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The gob-side entry retaining with the high-water filling material in Xin'an Coal Mine

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Abstract. With the increasing tension of current coal resources and the increasing depth of coal mining, the gob-side entry retaining technology has become a preferred coal mining method in underground coal mines. Among them, the technology of the gob-side entry retaining with the high-water filling material can not only improve the recovery rate of coal resources, but also reduce the amount of roadway excavation. In this paper, based on the characteristics of the high-water filling material, the technological process of gob-side entry retaining with the high-water filling material is introduced. The early and late stress states of the filling body formed by the high-water filling materials are analyzed and studied. Taking the 8th floor No.3 working face of Xin'an coal mine as engineering background, the stress and displacement of surrounding rock of roadway with different filling body width are analyzed through the FLAC^{3D} numerical simulation software. As the filling body width increases, the supporting ability of the filling body increases and the deformation of the surrounding rock decreases. According to the theoretical calculation and numerical simulation of the filling body width, the filling body width is finally determined to be 3.5m. Through the field observation, the deformation of the surrounding rock of the roadway is within the reasonable range. It is concluded that the gob-side entry retaining with the high-water filling material can control the deformation of the surrounding rock, which provides a reference for gob-side entry retaining technology with similar geological conditions.

Keywords: gob-side entry retaining; high-water filling material; filling body; numerical simulation; field observation

1. Introduction

The gob-side entry retaining technology can effectively improve mine recovery rate, extend the service life of the mine, prevent the formation of the island working face and relieve the tension between mining and excavation (Oreste *et al.* 2005, Guo *et al*. 2014, Zhang *et al*. 2014, Zhao *et al*. 2015, Ishwar and Kumar 2017, Yang *et al.* 2018). The gob-side entry retaining is in the low pressure area, the probability of rock burst is greatly reduced (Deng *et al*. 2014, Tan *et al*. 2015, Yang *et al*. 2016). In addition, it can achieve Y-type ventilation to effectively prevent gas accumulation in the upper corner of working face (Zhang *et al*. 2015, Jaouhar *et al.* 2018), and can reduce the labor intensity, which has the significant economic and social benefits (Venticinque *et al*. 2014, Guo *et al*. 2016, Chen *et al.* 2018, Fu *et al*. 2018).

Based on the existing research, Maleki *et al.* (1986) considered that the small coal pillar of gob-side entry retaining can effectively control the floor heave and minimize the interaction between the two coal seams. Haeamy *et al*. (1990) concluded that the application of small coal pillars in gob side entry can reduce the risk of impact and improve the recovery rate of coal resources, but the coal and rock properties, burial depth and mining height of working face affect the coal pillars width in gob side entry. Medhust *et al*. (1998) carried out the triaxial compression experiments on coal samples of different sizes, studied the mechanical characteristics and failure mechanisms of different coal pillar sizes and provided a basis for the technology of gob-side entry retaining.

Deng *et al*. (2010) adopted a new attempt to pack roadside by pumping ordinary concrete and proposed a scheme that cable is used to reinforce roadside supporting and a single hydraulic prop is used as the temporary supporting in gob side. Zhang *et al*. (2015) and Liu *et al*. (2018) conducted a study on the gob-side entry retaining project in deep soft rock mine and effectively controlled the severe deformation of the roadway. Ning *et al*. (2017) established a mechanical model of the supporting structure for the gob-side entry retaining. Gao (2018) took the three rock layers of roof, floor and coal pillar as the bedded composite rock mass and analyzed the influence of the bedded composite rock mass on the elastic core of coal pillar of the gob-side entry retaining. Ma *et al*. (2018) further improved the design system of roof cutting seam parameters of non coal pillar gob-side entry retaining, proposed the second roof cutting scheme of the upper side gob-side entry retaining and achieved a certain effect.

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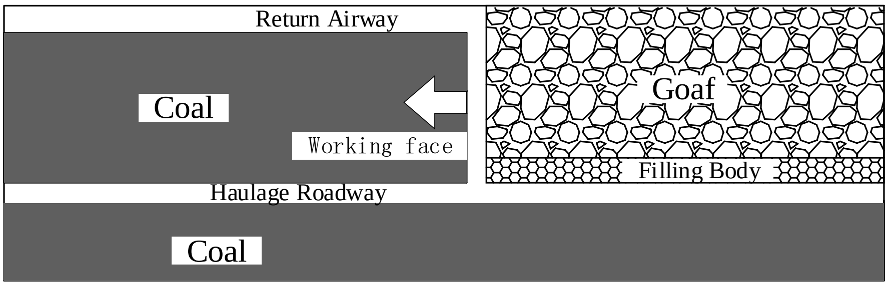


Fig. 1 Schematic diagram of gob-side entry retaining

In addition, lots of scholars have carried out the analysis on filling material and filling body of the gob-side entry retaining from the aspects of theory analysis, laboratory testing, numerical simulation. Karfakis *et al*. (1996) tested the backfilling materials produced from the Zonguldak Colliery coal mine, Turkey. The results obtained by experiments were related to the coefficient of uniformity of particle size distribution and the effective size. James *et al*. (1999) used waste glass as a substitute for Portland cement (SPC), which could be used for coal mine backfill. It is concluded that the Portland cement with 35% waste glass material has the best strength characteristics.

Tian *et al*. (2008) carried out experiments of different concentration and different additive dosage on the filling materials composed of fly ash and gangue. The results show that the early strength of the backfill composed of fly ash and coal gangue is very low, the later strength is increased, and it is still rising after 60 days. Guo *et al*. (2009) studied on the laws of the strata and surface movement with long wall fully mechanized gangue backfilling technology by similar material simulation and numerical simulation method, and pointed out that improving the filling rate of gangue backfilling in goaf and the initial density of filling body are the main technological way to enhance the controlling effect of strata movement.

2. Engineering backgroud

The Xin'an coal mine is located in Shuangyashan City, Heilongjiang Province, China. The buried depth of the 8th floor No.3 working face of Xin'an coal mine is 620 m. The average thickness of coal seam is 3 m. The immediate roof is the 4 m thick medium sandstone. The basic roof is the 8 m thick siltstone. The direct bottom is 2 m thick gritstone. The roadway along goaf is the haulage roadway. After the haulage roadway is successfully retained, the haulage roadway will become the return air roadway for the next working face. The schematic diagram of gob-side entry retaining is shown in Fig. 1.

To reduce mining costs and save the use of filling materials, the high-water filling material has been tested and used as a new mining technology (Liu *et al*. 2014, Doherty *et al*. 2015). According to the characteristics of high-water material, such as good fluidity, high early strength, and controllable setting time (Altunbas *et al*. 2017, Li *et al*. 2017), taking the 8th floor No.3 working face of Xin'an coal mine as the engineering background, the gob-side entry retaining with the high-water filling material is applied. The saved haulage roadway will be the return air roadway for the next working face.

3. The technological process of gob-side entry retaining with high-water filling material

The reasonable and efficient gob-side entry retaining technology can control the deformation of surrounding rock and isolate the goaf (Xu *et al*. 2014). The gob-side entry retaining can make workers dig one less roadway, and the mechanization degree of the gob-side entry retaining technology of high-water filling material is high, so that the labor intensity of workers is low.

