Its Application for Relieved Methane Control, Int. J. Coal Geol., Vol.85, No.3-4, pp.300-306 (2011).

41) H. Guo, L. Yuan, et al.; Mining-induced Strata Stress Changes, Fractures and Gas Flow Dynamics in Multi-seam Longwall Mining, Int. J. Rock Mech. Min. Sci., Vol.54, pp.129-139 (2012).
42) L. Yuan; Technology of Simultaneous Extraction of Coal and Gas with Boreholes Drilled in Retained Roadway, J. China Coal Society, Vol.33, No.8, pp.898-902 (2008), [in Chinese].
43) L. Yuan; Gas Distribution of the Mined-out side and Extraction Technology of First Mined Key Seam Relief-mining in Gassy Multi-seams of Low Permeability, J. China Coal Society, Vol.33, No.12, pp.1362-1367 (2008), [in Chinese].
44) N. Zhang, L. Yuan, et al.; Deformation Characteristic and Stability Analysis of Roof Roadway in Distressed Mining, J. China Coal Society, Vol.36, No.11, pp.1784-1789 (2011), [in Chinese].
45) China National Coal Association (CNCA); Forum on Mining Technology of 1000m-plus Deep Coalmines in China, Taian, China, (2013), [in Chinese].
46) Q. Liu, K. Liu; Characteristics of In-situ Stress Field for Deep Levels in Huainan Coal Mine. Rock and Soil Mechanics, Vol.33, No.7, pp.2089-2096 (2012), [in Chinese].
47) N. Zhang, C. Wang, et al.; Rapid Development of Coalmine Bolting in China, Procedia Earth and Planetary Science, Vol.1, No.1, pp.41-46 (2009).
48) N. Zhang, W. Wang, et al.; Roadway Support Difficulty Classification and Controlling Techniques for Huainan Deep Coal Mining, Chinese J. Rock Mech. Eng., Vol.20, No.12, pp.2421-2428 (2009), [in Chinese].