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Application of Goaf-side Roadway Retained and New Type Ventilation System in Deep Longwall Face

by

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Abstract

Goaf-side Roadway Retained (GRR) without coal pillar can achieve Y-type ventilation, mitigate outburst hazard of coal and gas, etc., the stability of which is the key basis of simultaneous extraction of coal and methane (SECM) for multiple coal seams with rich gas and low permeability. However, its long-term stability until the end of longwall face mining is extremely difficult to control and maintain under intense mining dynamic pressure, especially in deep coal mines. To achieve SECM for multiple coal seams with rich gas and low permeability in Zhuji Coal Mine, GRR with multiple segments innovating Y-type ventilation system is put forward and applied in 910 m deep longwall face. The numerical simulation model is established by means of Universal Distinct Element Code (UDEC) software to analyze the influence of filling wall width on the stability of GRR. The results show that 3000 mm wide filling wall is relatively appropriate. Engineering practice indicates the maintenance duration of GRR with multiple segments is greatly reduced, compared with that of traditional GRR and the deformations are effectively controlled. The amount of methane extraction was 14.49 m^3 per ton of coal on average. SECM has been successfully achieved.

Keywords: Goaf-side roadway retained, Y-type ventilation, Simultaneous extraction of coal and methane, Longwall face, Stability

1. Introduction

Goaf-side Roadway Retained (GRR) is usually a roadway that is retained and preserved along a goaf side by constructing a man-made support wall such as filling wall during the extraction of a coal face [1, 2]. There are many advantages about GRR especially in rich gassy coal mine including

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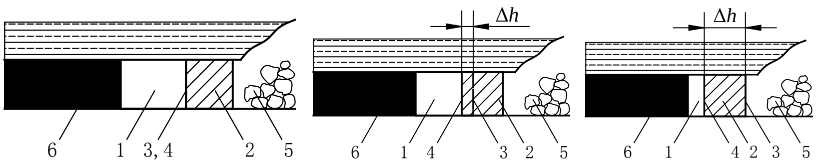
achieving Y-type ventilation, conducting methane extraction, avoiding gas accumulation in the upper corner of traditional U-type ventilation coal face, eliminating island coal faces, effectively improving coal recovery, reducing excavation rate, maintaining the balance of mining and tunneling, mitigating outburst hazard of coal and gas and preventing mining-induced disasters from remaining pillars [2, 3, 4, 5, 6, 7, 8].

There are usually three kinds of GRR as shown in **Fig. 1**, including (a) outside original roadway, (b) part inside the original roadway, (c) entirely inside the original roadway according to the relationship between the location of the filling wall of GRR and the original roadway [9].



(*a*) Outside the original roadway (*b*) Part inside the original roadway (*c*) Entirely inside the original roadway

1 - Original roadway before mining; 2 - Filling wall; 3 - Mining sidewall; 4 - The edge of filling wall; 5 - Goaf; 6 - Non-mining sidewall

Fig. 1 Relationship between the filling wall of GRR and the original roadway.

China is the coal production country with the most serious coal and gas outburst disasters in the world [10, 11]. In order to prevent gas outburst and explosion and promote a safer coal mining environment, over the last decade, GRR has been further developed as the key basis of simultaneous extraction of coal and methane (SECM) without pillar for multiple coal seams with rich gas and low permeability in China. GRR plays an important role in providing safe and appropriate space for drilling and maintaining methane extraction boreholes [7, 10, 12, 13]. The system of SECM effectively integrates the two previously separate operations of coal mining and methane extraction in multiple coal seams. The mining of one seam in multiple coal seams will lead to stress relief of adjacent seams, and lots of fractures in the overlying strata. Moreover, methane permeability, desorption and extraction capacities will increase, and methane pressure will decrease, thus the risk of coal and gas outburst will be reduced or avoided. Besides, coal bed methane will contribute to a reduction of green house gas emission [13].

However, due to mining dynamic pressure influence, deformations of GRR are very severe and are about 5~8 times as large as that of the roadway during excavation [2]. The high dynamic pressure often results in excessive deformations and rapid cross-section shrinkage of the roadway. Based on the engineering practice in deep coal mines in recent years, the long-term stability of GRR under intense mining dynamic pressure is extremely difficult when the length of the roadway in deep coal mine exceeds 1000 m, not to mention service as a roadway for the next adjacent coal face. Moreover, currently the continuous mining length of a longwall face in deep coal mines in China is commonly more than 1500 m, even up to 3000 m. In order to achieve Y-type ventilation and SECM for multiple coal seams with rich gas and low permeability in deep coal mines, GRR with multiple segments is put forward, which is applied in the 910 m deep longwall face in Zhuji Coal Mine, China.

2. Mining Geological Profiles

Huainan Mining (Group) Co., Ltd. is one of typical mining companies applying the multiple coal seams mining. The geological conditions in Huainan mining area are very complicated with characteristics of large overburden depth of 400 ~ 1500 m, 8 ~ 15 layers of coal seams, soft coal, rich gas with content of 12 ~ 36 m^3/t, low permeability of 0.001 mD (1 mD = 10^{-3} μm^2) in coal seams, high gas pressure (up to 6.2 MPa), and complicated geological structure. Coal Bed Methane Drainage Engineering Design Specification (GB50471-2008) illustrates that the methane in coal seams with low permeability less than 1 mD is difficult to be extracted [10]. Zhuji Coal Mine is a newly developed mine in Huainan Mining (Group) Co., Ltd and its design annual production capacity is 4 million tons. Seam 11-2 and seam 13-1 are two of main coal seams of Zhuji Coal Mine and are nearly horizontal. Seam 11-2 and seam 13-1 with rich gas and low permeability both have coal and gas outburst hazard while the risk in seam 13-1 is much higher than seam 11-2. In recent years, research and practice have proved that the extraction of 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 rich gassy multiple seams with low permeability [12, 13, 14, 15, 16, 17]. Therefore, seam 11-2 is selected as the protective coal seam to conduct methane extraction with long upward boreholes and eliminate coal and gas outburst hazard in seam 13-1. After that, Seam 13-1 above the goaf in seam 11-2 is exploited. Because of coal and gas outburst hazard in seam 11-2, two rock roadways under longwall face 1111(1) are excavated in advance to conduct methane extraction to ensure construction safety of haulage and rail roadways.

Longwall face 1111(1) is the first mining face in Zhuji Coal Mine, which is located in seam 11-2 and at -906 m mining level. The elevation of longwall face 1111(1) ranges from -877.6 m to -907.0 m with an average mining depth of 910 m. The mining length and width of the longwall panel are about 1612 m and 220 m, respectively. Seam 11-2 is weak glassy luster without coal gangue, and simple seam structure with its average thickness of about 1.2 m. Mining thickness along the roof is 1.8 m including floor rock of about 0.6 m. The faults simply develop with the maximum drop of less than 5 m. In simple hydrogeological conditions, its main water-filling source comes from the water of sandstone cracks between seam 13-1 to seam 11-2 as mainly static water reserves [18]. Geological profile is shown in **Fig. 2**. In addition, the vertical distance between seam 11-2 and seam 13-1 is about 70 ~75 m. The thickness of seam 13-1 varies from 1.65 m to 5.6 m with the average thickness of 4.03 m. The Y-type ventilation system in longwall face 1111(1) is illustrated in **Fig. 3**. The fresh air for the longwall face flows from haulage roadway to GRR through the longwall face. And the fresh air from rail roadway and polluted air from the coal face flow through GRR, connection roadways (CR), then into rock roadway in the floor.