3.1 Mechanical properties of high-water filling materials

The high-water filling material is made by mixing fly ash in the waste slag of power plant, fluidic agent, early strength agent and accelerator. The filling slurry is formed by adding a large amount of water into the high-water filling material (the water-cement ratio is greater than 3) and stirring it. The filling slurry begins to solidify gradually and form the filling body after reaching the filling site.

According to the technical requirements of the gob-side entry retaining with the high-water filling material, the final strength of the filling body needs to reach 32 MPa. The Fig. 2 is the relationship between the compressive strength and age of filling body determined by laboratory tests. As can be seen from the figure, the strength of the filling body can reach 4 MPa within 8 hours, and then increase gradually with the age. The strength of the filling body can finally reach 50 MPa, which meets the technical requirements for the gob-side entry retaining. The mechanical parameters of the filling body are shown in Table 1.

It can be seen from Fig. 2 that there are three key periods of filling body and age: the rapid growth period (0~7 days), slow growth period (7~28 days) and stable period (> 28 days).

Table 1 Mechanical parameters of the filling body

Lithology	Bulk Modulus/ GPa	Shear Modulus/ GPa	Density/ (kg/m^3)	Friction Angle/(°)	Cohesion /MPa	Tensile Strength/ MPa
Filling body	6.1~7.9	2.7~3.5	14~21	31~52	2.2~3.2	1.4~2.6

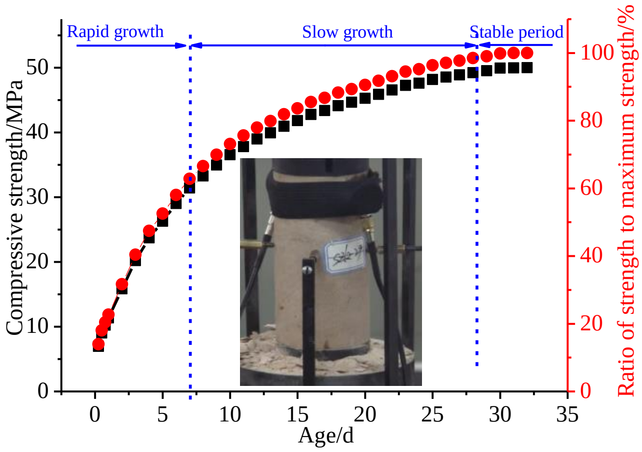


Fig. 2 The compressive strength- age curve

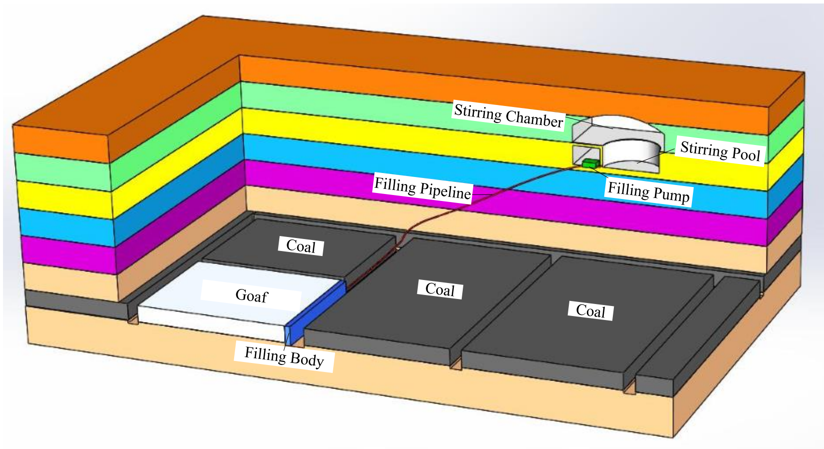


Fig. 3 The technology of gob-side entry retaining with high water material

(a) Stirring pool (b) Stirring blade (c) Filling pump and filling pipeline

Fig. 4 Equipment in the stirring chamber

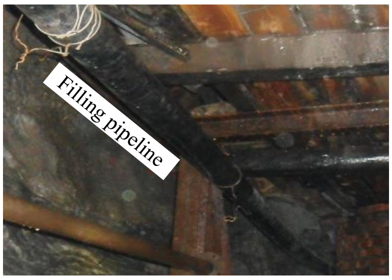
The compressive strength of the filling body increased rapidly within 7 days, and reaches 31 MPa after 7 days, and its strength reached 63%, which can basically resist the subsidence and deformation of the roof surrounding rock.

The filling body still shows an increasing trend within 28 days, and reaches 49.23 MPa after 28 days, and its strength can reach more than 98% of the maximum strength.

The compressive strength of the filling material gradually reached the maximum value 50 MPa and remained unchanged after 28 days.

3.2 The technological process of gob-side entry retaining with high-water filling materials

According to the characteristics of high-water materials, the gob-side entry retaining technology with high-water filling material is shown in Fig. 3. The key parts of gob-side entry retaining technology are stirring chamber, the filling pipeline, filling frame and filling bag.