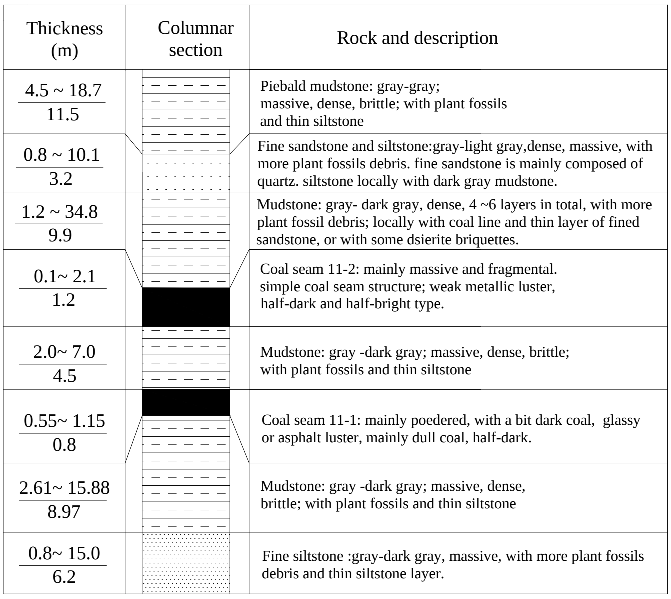
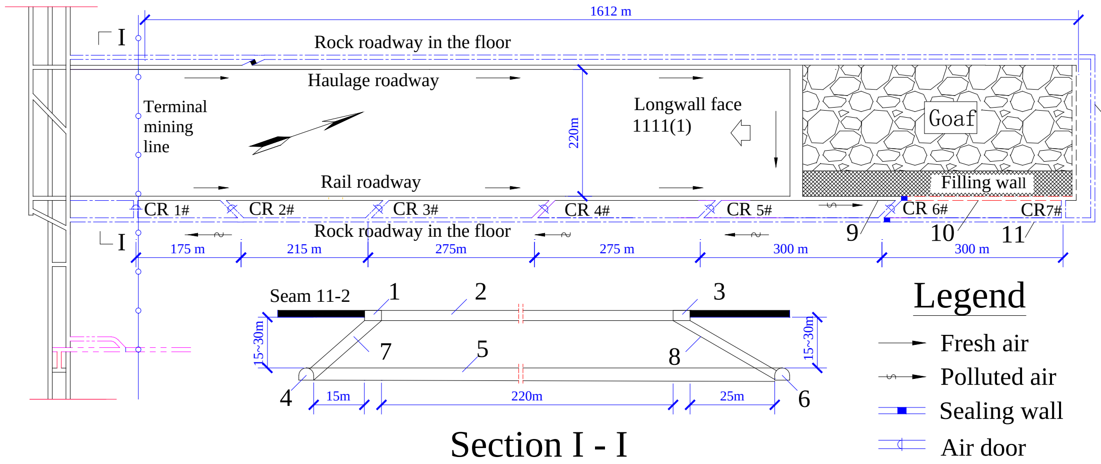


Fig. 2 Geological profile of coal seam 11-2.

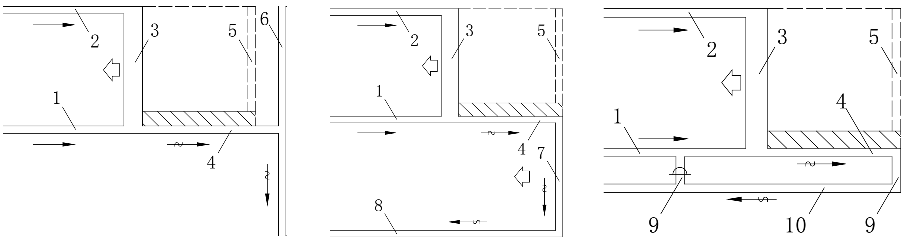


1 - Haulage roadway; 2 - Longwall face 1111(1); 3 - Rail roadway; 4 & 6 – Rock roadway in the floor; 5 – Connection roadway between rock roadways in the floor; 7 - Connection roadway between haulage roadway and rock roadway in the floor; 8 - Connection roadways (CR1#~CR7#) between rail roadway and rock roadway in the floor; 9 - Goaf-side Roadway Retained; 10 - Goaf-side Roadway Retained that will be abandoned, 11 - Rock roadway in the floor that will be abandoned.

Fig. 3 Y-type ventilation system by GRR with multiple segments in longwall face 1111(1).

3. Y-type Ventilation and GRR

There are usually two kinds of Y-type ventilation system in SECM technique without pillar as shown in **Fig. 4**: (a) Y-type ventilation with return-air rise roadway on boundary (b) Y-type ventilation with roadways in adjacent coal face [9]. Special return-air rise roadway on boundary or roadways in adjacent coal face should be excavated in advance if the kinds of Y-type ventilation in **Fig. 4**(a) and **Fig. 4**(b) are adopted, which increase the amount of roadway excavation. Moreover, the long-term maintenance duration of GRR is extremely difficult in deep coal mines. The project in Zhuji Coal Mine adopts a new way that is Y-type ventilation by GRR with multiple segments that takes advantage of the rock roadway in the floor as the return-air roadway (**Fig. 4**(c)). The maintenance duration of return-air roadway under mining dynamic pressure is greatly reduced because some segments of the rock roadway and GRR will be abandoned when the longwall face moves forward and passes some connection roadways.



(*a*) Y-type ventilation with return-air rise roadway on boundary

(*b*) Y-type ventilation with roadways in adjacent coal face

(*c*) New Y-type ventilation by Goaf-side Roadway Retained with multiple segments

1 - Rail roadway; 2 - Haulage roadway; 3 - Coal face; 4 - Goaf-side Roadway Retained; 5 - Open-off cut; 6 - Return-air rise roadway on boundary; 7 - Open-off cut in adjacent coal face; 8 - Rail roadway in adjacent coal face; 9 - Connection roadway; 10 - Rock roadway in the floor

Fig. 4 Common kinds and new kind of Y-type ventilation and GRR.

For example, if the Y-type ventilation with or without return-air rise roadway on boundary (**Fig. 4**(a) and **Fig. 4**(b)) is adopted, the maintenance duration of return-air roadway under mining dynamic pressure is at least 268 days according to mining length of 1,612 m and the average mining speed of 6 m/d in Zhuji Coal Mine. By contrast, if the Y-type ventilation by GRR with six multiple segments from 175 m to 300 m long (**Fig. 3**) is utilized, the maximum maintenance duration of return-air roadway under mining dynamic pressure is about 50 days (300/6= 50 days). Therefore, the maintenance duration of GRR with multiple segments is greatly reduced, which reduces the maintenance cost and difficulty of the roadway under mining pressure.

4. Numerical Simulation

4.1 Simulation Model

As illustrated in **Fig. 5** and **Table 1**, the numerical simulation model is simplified as a plane strain problem and performed by means of Itasca's Universal Distinct Element Code (UDEC) software to analyze the influence of filling wall widths on stability of GRR [19]. The dimensions of numerical model including eighteen strata layers are 220 m wide and 127 m high, respectively. And the length and height of the goaf are 110 m and 1.8 m, respectively. The mechanical parameters of the coal and rock strata are described in **Table 1**. According to the results of in-situ stress measurements in Zhuji Coal Mine, vertical stress is 19 MPa. A stress boundary of 17 MPa is applied in the vertical direction to the top boundary considering the model size. Roller boundary conditions are applied to the lateral boundary, and the bottom boundary is fixed from movement in the vertical direction. The criterion of Mohr-Coulomb's model is adopted. The cross-sections of the roadway during excavation and GRR are 4800 mm in width and 2800 mm in height, 3800 mm in width and 2800 mm in height, respectively. Support parameters are shown in **Fig. 6** and **Fig. 7**. The specifications of bolts in the roof and sidewalls are the diameter of 22 mm and length of 2800 mm, and the diameter of 22 mm and length of 2500 mm, respectively. The diameter and length of anchor cables in roof are 21.8 mm and 6300 mm, respectively. Three simulation schemes of filling wall widths including 2000 mm, 3000 mm and 4000 mm are proposed to determine a relatively rational width.

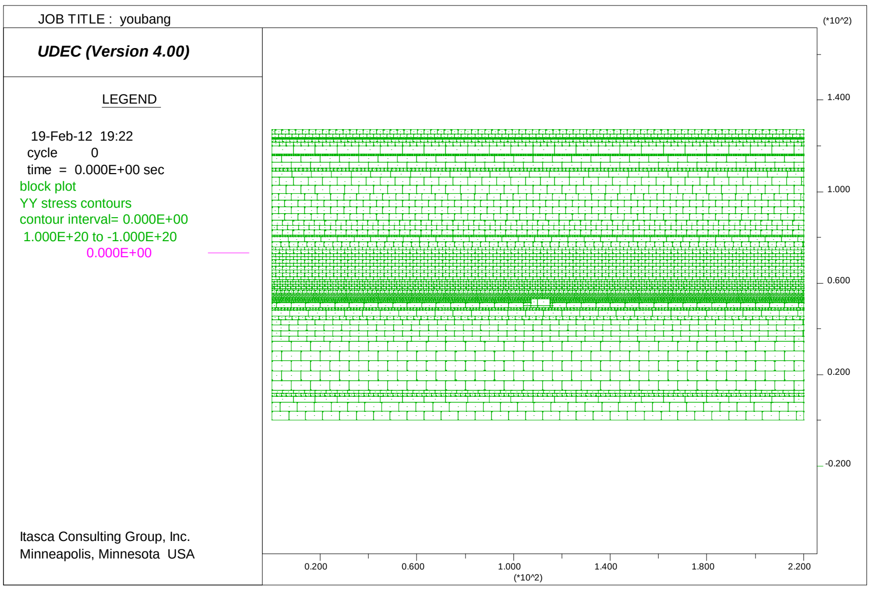


Fig. 5 Simulation model.

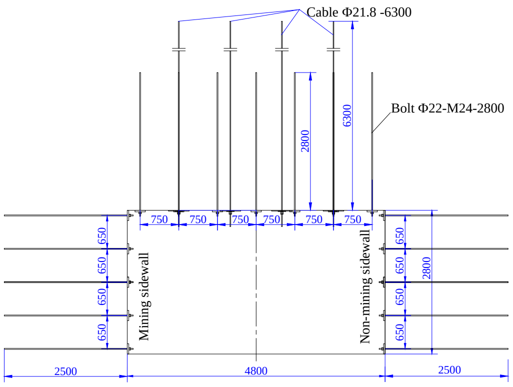


Fig. 6 Support parameters during excavation (Unit: mm).

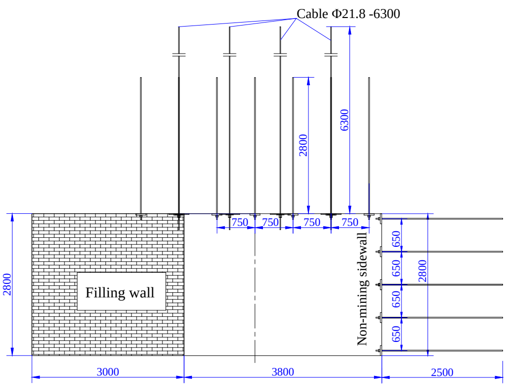


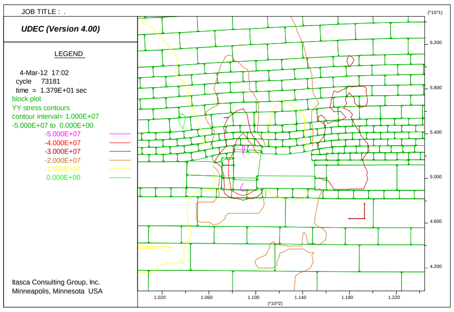
Fig. 7 Support parameter of GRR (Unit: mm).

Table 1 Mechanical parameters of the rock strata and filling wall.

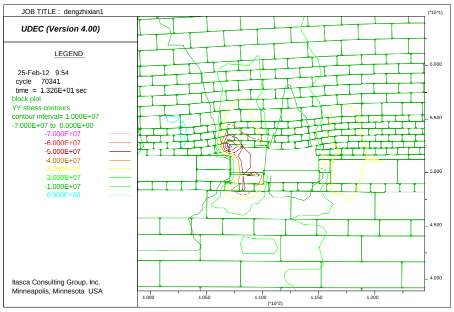
No.	Strata	Density (kg/m^3)	Thickness (m)	Bulk modulus (GPa)	Shear modulus (GPa)	Compressive strength (MPa)	Cohesion (MPa)	Friction (°)
1	Mudstone	2,300	1.0	3.03	1.56	25	1.2	27
2	Siltstone	2,700	2.0	2.68	1.84	50	2.0	32
3	Mudstone	2,300	3.6	3.03	1.56	25	1.2	27
4	Thin seam	1,400	0.6	1.19	0.37	15	0.8	23
5	Mudstone	2,300	6.0	3.03	1.56	25	1.2	27
6	Siltstone	2,700	18.0	2.68	1.84	50	2.0	32
7	Mudstone	2,300	9.0	3.03	1.56	25	1.2	27
8	Siltstone	2,700	10.0	2.68	1.84	50	2.0	32
9	Mudstone	2,300	11.5	3.03	1.56	25	1.2	27
10	Fine sandstone	2,600	3.2	5.56	4.17	60	2.0	35
11	Mudstone	2,300	9.9	3.03	1.56	25	1.2	27
12	Seam 11-2	1,400	1.8	1.19	0.37	15	0.8	23
	Filling wall	2,500	2.8	5.00	4.20	37	3.0	35
13	Mudstone	2,300	3.9	3.03	1.56	20	1.2	27
14	Seam 11-1	1,400	0.8	1.19	0.37	15	0.8	23
15	Mudstone	2,300	9.0	3.03	1.56	25	1.2	27
16	Siltstone	2,700	6.2	2.68	1.84	50	2.0	32
17	Mudstone	2,300	9.5	3.03	1.56	25	1.2	27
18	Siltstone	2,700	21.0	2.68	1.84	50	2.0	32