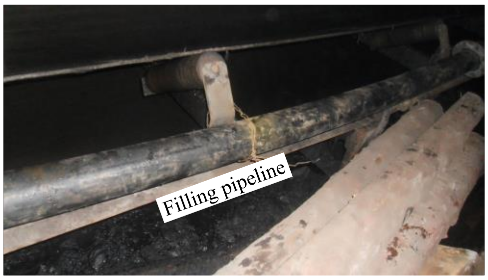


Fig. 5 Filling pipeline

Fig. 6 Filling frame

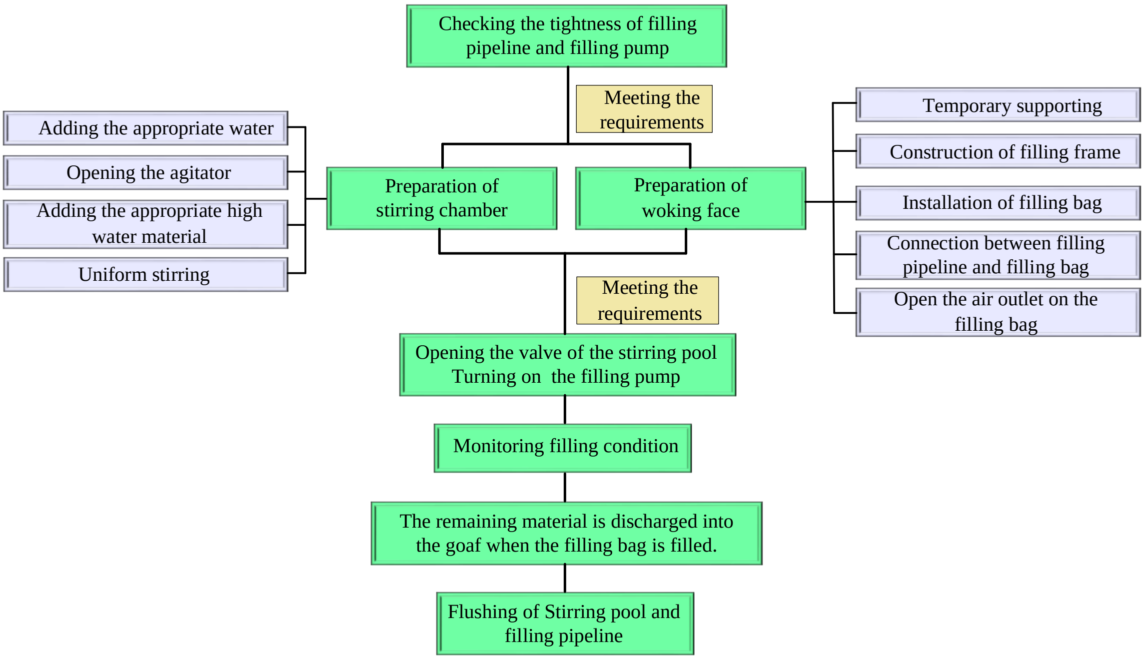


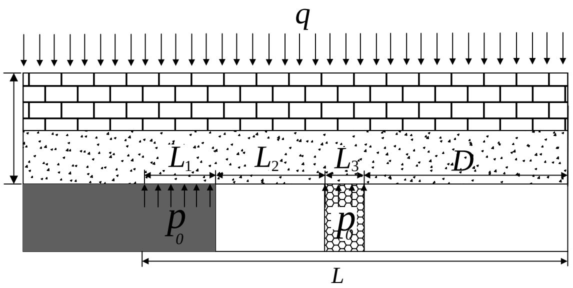
Fig. 7 Process of gob-side entry retaining with high-water filling materials

(1) Stirring chamber

The stirring chamber is composed of the stirring pool, filling pump and the filling pipeline, as shown in Fig.4. The filling slurry is made by mixing the high-water material and water. The agitator is used to evenly stir the filling slurry, there are two layers of stirring blades on the agitator, the bottom stirring blade and the upper stirring blade. When the agitator is running, the bottom stirring blade can lift up the high-water material in the bottom of stirring pool to prevent high-water material from accumulating at the bottom of stirring pool, the upper stirring blade can prevent the filling slurry from overflowing the stirring pool. The filling pump adopts horizontal pump, the flow and head of the filling pump should meet the requirements of the filling engineering.

(2) Filling pipeline

The filling site is connected with the stirring chamber through the filling pipeline. The filling pipeline should meet safety requirements of coal mine. The laying of filling pipeline should be stable, and the laying position of filling pipeline should avoid collision with mining vehicle and other equipment. The filling pipeline is shown in Fig. 5.



p_0— The compressive strength of the coal body p_1— The compressive strength of the filling body
L—The length of the force L_1—The effective force length of coal body L_2—The roadway width L_3— The filling body width
q— The loading of the overlying roof D— The length of working face H—The thickness of the overlying strata

Fig. 8 Mechanical model of filling body in the initial stage of mining

(3) Filling frame and filling bag

Because the filling site is adjacent to the goaf, the temporary supporting should be taken at the filling site to ensure the safety of person and equipment. The temporary supporting is shown in Fig. 6.

The filling frame is fixed on the temporary supporting to ensure the flatness of the filling frame. The filling bag is an anti-leakage and anti-static special bag for filling slurry. It has a slurry inlet and an air outlet. The slurry inlet is the hole that the filling material enter the filling bag. The air outlet is the hole that the air is discharged from the filling bag when the filling slurry enters the filling bag to ensure that the filling bag is filled with the filling slurry and the filling body is in close contact with the roof.

3.3 Process of gob-side entry retaining with high-water filling material

Because the high-water filling material have the characteristics of good fluidity, high early strength, and controllable setting time, the process of gob-side entry retaining with high-water filling material should follow the steps in Fig.7.

Before adding the high-water filling material, the tightness of the filling pump and the filling pipeline should be inspected with the clean water. When the tightness of filling pipeline and filling pump reaches the requirement, the high-water filling material can be stirred and pumped. When the filling work is finished, the stirring pool and the filling pipeline should be flushed again with the clean water to avoid clogging of the filling pump and the filling pipeline.

4. Force analysis of filling body

The stability of surrounding rock of gob-side entry retaining is determined by filling body, coal body and supporting structure (Yin *et al*. 2017).

According to the force state of the overlying strata acting on the filling body, the force on the filling body can be divided into the initial stage and the late stage. The overlying strata in the initial stage did not collapse, and the overlying strata in the late stage was failed. Therefore, it is necessary to analyze the mechanical characteristics of filling body in the initial and late stages respectively.

4.1 The force analysis of filling body in the initial stage

In the initial stage, the overlying strata will not immediately bend, sink or break. The overlying strata is mainly supported by the coal body, the filling body and the supporting structure. The mechanical model of the filling body in the initial stages is shown in Fig. 8.

The force in the vertical direction should satisfy the equation:

$$P_1 + P_0 = L\gamma H \tag{1}$$

where P_1 is the compressive strength of the filling body; P_0 is the compressive strength of the coal body; L is the length of the force; γ is the bulk density of the overlying roof; H is the thickness of the overlying strata.

According to Fig. 7, Eq. (1) can be expressed as:

$$P_1 + P_0 = \left(D + L_1 + L_2 + L_3\right)\gamma H \tag{2}$$

where D is the length of working face; L_1 is the length of effective force on coal body; L_2 is the roadway width; L_3 is the filling body width.

4.2 The force analysis of filling body in the late stage

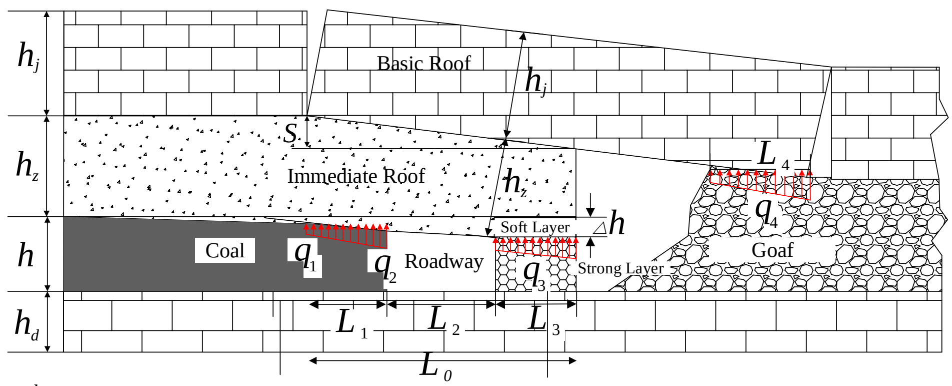
When the working face advanced a distance, the immediate roof behind the working face was sank and broken. The broken immediate roof rock filled the goaf. And the basic roof was rotated and sank, with one side acting on the coal body and the other side acting on the goaf gangue. The mechanical model of the filling body in the late stage is shown in Fig. 9.