4.2 Influence of Filling Wall Widths on the Stability of GRR

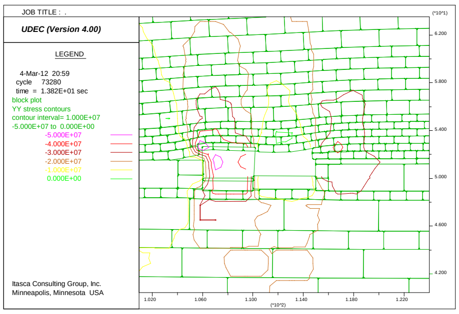
The width of the filling wall affects vertical stress distributions of GRR as shown in **Fig. 8**. With the wall width increasing, vertical stress peak transfers along the filling wall. When the width is 2000 mm, stress peak of 40 MPa appears in the roof on the filling wall. As the width is 3000 mm, stress peak shifts to the roof on the goaf and left shoulder corner on the filling wall, which is beneficial for the fracture of the roof along the edge between goaf and filling wall. By contrast, when the width continues to increase to 4000 mm, stress concentration appears both in the filling wall, its roof and the non-mining sidewall. The stress reaches 40 MPa that is not beneficial for the stability of the filling wall. Moreover, the stress concentration in the non-mining sidewall results in the large deformation of the non-mining sidewall. Therefore, 3000 mm wide filling wall effectively avoids the stress concentration in the filling wall itself, which is transferred to the roof on the goaf. In addition, according to the simulation results of the displacements, the displacements of the roof and the non-mining sidewall when the filling wall width is 3000 mm are smaller than that of 2000 mm and 4000 mm wide filling wall as illustrated in **Table 2**. Given the variation characteristics of stress and displacement as well as the cost of backfill and mining efficiency, 3000 mm wide filling wall can meet the requirements of GRR.



(a) 2000 mm wide filling wall



(b) 3000 mm wide filling wall



(c) 4000 mm wide filling wall

Fig. 8 Simulation results on vertical stress distribution of GRR with different wide filling wall.

Table 2 Displacements of GRR with different wide filling wall.

Widths of filling wall (m)	Filling wall (mm)	Non-mining sidewall (mm)	Roof (mm)	Floor (mm)
2	119	1510	585	1350
3	67	1289	570	1230
4	51	1320	582	1100

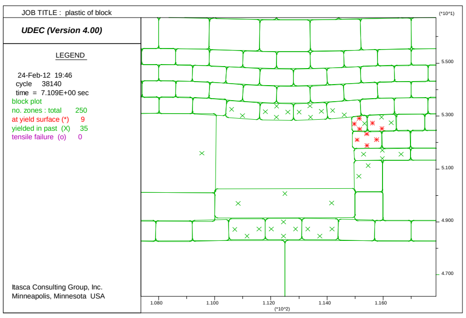


Fig. 9 Elastic and plastic zones during excavation.

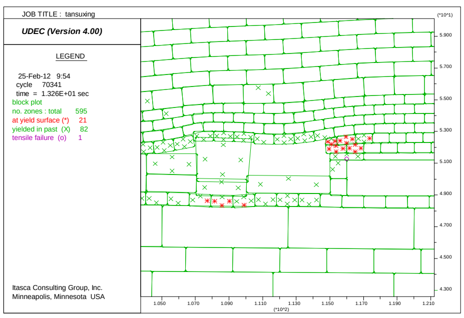


Fig. 10 Elastic and plastic zones after mining and filling (3000 mm wide filling wall).

In addition, the elastic and plastic zones during the excavation and after the mining and filling are shown in **Fig. 9** and **Fig. 10**. Compared with the plastic zones in the non-mining sidewall during excavation, the plastic zones after the mining and filling increases to 2500 mm wide range in the non-mining sidewall. The anchor performance of 2500 mm long bolts support in the non-mining sidewall is difficult to work due to the low bearing capacity of the plastic and mining-induced damaged zones, which leads to the severe displacements of the non-mining sidewall. Therefore, given the mining influence, the large displacements in the non-mining sidewall, in order to ensure safety and stability of GRR during the operation, individual hydraulic prop (IHP) support and cable reinforcement in the non-mining sidewall should further be carried out. Besides, the roof on the filling wall should also be supported before constructing the filling wall to prevent it from falling and sliding to the goaf.

5. Engineering Application

5.1 Support Parameters and Displacements during the Excavation

The high strength and pre-stressed thread steel bolt support system combined with pre-stressed cable was carried out to control the roadway stability during excavation. The cross-section of roadways is 4800 mm in width and 2800 mm in height. Support parameters are shown in **Fig. 11**.

(1) The roof support adopted seven high strength bolts (left-hand twist and IV class thread steel) with high pre-stress combined with 4600 mm long steel strips of Type M5 and a diamond-shaped metal mesh whose dimensions were 5400 mm in length and 1000 mm in width. The performance of M-steel strips [20] is shown in **Table 3**. Two resins of Z2360 were used to install the bolt. The resin of Z2360 was medium-fast resin anchoring agent with the diameter of 23 mm and the length of 600 mm. The spacing and array pitch of bolts were 750 mm and 800 mm, respectively.

(2) Each sidewall was supported with five high strength bolts, 3200 m long steel belts of Type M4 and a diamond-shaped metal mesh whose dimensions were 3400 mm in length and 1100 mm in width, respectively. The length of bolts with the diameter of 22 mm in the roof and two sidewalls were 2800 mm and 2500 mm, respectively. Two resins of Z2360 were used to anchor the bolt. The spacing and array pitch of bolts were 650 mm and 800 mm, respectively.

(3) Pre-stressed anchor cable beams were applied between every two rows of roof bolts in the roof. The anchor cable beams were composed of the anchor cables and channel steel strips No.20. The specifications of anchor cables were the diameter of 21.8 mm and length of 6,300 mm. One resin of K2360 and two resins of Z2360 were used to anchor the cable. The resin of K2360 was fast resin anchoring agent with the diameter of 23 mm and the length of 600 mm. Pretension force of 80 ~100 kN should be preloaded to cables to achieve high pre-stress to effectively reinforce the roof.

Table 3 Performance of M-steel strips.

Type \ Index	Broadening width (mm)	Thickness (mm)	Weight (kg/m)	Yield load (kN)	Breaking load (kN)
M3	173	3	4.05	124.56	197.22
M4	173	4	5.40	166.08	262.96
M5	173	5	6.75	207.6	328.70
M6	173	6	8.09	249.12	394.44

The displacement velocities of mining sidewall, non-mining sidewall, roof and floor decreased quickly after excavation. As shown in **Fig. 12**, a total of 88 mm, 113 mm, 202 mm and 260 mm were recorded for mining sidewall, non-mining sidewall, roof and floor respectively for a period of 262 days after the excavation. 262 days later, the corresponding velocities of mining sidewall, non-mining sidewall, roof and floor were 0.16 mm/d, 0.27 mm/d, 0.31 mm/d and 0.63 mm/d, respectively.

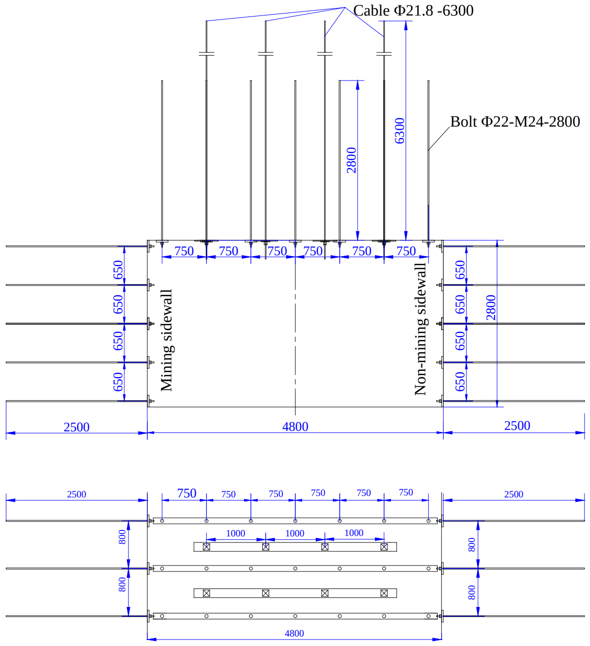


Fig. 11 Section and plan of support parameters during excavation (Unit: mm).

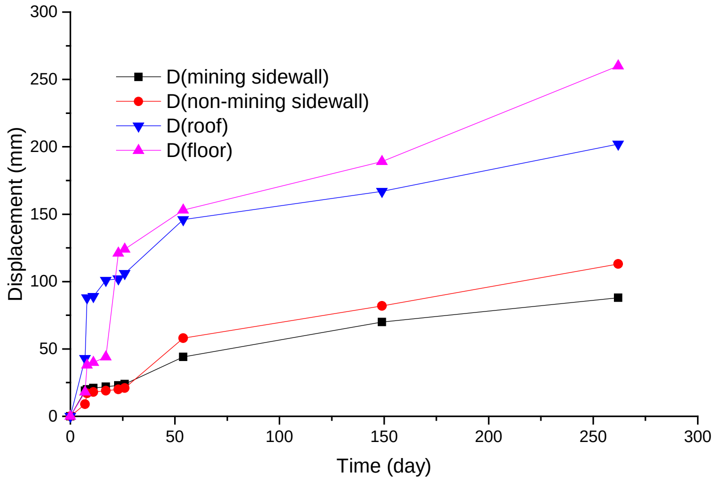


Fig. 12 Displacements during excavation.

5.2 Reinforcing Non-mining Sidewall and Roof Support on the Filling Wall

As illustrated in **Fig. 13**, pre-stressed anchor cable beams were applied in the non-mining sidewall from 200 m ahead of the longwall face. Pre-stressed anchor cable beams that were composed of cables and 2400 mm long strips of I-steel No.11. The specifications of cables were the diameter of 21.8 mm and length of 5200 mm, respectively. Three resins of Z2360 were used to anchor the cable. The pretension force of 80 ~ 100 kN should be preloaded to cables to achieve high pre-stress to effectively reinforce the non-mining sidewall.

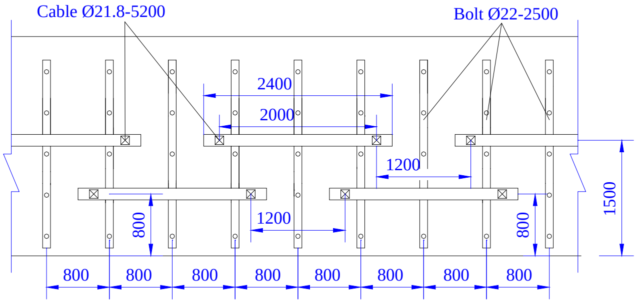


Fig. 13 Cable reinforcement in non-mining sidewall in advance (Unit: mm).

Reinforcing the roof in advance was conducted before the constructing filling wall as shown in **Fig. 14**. The specifications of bolts in the roof were the diameter of 22 mm and length of 1500 mm. The spacing and array pitch of bolts were 1100 mm and 800 mm, respectively. The diameter and length of anchor cables in the roof were 21.8 mm and 6200 mm, respectively. The spacing of cable was 800 mm.

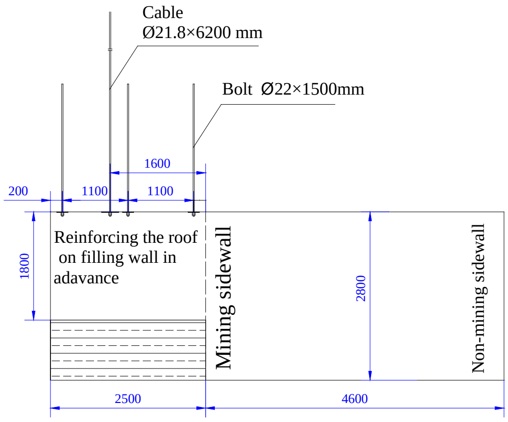


Fig. 14 Support of the roof on the filling wall in advance (Unit: mm).

5.3 Construction Process of GRR

GRR with multiple segments was adopted in 910 m deep longwall face 1111(1) in Zhuji Coal Mine. The average width was 4600 mm due to the two sidewalls' displacement of about 200 mm before mining. The GRR adopted the type of part inside the original roadway as shown in **Fig. 1**(b). The filling wall was 3000 mm in width and 1800 mm in height (2800 mm in height in some areas). The new concrete filling pump of BSM1002E (**Fig. 15**) was adopted. The maximum transmission capacity, delivery pressure and transmission distance of the pump were 12~15m^3/h, 100 bar and 800 m, respectively. According to the mining advance speed of 6 m/d, the filling length was 3 m at a time. The filling times were twice per day. Layout diagram of filling system in longwall face 1111(1) is illustrated in **Fig. 16**. Filling process of GRR is listed below: Transporting of filling material and moving hydraulic support → Roof support and individual hydraulic prop (IHP) support → Cleaning the coal and rock in the floor → Preparing backfill formwork → Filling → Cleaning pump and pipe.

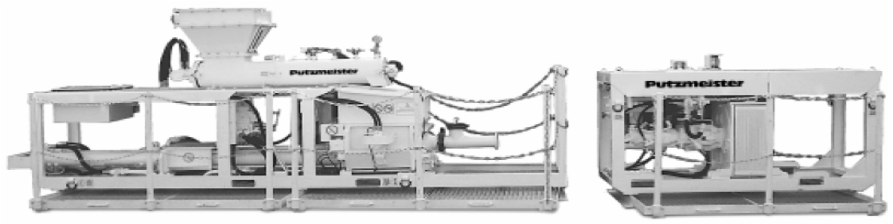


Fig. 15 The concrete filling pump of BSM1002E.

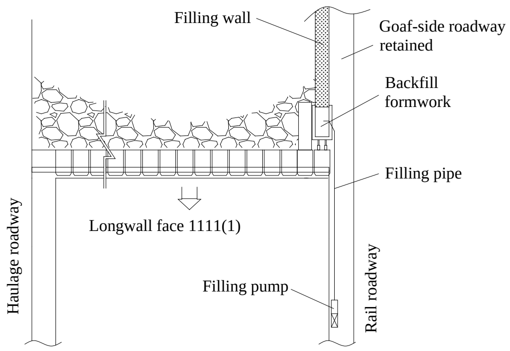


Fig. 16 Layout diagram of filling system.

Individual hydraulic prop (IHP) support is shown in **Fig. 17**, **Fig. 18** and **Fig. 19**. Four IHPs support combined with 4000 mm long beam of I-steel No.11 was carried out from 60 m ahead of the longwall face to 250 m behind the longwall face along the direction of roadway axis. The spacing of IHPs was 1000 mm.