The force of coal body on roof F_1 is:

$$F_1 = \frac{1}{2}L_1\left(q_1 + q_2\right) \tag{3}$$

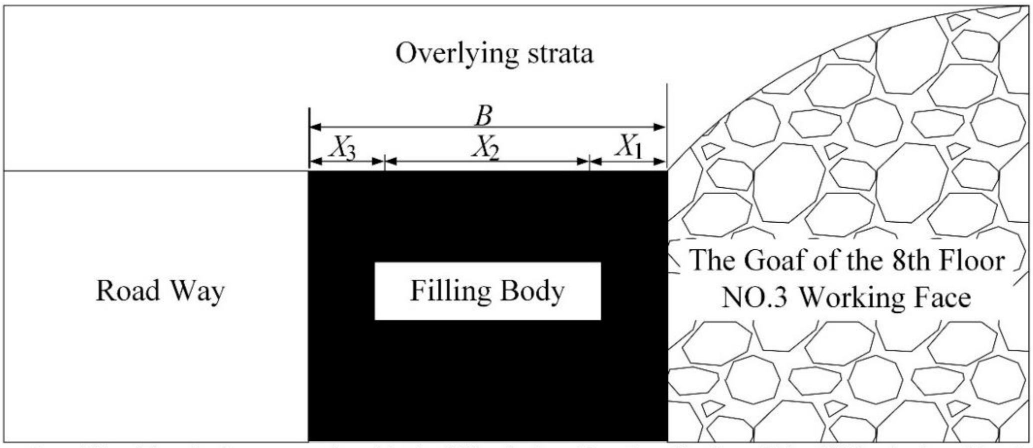
where F_1 is the force of the coal body on roof, kN; q_1, q_2 are the loading strength inside coal body and the loading strength of the coal body at the roadway when the basic roof is broken respectively, kN/m; L_1 is the length of effective force on coal body, m.

Assuming the loading of the filling body on the immediate roof is trapezoidal distribution, the equivalent loading strength in the middle of the filling body is q_3, then the force of the filling body on roof F_3 is:



h_j— Basic roof thickness h_z— Immediate roof thickness h— Coal thickness h_d— Floor thickness
L_1—The effective force length of coal body L_2—The roadway width L_3— The filling body width L_4— The compression length of goaf gangue
q_1—The loading strength inside coal body when the basic roof is broken q_2—The loading strength of the coal body at the roadway when the basic roof is broken
q_3—The equivalent loading strength in the middle of the filling body q_4 — The maximum loading at the contact point of roof and goaf gangue

Fig. 9 Mechanical model of filling body in the late stage of mining



X_1 —the width of the plastic zone produced in the filling body; X_3 —the effective width of filling body, taking 1.2m;
X_2 —filling body stability coefficient, which calculating as $(X_1+X_3)(30\%\sim50\%)$.

Fig. 10 Filling body width calculation

$$F_3 = q_3 L_3 \tag{4}$$

where the F_3 is the force of the filling body on roof beside the roadway, kN; q_3 is the equivalent loading strength in the middle of the filling body, kN/m; L_3 is the filling body width, m.

When the sank roof was contacted with the goaf gangue, the force will be produced on the goaf gangue. With the continuous subsidence of the roof, the scope and the force on the goaf gangue continued to increase.

Assuming the loading of the goaf gangue on the immediate roof is linear distribution, and the force of goaf gangue on roof F_4 is:

$$F_4 = \frac{1}{2} q_4 L_4 \tag{5}$$

where the F_4 is the force of goaf gangue on roof, kN; L_4 is contact length between goaf gangue and roof, m, q_4 is the maximum loading at the contact point of roof and goaf gangue, kN/m.

In order to ensure the stability of the overlying strata, the strong layer force $[F_3]$ of the filling body should be satisfied the following equation:

$$[F_3] \geq (L_1 + L_2 + L_3) h_Z \gamma_Z + L_0 h_j \gamma_j - F_1 - F_4 \tag{6}$$

where the $[F_3]$ is the force on strong layer of the filling body; L_2 is the roadway width, m; h_Z is the thickness of immediate roof, m; γ_Z is the bulk density of immediate roof, kN/m^3; L_0 is the length of hard roof, m; h_j is the thickness of hard basic roof, m, γ_j is the bulk density of hard basic roof, kN/m^3.

The relationship between the strong layer of the filling body and the filling body width can be obtained as follows:

$$[\sigma] L_3 \geq [F_3] \tag{7}$$

where the $[\sigma]$ is the strength of the strong layer acting on the filling body, kPa.

Based on the above analysis, the force on the filling body is related to the filling body width, the roadway width, the mining height, the thickness of the immediate roof and the basic roof.

4.3 Filling body width calculation

The filling body width should be reasonable to reduce

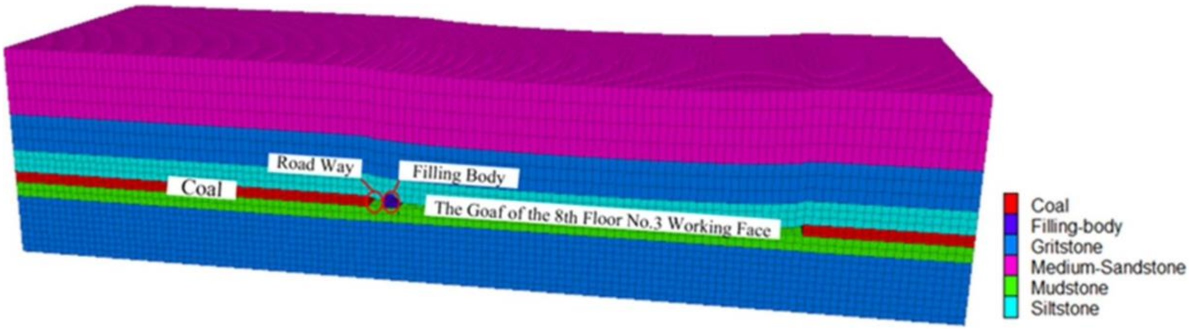


Fig. 11 Simulation model

Table 2 Mechnical parameters of the various strata

Lithology	Bulk Modulus/GPa	Shear Modulus/GPa	Density/ (kg/m)	Friction Angle/ (°)	Cohesion/MPa	Tensile Strength/MPa
Siltstone	5.2	2.8	2300	36	3.7	1.9
Medium Sandstone	4.1	4.2	2000	35	2.8	2.6
Coal	1.6	1.5	1400	24	1.2	1.3
Gritstone	5.2	5.3	2400	34	2.3	2.7
Mudstone	8.1	3.2	3000	24	2.7	1.6

Table 3 Schemes of different coal pillar width

Scheme	1	2	3	4	5	6	7	8	9
Filling body width/m	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0

the influence of the supporting stress, comprehensively consider the deformation of the roadway and reduce the loss of coal resources.

Therefore, the reasonable filling body width B should be calculated by the limit equilibrium theory, as shown in Fig. 10 (Xie *et al*. 2011, Wang *et al*. 2016).

$$B=X_1+X_2+X_3 \tag{8}$$

where B is the filling body width; X_1 is the width of the plastic zone produced in the filling body; X_3 is the effective width of filling body, taking 1.2 m (According to the final strength of the filling body and the calculation results of Eqs. (1)-(7), the effective width of the filling body is 1.2 m); X_2 is filling body stability coefficient, which calculating as $(X_1+X_3)(30\%\sim50\%)$.

According to field experience, the X_1 can be expressed as:

$$X_1=\frac{mA}{2\tan\varphi_0}\ln\left(\frac{K\gamma H+\dfrac{C_0}{\tan\varphi_0}}{\dfrac{C_0}{\tan\varphi_0}+\dfrac{p_Z}{A}}\right) \tag{9}$$

where m is the mining thickness, A is the lateral pressure coefficient, φ_0 is the internal friction angle of the filling body C_0 is the cohesion of the filling body, K is the stress concentration coefficient, γ is the average bulk density, and H is the buried depth of the roadway, p_Z is the support resistance of the bracket to the coal wall.

The above parameters are from the actual coal mine site and laboratory, and have been verified accordingly.

5. Numerical simulation

5.1 Simulation scheme

Based on the above analysis, the filling body width play an important role in the stability of surrounding rock. When the filling body width is small, the stress concentration caused by the rotation and subsidence of roof strata can lead to the rupture and instability of the surrounding rock. When the filling body width is large, the surrounding rock of the roadway will be effectively controlled. However, the consumption of the filling materials will increase as the filling body width increase, which will lead to the increase of the cost of gob-side entry retaining. Therefore, it is necessary to simulate and analyze the influence of different filling body width on the stress and displacement of surrounding rock.

$FLAC^{3D}$ numerical simulation software is a software specially developed for the analysis of geotechnical engineering mechanics. It can simulate various complex engineering mechanical behavior by relying on the powerful analysis function.

In this paper, the $FLAC^{3D}$ numerical simulation software is used to analyze the influence of different filling body width on the deformation and stress of surrounding rock. The length × width × height of the model is: 250 m × 100 m × 107 m. The model includes 3m thick coal seam, 82 m thick overlying strata and 22 m thick bottom strata. The pressure coefficient is 0.8. The simulation model is shown in Fig. 11.

Based on the mechanical test of the filling body, it is

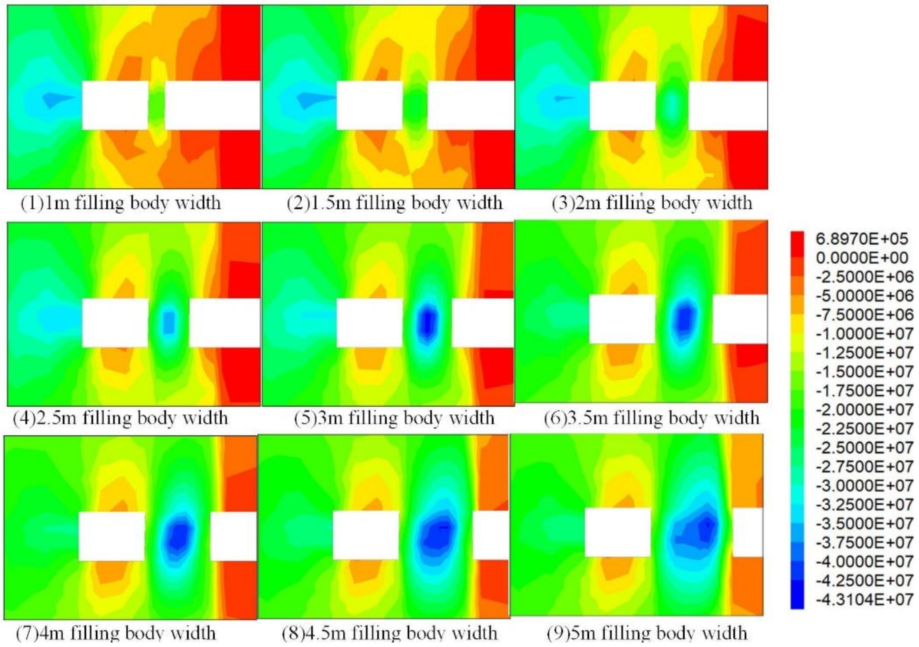


Fig. 12 Stress distribution of surrounding rock

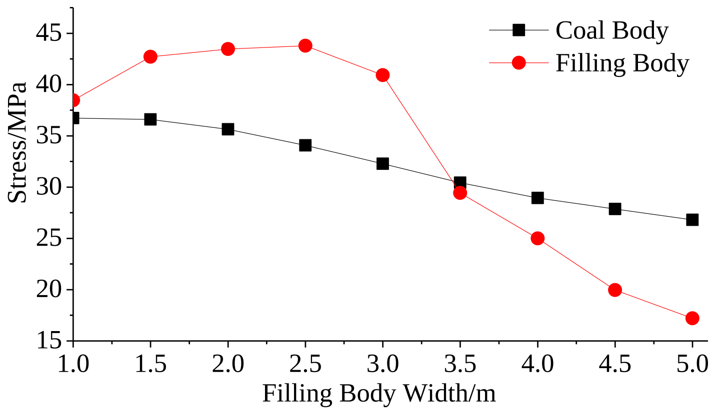


Fig. 13 The maximum stress on coal wall and filling body

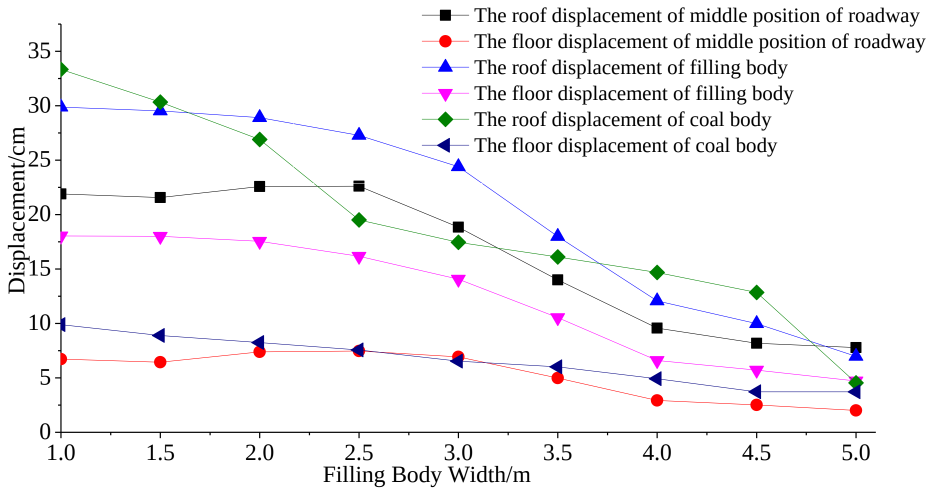


Fig. 14 Displacement of roof and floor

concluded that the mechanical parameters of the filling body are as follows: the bulk modulus is 6.9 GPa; the shear modulus is 3.1 GPa; the bulk density is 15 kN/m^3; the friction angle is 49°; the cohesive force is 2.4 MPa; and the tensile strength is 2.35 MPa.