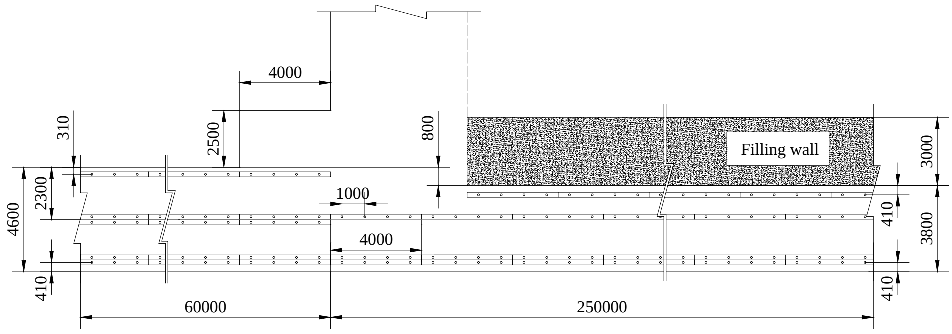


Fig. 17 Schematic plan of IHP support (Unit: mm).

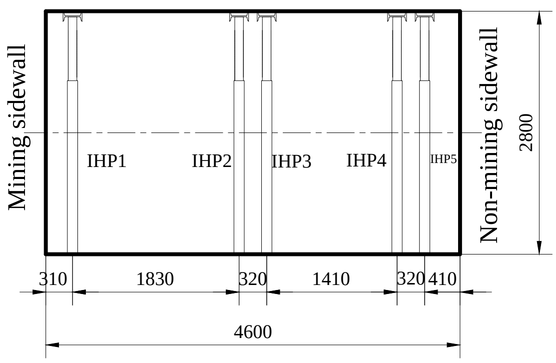


Fig. 18 Schematic section of IHP support ahead of the longwall face (Unit: mm).

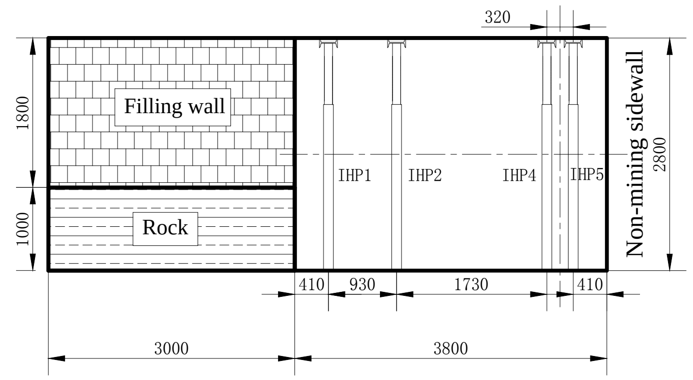


Fig. 19 Schematic section of IHP support in GRR behind the longwall face (Unit: mm).

The backfill material and performance are as follows.

(1) The ingredient composition and proportion

The backfill material is composed of ordinary Portland cement, fly ash, gravel and sand mixed with water. The weight ratio of the various compositions are cement of 20%, fly ash of 7%, gravel of 40%, sand of 20% and of water 13%, respectively. Strength grade of the ordinary Portland cement is 42.5 MPa. The fineness of fly ash of grade Ⅱ is not more than 0.045 mm. The maximum particle size of the gravel is less than 6 mm. The sand is medium sand. In addition, the compound admixture is 1.6% of the total cement and fly ash by weight percent.

(2) Compound admixtures

The compositions of compound admixtures by weight percentage are poly carboxylic acid of 30% as water reducing agent, carboxymethyl cellulose of 1.5% as water-retaining agent, rosin hot polymer of 1.2% as air-entraining agent, calcium chloride of 67.3% as early strength agent, respectively.

(3) Performance of backfill material

The backfill material with the slump of 220 mm achieving pumping distance of 550 m can be pumped into the backfill formwork, then self-compacts. Compressive strengths of backfill material in 1 d, 3 d, 7 d and 28 d are 9.8 MPa, 15.6 MPa, 21.5 MPa and 37.0 MPa, respectively. The residual strength is 36.6% of the ultimate compressive strength.

5.4 Filed Measurements during the mining

Field measurements such as surface displacements, load of individual hydraulic prop (IHP) and coal bed methane extraction monitoring were carried out during the mining and the operation of GRR.

5.4.1 Displacements ahead of and behind the longwall face

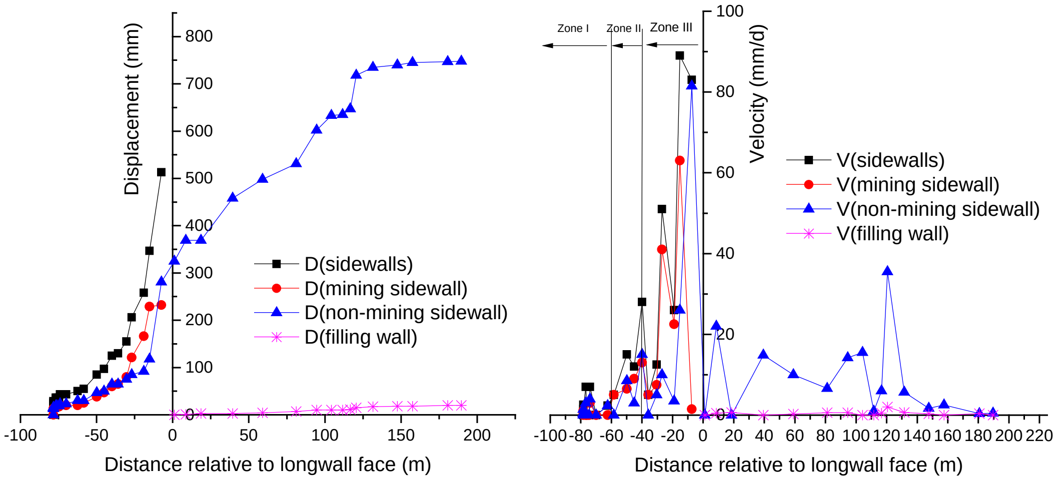
Displacement monitoring was carried out when the longwall face approached from 78 m away and passed the measurement point by 190 m.

(1) Mining-induced displacements ahead of the longwall face (**Fig. 20** and **Fig. 21**)

According to the relationship of displacements and the distance relative to longwall face, displacements ahead of the longwall face could be divided into three zones. Zone I: small mining-induced displacements (Distance $\leq$ -60 m). The displacements were small and the velocities were less than 10 mm/d. Zone II: mining-induced accelerating displacements (-60 m $\leq$ distance $\leq$-40 m). The displacements of two sidewalls and roof-to-floor started to accelerated when the distance was 40 m. The corresponding velocities increased to 28 mm/d and 39 mm/d, respectively. Zone III: severe mining-induced displacements (-40 m ≤ distance ≤ 0 m). The maximum velocities of two sidewalls and roof-to-floor were 89 mm/d and 136 mm/d, respectively. The displacements of mining sidewall, non-mining sidewall, roof and floor were 232 mm, 281 mm, 269 mm and 687 mm, respectively when the longwall face was near the monitoring location.

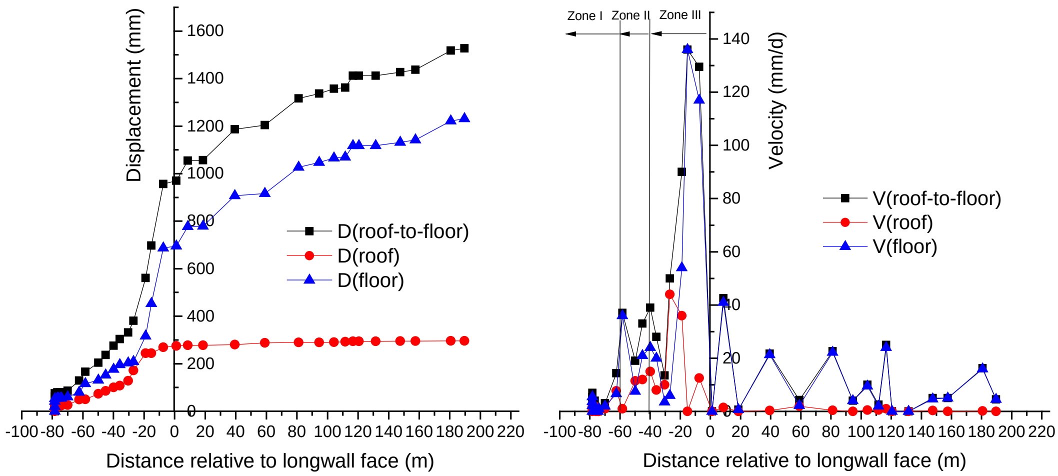
(2) Displacements of GRR behind the longwall face (**Fig. 20** and **Fig. 21**)

During the construction of GRR, the maximum velocities of two sidewalls and roof-to-floor were about 22 mm/d and 40 mm/d, respectively as the longwall face passed the monitoring location by 9 m (distance = 9 m). When the distance was 130 m, displacements of GRR tended to be stable. Afterwards, the displacements of surrounding rock were rheological. The accumulative displacements of filling wall, non-mining sidewall, roof and floor were 20 mm, 748 mm, 296 mm and 1,231 mm, respectively, when the monitoring location was 190 m away from the longwall face (distance = 190 m). The displacements showed evidently asymmetry. The displacement of the non-mining sidewall was much larger than that of the filling wall. The support effect of GRR is shown in **Fig. 22**.



(a) Displacement versus distance (b) Velocity versus distance

Fig. 20 Displacements of sidewall and filling wall when the longwall face approached (distance <0) and passed (distance >0) the monitoring location.



(a) Displacement versus distance (b) Velocity versus distance

Fig. 21 Displacements of roof and floor versus the distance relative to the longwall face.

(a) Filling wall (b) GRR behind the longwall face

Fig. 22 Support effect of GRR.

5.4.2 Loads of individual hydraulic prop

The monitoring results of loads of individual hydraulic prop (IHP) are shown in **Fig. 23**. Loads of IHP 4 near non-mining sidewall were much larger than that of IHP 1 near the filling wall and mining sidewall, which is similar to the monitoring results of displacements, e.g. the displacement of the non-mining sidewall was much larger than that of the filling wall and mining sidewall. More precisely, the maximum Load of IHP 4 was 366.4 kN while the maximum loads of (IHP1) near mining sidewall and the filling wall and were only 87.7 kN. This illustrates that the mining-induced stress causes the severe displacements of the non-mining sidewall.

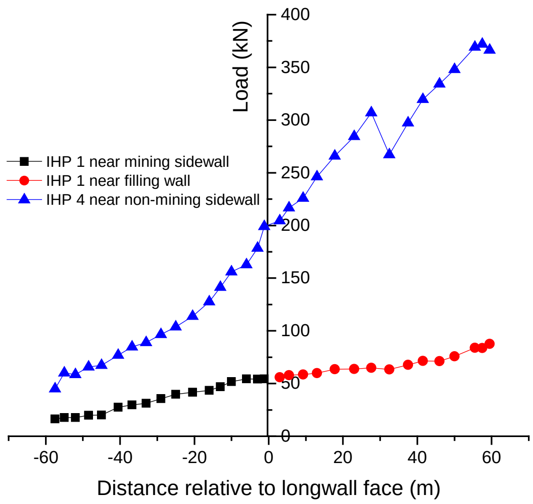


Fig. 23 Loads of individual hydraulic prop (IHP) support in GRR.

5.4.3 Extraction monitoring of Coal Bed Methane

Coal bed methane extraction during the mining of longwall face 1111(1) through ascending stress-relief mining method in multiple coal seams was carried out by boreholes and pre-embedded pipes as shown in **Fig. 24**, including long upward boreholes through seam 13-1, long boreholes through the roof of seam 11-2 and pre-embedded pipes through the filling wall connecting the goaf, etc. For instance, the layout of four long upward extraction boreholes in connection roadway 4 and GRR is shown in **Fig. 25** and **Table 4**. The methane extraction monitoring of long upward borehole 4 is shown in **Fig. 26**. As the longwall face moved forward, the daily average concentration increased quickly from 3.63% at a distance of 28 m ahead of the longwall face to 47% at a distance of 14.4 m ahead of the longwall face, peaking at 91% at a distance of 28 m behind the longwall face. The daily average net flow quantity peaked at 0.22 m^3/min at a distance of 28 m behind the longwall face. Therefore, methane permeability, desorption and extraction capacities in overlying seam 13-1 are improved due to ascending stress-relief mining in multiple coal seams. Thus, the risk of coal and gas outburst in seam 13-1 will be reduced or avoided after methane extraction.

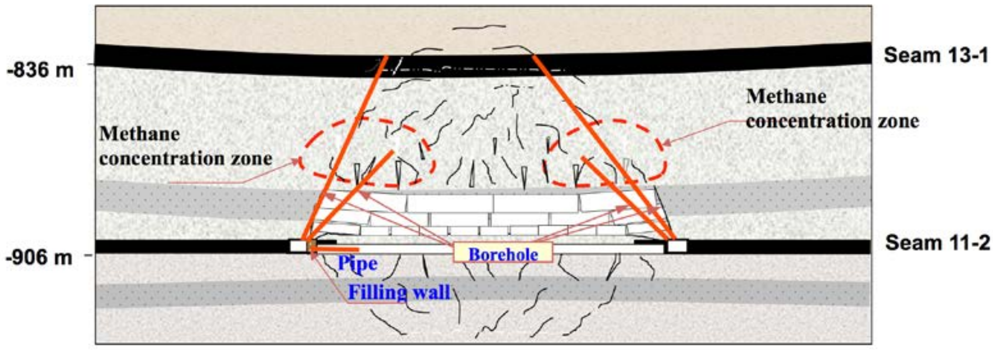


Fig.24 Schematic diagram of methane extraction through ascending stress-relief mining in multiple seams.

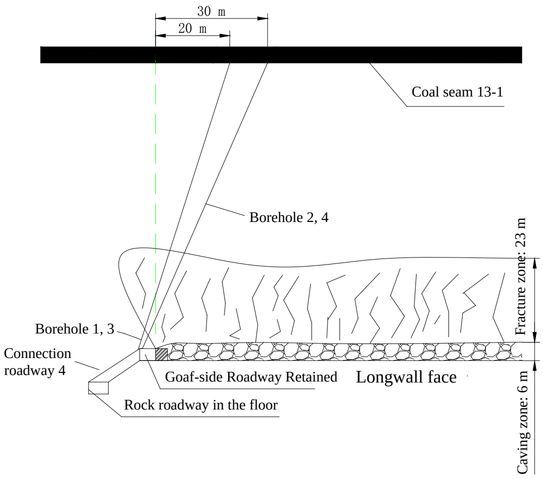


Fig. 25 Layout of long upward extraction boreholes in connection roadway 4 and GRR.

Table 4 Design parameters of long upward extraction boreholes in connection roadway 4 and GRR.