The mechanical parameters of various strata are shown in Table 2.

The simulation schemes with different filling body width are proposed, as shown in Table 3.

5.2 Result analysis

According the simulation results, the stress distribution characteristics and deformation characteristics of surrounding rock with the different filling body width were analyzed.

(1) Stress distribution of surrounding rock

The stress distribution of surrounding rock with different filling body width is shown in Fig. 12. It can be seen that the stress of surrounding rock has a significant variation with the increase of the filling body width. When the filling body width is in the range of 1.0 m~2.0 m, the stress on the coal body is large, and the stress on the filling body is small. The filling body have no effective supporting capacity on the roof. When the filling body width is in the range of 2.5 m~5.0 m, the stress on the coal body decreases gradually, and the stress on the filling body increases gradually. With the increase of the filling body width, the filling body can not only support the more overlying loads, but also make the stress concentration area gradually transfer to the deep. It can be seen from the stress cloud diagram that the larger the filling body width is, the greater the distance of the stress concentration area moving to the filling body is. When the filling body width is 3.5 m, the width from the stress concentration area to the edge of the filling body can meet the needs of the project site.

Meanwhile, the filling body can effectively isolate the goaf and prevent the toxic and harmful gases from entering the roadway.

(2) The maximum stress on the coal body and filling body

The maximum stress on coal body and filling body with the different filling body width is shown in Fig. 13. With the increase of the filling body width, the maximum stress on the coal body presented a decreasing trend and the maximum stress on the filling body first increased and then decreased. When the filling body width was in the range of 1.0~3.5 m, the maximum stress on the filling body was higher than that on the coal body. When the filling body width was in the range of 3.5~5.0 m, the maximum stress on the filling body was lower than that on the coal body. When the filling body width was 3.5 m, the maximum stress of the coal body and the filling body was approximately equal.

(3) Displacement of roof and floor

The displacement of roof and floor are shown in Fig. 14. With the increase of the filling body width, the displacement of the roof and floor gradually decreases. When the filling body width increased from 1 m to 5 m, the reduction rate of roof displacement of filling body was 76.7%, the reduction rate of the roof displacement of coal body was 86.3%, the reduction rate of the middle displacement of the roadway roof was 90.8%. Among them, when the filling body width was 3.5 m, the middle displacement of the roadway roof was 14 cm, the roof displacement on the side of filling body was 17 cm, and the roof displacement on the side of coal body was 16cm, which met the requirements for deformation of the surrounding rock.

5.3 Determination of filling body width

This paper comprehensively analyzes the stress distribution of surrounding rock, the maximum stress on the coal body and the filling body and the displacement of surrounding rock. The filling body can not only meet the requirements of strength, but also ensure the isolation of goaf.

Therefore, the parameters of 8th floor No.3 working face of Xin'an coal mine are substituted into the Eq. (8), the filling body width is 3.25~3.75 m. Combined with the simulation results of different filling body width by numerical simulation, it is comprehensively determined that the reasonable filling body width of the gob-side entry retaining was 3.5 m.

6. Field tests

6.1 Field tests

According to the field engineering practice, it is determined that the periodic weighting distance of the No. 3 working face is 18 m, and the supporting capacity of the roadway side is 11 ~ 14 MPa. From the advancing speed of the No. 3 working face and the filling technology of high-water material, it is known that the periodic weighting will occur on the 9th day, and the uniaxial compressive strength of the filling body reaches 12.01 MPa after 3th day, so the temporary support can be withdrawn after 3th day.

The filling body with the filling frame is shown in Fig. 15. The filling body without the filling frame is shown in Fig. 16.

Fig. 15 The filling body with the filling frame

Fig. 16 The filling body without the filling frame

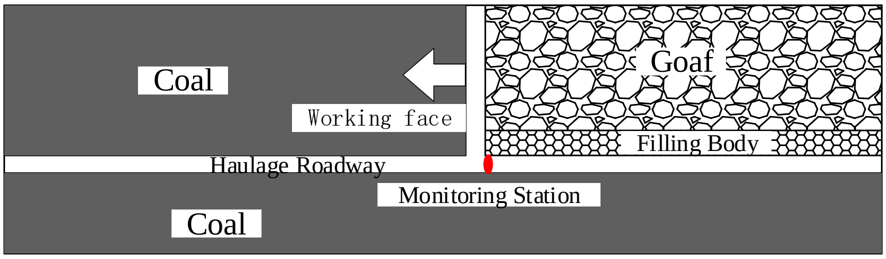


Fig. 17 Location of the monitoring station

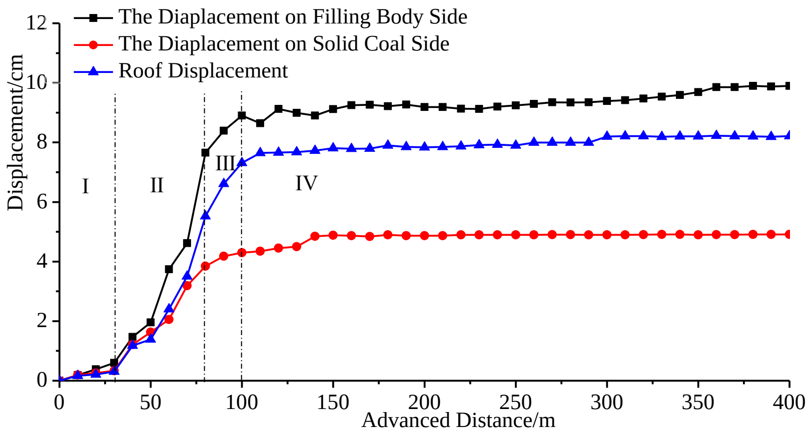


Fig. 18 The displacement monitoring of roadway surrounding rock

6.2 Monitoring

The displacement of surrounding rock was monitored in order to verify the effect of gob-side entry retaining with the high-water material. The monitoring station was set up behind the working face. The location of the monitoring station is shown in Fig. 17.

When the filling body reached the required strength, the filling frame can be removed. The displacement of surrounding rock was measured with the advancement of working face. The monitoring results are shown in Fig.18. The roof displacement of the filling body was the largest, the roof displacement of the middle of the roadway was the second, and the roof displacement of the coal body was minimum.

When the working face advanced 30 m, the roof displacement of the filling body was 0.6 cm, the roof displacement of the coal body is 0.3 cm, and the roof displacement of the middle position of the roadway was 0.3cm. This was mainly because the temporary supporting that had not been removed played a role in supporting the roof. When the working face advanced 80 m, the roof displacement of the filling body was 7.7 cm, the roof displacement of the coal body was 3.8 cm, and the roof displacement of the middle position of the roadway was 5.5 cm. And in the range of 30-80 m behind the working face, the roof displacement of the filling body, the roof displacement of the coal wall and the roof displacement of the middle position of the roadway all rapid increase. This is mainly because the temporary supporting had been removed, the filling body was in contact with the roof and supported the roof. When the working face advanced 100 m, the displacement of the roadway surrounding rock was stable, the roof displacement of the filling body was 8.9cm, the roof displacement of the coal body was 4.3cm, and the roof displacement of the middle position of the roadway was 7.3 cm. The deformation of roadway tended to be stable.

Meanwhile, the filling body height at the monitoring station was measured every day and the monitoring data were analyzed and processed. It is concluded that the deformation of the filling body can be divided into four stages:

The first stage (I): 0 m-30 m away from the working face. Because the temporary supporting was arranged around the filling body, it played a certain supporting role for the roof. The force acting on the filling body was small, the deformation of the filling body was small and the deformation velocity was slow.

The second stage (II): 30-80 m away from the working face. Because the temporary supporting was removed, the force of roof was mainly concentrated on the filling body. The roof rock settled violently and the loading of the filling body increased rapidly. The deformation rate of the filling body was big.

The third stage (III): 80-100 m away from the working face. Because the strength of the filling body had reached the expected level. The rotary subsidence of the roof was slow, the force acting on the filling body increased slowly, and the deformation rate of the filling body became small. The roof can be effectively controlled.

The fourth stage (IV): 100 m away from the working face. The deformation of the surrounding rock remained in a stable state.

7. Discussions

The high-water materials have the characteristics of good fluidity, high early strength and controllable setting time. The system of gob-side entry retaining with the high-water material is simple and easy to operate. The filling body formed by the high-water materials can not only effectively isolate the goaf, but also effectively control the deformation of the surrounding rock. According to the state of the overlying strata acting on the filling body, the force on the filling body can be divided into the initial stage and the late stage. And the influencing factors of the initial stage and the late stage of the filling body were analyzed and studied respectively. Through the theoretical analysis, the force on the filling body is related to the filling body width, the roadway width, the mining height, the thickness of the immediate roof and basic roof.

Taking the 8th floor No.3 working face of Xin'an coal mine as the engineering background, the stress and displacement of surrounding rock with the different filling body width are analyzed through the FLAC3D. Based on the field observation of the surrounding rock deformation, the filling body can ensure that the deformation of surrounding rock is within the reasonable range.

However, the long-term monitoring of filling body still needs further tracking and monitoring, which is also the main direction of future research.

8. Conclusions

• The mechanical models of the filling body in the initial stage and late stage are established respectively. Through the theoretical analysis, the stability of surrounding pressure of the gob-side entry retaining with the high-water material is related to the width of filling body, roadway, mining height, direct roof and basic roof thickness.

• Based on the geological conditions of the 8th floor No.3 working face of Xin'an coal mine, the stress and deformation of the surrounding rock with the different filling body widths is studied by using $FLAC^{3D}$ simulation software. The greater the filling body width, the smaller the effect of stress on the surrounding rock, and the smaller the deformation of the surrounding rock. Through the theoretical calculation and numerical simulation, the filling body width of gob-side entry retaining is 3.5 m.

• In the mining process of the working face, the deformation process of the filling body is divided into four stages. The first stage is 0 m-30 m away from the working face, the deformation of the filling body is small and the deformation speed is slow. The second stage is 30 m-80 m away from the working face, the deformation of filling body is large and the deformation rate of filling body is fast. The third stage is 80 m-100 m away from the working face, the deformation rate of the filling body becomes small, and the deformation of the filling body is still increasing. The fourth stage is 100 m away from the working face, the deformation rate of the filling body is about 0.

Disclosure statement

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References

Altunbas, A., Soltanbeigi, B. and Cinicioglu, O. (2017), "Determination of active failure surface geometry for cohesionless backfills", *Geomech. Eng.*, **12**(6), 983-1001. https://doi.org/10.12989/gae.2017.12.6.983.

Archibald J.F., Chew J.L. and Lausch P. (1999), "Use of ground waste glass and normal Portland cement mixtures for improving slurry and paste backfill support performance", *Cim. Bull.*, **92**(10), 74-80. https://doi.org/10.1016/S0925-8388(98)01038-X.

Chen, S.J., Qu, X., Yin, D.W., Liu, X.Q., Ma, H.F. and Wang, H.Y., (2018), "Investigation lateral deformation and failure characteristics of strip coal pillar in deep mining", *Geomech. Eng.*, **14**(5), 421-428. https://doi.org/10.12989/gae.2018.14.5.421.

Deng, Y.H., Tang, J.X., Zhu, X.K., Fu, Y. and Dai, Z.Y. (2010), "Analysis and application in controlling surrounding rock of support reinforced roadway in gob-side entry with fully mechanized mining", *Min. Sci. Technol.*, **20**(6), 839-845. https://doi.org/10.1016/S1674-5264(09)60292-1.

Deng, Y.H., Wang, S.Q. and Fan, Y.C. (2014), "Feasibility analysis of gob-side entry retaining in steep coal seam", *Proceedings of the International Conference on Digital Manufacturing & Automation*, Hefei, China, March.

Doherty, P., Hasan, A., Suazo, G.H. and Fourie, A. (2015), "Investigation of some controllable factors that impact the stress state in cemented paste backfill", *Can. Geotech. J.*, **52**(12), 1901-1912. https://doi.org/10.1139/cgj-2014-0321.

Fu, J.X., Song, W.D. and Tan, Y.Y. (2018), "Study of stability and evolution indexes of gobs under unloading effect in the deep mines", *Geomech. Eng.*, **14**(5), 439-451. https://doi.org/10.12989/gae.2018.14.5.439.

Gao, W. (2018), "Influence of interaction between coal and rock on the stability of strip coal pillar", *Geomech. Eng.*, **16**(2), 151-157. https://doi.org/10.12989/gae.2018.16.2.151.

Guo, G.L., Zha, J.F., Miao, X.X., Wang, Q. and Zhang, X.N. (2009), "Similar material and numerical simulation of strata movement laws with long wall fully mechanized gangue backfilling", *Procedia Earth Planet. Sci.*, **1**(1), 1089-1094. https://doi.org/10.1016/j.proeps.2009.09.167.

Guo, G.L., Zhu, X.J. and Zha, J.F. (2014), "Subsidence prediction method based on equivalent mining height theory for solid backfilling mining", *T. Nonferr. Metal. Soc. China*, **24**(10), 3302-3308. https://doi.org/10.1016/S1003-6326(14)63470-1.

Guo, W.B., Wang, H. and Chen, S. (2016), "Coal pillar safety and surface deformation characteristics of wide strip pillar mining in deep mine", *Arab. J. Geosci.*, **9**(2), 1-9. https://doi.org/10.1007/s12517-015-2233-5.

Haramy, K.Y. and Kneisley, R.O. (1990), "Yield pillars for stress control in longwall mines- case study", *Geotech. Geol. Eng.*, **8**(4), 287-304. https://doi.org/10.1007/bf00920642. https://doi.org/10.1016/j.tust.2004.04.002.