Long upward borehole No.	The angle relative to the roadway axis (°)	Dip (°)	Borehole depth reaching seam 13-1 (m)	Borehole depth through seam 13-1 (m)	Depth of borehole bottom (m)
1	32	58	86	91	91
2	40	55	89	94	94
3	52	66	75	79	79
4	60	62	80	84	84

Methane concentration and methane discharge quantity in return air are shown in **Fig. 27** and **Fig. 28**, respectively. Total return air volume was between 2290 m^3/min and 2700 m^3/min during the mining of the longwall face. The maximum methane discharge quantity in return air was up to 14.57 m^3/min, with an average of about 9.45 m^3/min. Methane concentration in return air was less than 0.6%, with an average of 0.38%. The methane emission from the goaf is effectively controlled. Safe mining of the first longwall face in multiple coal seams in the deep coal mine is achieved.

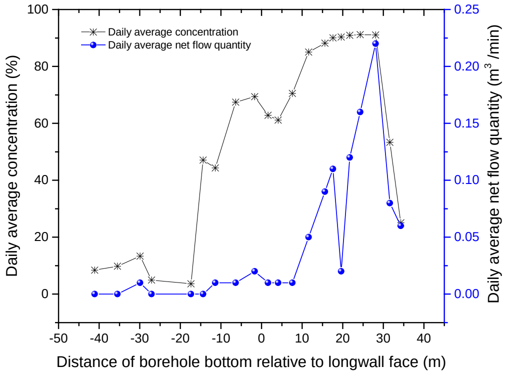


Fig. 26 Methane extraction versus horizontal distance of long upward borehole bottom relative to the longwall face.

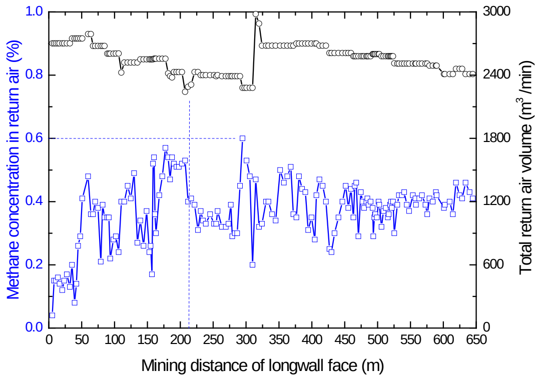


Fig. 27 Methane concentration in return air and total return air volume.

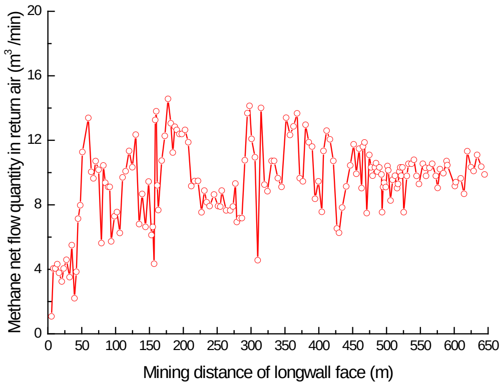


Fig. 28 Methane discharge quantity in return air.

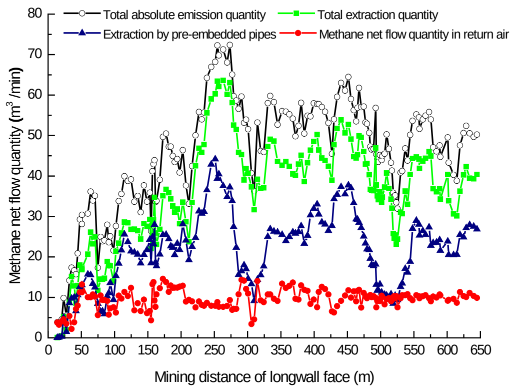


Fig. 29 Total absolute methane emission quantity and total methane extraction quantity.

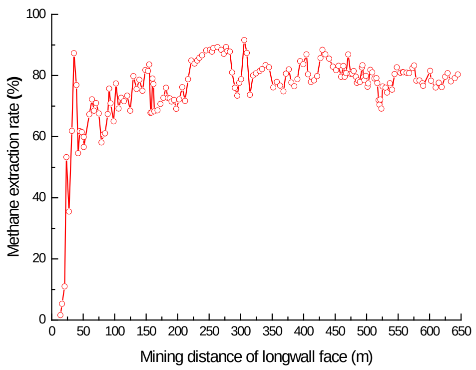


Fig. 30 Methane extraction rate.

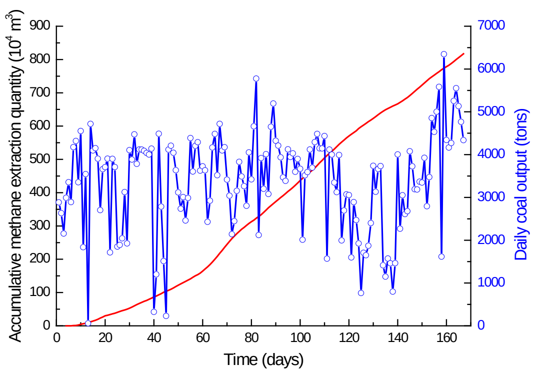


Fig. 31 Accumulative methane extraction quantity and daily coal output.

Total absolute methane emission and methane extraction quantity, and methane extraction rate during the mining of longwall face 1111(1) are illustrated in **Fig. 29** and **Fig. 30**, respectively. The total absolute emission quantity of the methane was up to 72.39 m^3/min, with an average of 43.42 m^3/min. The total average extraction quantity was 33.98 m^3/min. Methane extraction net flow quantity by pre-embedded pipes was 20.78 m^3/min on average, accounting for 47.9% of the total average absolute methane emission quantity (43.42 m^3/min) and 61.2% of the total average extraction quantity (33.98 m^3/min), respectively. The methane extraction rate of the longwall face was usually more than 60%, with an average of 78.3%.

Methane extraction rate *K* is calculated according the equation as follows.

$$K = Q_{ext} / Q_{emi} \tag{1}$$

Where K is methane extraction rate; Q_{ext} is methane extraction quantity; Q_{emi} is absolute methane emission quantity.

The monitoring of over 160 days about the amount of accumulative methane extraction quantity and daily coal output is shown in **Fig. 31**. The average daily output was 3377 tons. And the amount of accumulative methane extraction was 8 million m^3. The amount of methane extraction was about 14.49 m^3 per ton of coal on average. The high concentration methane extracted can be utilized directly such as producing electricity. SECM has been successfully achieved in Zhuji Coal Mine.

6. Conclusions

(1) Goaf-side Roadway Retained (GRR) with multiple segments has been put forward and successfully applied in the 910 m deep longwall face. The maintenance duration of GRR with multiple segments is greatly reduced, compared with that of traditional GRR under mining dynamic pressure. Numerical simulation and engineering practice indicate that 3000 mm wide filling wall can meet the requirement of GRR.

(2) Field measurements indicate mining-induced displacements ahead of the longwall face could be divided into three zones including Zone I: small mining-induced displacements (Distance $\leq$ -60 m), Zone II: mining-induced accelerating displacements (-60 m $\leq$ distance $\leq$ -40 m) and Zone III: severe mining-induced displacements (-40 m $\leq$ distance $\leq$0 m). Individual hydraulic prop (IHP) support should be carried out from 60 m ahead of the longwall face.

(3) GRR with multiple segments innovates Y-type ventilation system, which successfully achieves simultaneous extraction of coal and methane in Zhuji Coal Mine. The methane extracted can be utilized directly.

(4) Ascending mining increases methane permeability, desorption and extraction capacities in the overlying seam. The overlying coal seam 13-1 will be safely exploited through ascending stress-relief mining method after methane extraction.

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