Ishwar, S.G. and Kumar, D. (2017), "Application of DInSAR in mine surface subsidence monitoring and prediction", *Current*

Sci., **112**(1), 46-51. https://doi.org/10.18520/cs/v112/i01/46-51.
Jaouhar, E., Li, L. and Aubertin, M. (2018) "An analytical solution for estimating the stresses in vertical backfilled stopes based on a circular arc distribution", *Geomech*. *Eng*., **15**(3), 889-898. https://doi.org/10.12989/gae.2018.15.3.889.
Karfakis, M.G., Bowman, C.H. and Topuz, E. (1996), "Characterization of coal-mine refuse as backfilling material", *Geotech*. *Geol*. *Eng*., **14**(2), 129-150. https://doi.org/10.1007/bf00430273.
Li, H.J., Zhang. Y.C., Xu, L., Jia, X.G. and Gu, X.M. (2017), "Examination of the treatment quality of filling mined-out voids using super-high-water material by the TEM technique", *Environ*. *Earth Sci*., **76**(3). https://doi.org/10.1007/s12665-017-6431-1.
Liu, H., Lei, S.G., Deng, K.Z., Yu, Y. and Wang, Y.X. (2014), "Research on ground fissure treatment filling with super-high-water material", *J. China Coal Soc*., **39**(1), 72-77. https://doi.org/10.13225/j.cnki.jccs.2013.1296.
Liu, X.S., Ning, J.G., Tan, Y.L., Xu, Q. and Fan, D.Y. (2018), "Coordinated supporting method of gob-side entry retaining in coal mines and a case study with hard roof", *Geomech*. *Eng*., **15**(6), 1173-1182. https://doi.org/10.12989/gae.2018.15.6.1173.
Ma, X.G., He, M.C., Sun, J.D., Hu, J., Zhang, X.Y. and Zhang, J.B. (2018), "Research on the design of roof cutting parameters of non coal pillar gob-side entry retaining mining with roof cutting and pressure releasing", *Geotech*. *Geol*. *Eng*., **37**(3), 1169-1184. https://doi.org/10.1007/s10706-018-0676-7.
Maleki, H.N., Agapito, J.F.T., Wangsgard M. and Cort, J. (1986), "Gate road layout design for two-seam longwall mining", *Geotech*. *Geol*. *Eng*., **4**(2), 111-127. https://doi.org/10.1007/bf01560670.
Medhurst, T.P. and Brown, E.T. (1998), "A study of the mechanical behaviour of coal for pillar design", *Int*. *J*. *Rock Mech*. *Min*. *Sci*., **35**(8), 1087-1105. https://doi.org/10.1016/S0148-9062(98)00168-5.
Ning, J.G., Wang, J., Bu, T.T., Hu, S.C. and Liu, X.S. (2017), "An innovative support structure for gob-side entry retention in steep coal seam mining", *Minerals*, **7**(5), 1-18. https://doi.org/10.3390/min7050075.
Oreste, P. (2005), "Back-analysis techniques for the improvement of the understanding of rock in underground constructions", *Tunn*. *Undergr*. *Sp*. *Tech*., **20**(1), 7-21. https://doi.org/10.1016/j.tust.2004.04.002.
Tan, Y.L., Yu, F.H., Ning, J.G. and Zhao, T.B. (2015), "Design and construction of entry retaining wall along a gob side under hard roof strata", *Int*. *J*. *Rock Mech*. *Min*. *Sci*., **100**(77), 115-121. https://doi.org/10.1016/j.ijrmms.2015.03.025.
Tian, D.M., Yao, J., Jiang, Z.A., Wang, X.M. and Zhang, Q.L. (2008), "The experimental study of the coal gangue as gel filling materials", *J*. *Coal Sci*. *Eng*. *China*, **14**(1), 125-130. https://doi.org/10.1007/s12404-008-0025-1.
Venticinque, G., Nemcik, J. and Ren, T. (2014), "A new fracture model for the prediction of longwall caving characteristics", *Int*. *J*. *Min*. *Sci*. *Technol*., **24**(3), 369-372. https://doi.org/10.1016/j.ijmst.2014.03.014.
Wang, X.Y., Bai, J.B., Wang, R.F. and Sheng, W.L. (2016) "Bearing characteristics of coal pillars based on modified limit equilibri-um theory", *Int*. *J*. *Min*. *Sci*. *Technol*., **25**(6), 943-947. http://doi.org/10.1016/j.ijmst.2015.09.010.
Xie, X.Z., Fan, Z.Z., Huang, Z.Z. and Xu, G. (2011), "Research on unsymmetrical loading effect induced by the secondary mining in the coal pillar", *Procedia Eng*., **26**(26), 725-730. http:/doi.org/10.1016/j.proeng.2011.11.2229.
Xu, M.T., Zhang,D.S., Ma, L.J., Wang, X.F. and Zhang, W. (2014), "Roof control technology for longwall filling mining of superhigh- water material", *J. China Coal Soc*., **39**(3), 410-416. https://doi.org/10.13225/j.cnki.jccs.2013.0688.
Yang, B., Chai, J. and Wang, M.H. (2018), "Study on roadside support method of gob-side entry retaining in condition of overlying and thick-hard roof", *Safety Coal Mines*, **49**(7), 220-223. https://doi.org/10.13347/j.cnki.mkaq.2018.07.057.
Yang, H.Y., Cao, S.G., Wang, S.Q., Fan, Y.C., Wang, S. and Chen, X.Z. (2016), "Adaptation assessment of gob-side entry retaining based on geological factors", *Eng*. *Geol*., **209**, 143-151. https://doi.org/10.1016/j.enggeo.2016.05.016.
Yin, Y.C., Zou, J.C., Zhang, Y.B., Qiu Y., Fang, K. and Huang, D.M. (2018), "Experimental study of the movement of backfilling gangues for goaf in steeply inclined coal seams", *Arab*. *J*. *Geosci*., **11**(12), 318. https://doi.org/10.1007/s12517-018-3686-0.
Zhang, N., Chen, H. and Chen, Y. (2015), "An engineering case of gob-side entry retaining in one kilometer-depth soft rock roadway with high ground pressure", *J. China Coal Soc*., **40**(3), 494-501. https://doi.org/10.13225/j.cnki.jccs.2014.0326.
Zhang, N., Han, C.L., Kan, J.G. and Zhen, X.G. (2014), "Theory and practice of surrounding rock control for pillarless gob-side entry retaining", *J. China Coal Soc*., **39**(39), 1635-1641. https://doi.org/10.13225/j.cnki.jccs.2014.9026.
Zhang, Z.Z., Bai, J.B., Chen, Y. and Yan, S. (2015), "An innovative approach for gob-side entry retaining in highly gassy fully-mechanized longwall top-coal caving", *Int*. *J*. *Rock Mech*. *Min*. *Sci*., **80**, 1-11. https://doi.org/10.1016/j.ijrmms.2015.09.001.
Zhao, Y.M., Zhang, N., Zheng, X.G. and Li, B.Y. (2015), "Structural optimization of overlying strata for gob-side entry retaining in 1000 m deep mine with direct thick and hard roof", *J*. *Min*. *Safety Eng*., **32**(5), 714-720. https://doi.org/10.13545/j.cnki.jmse.2015.05.003.

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