

Distribution and Evolution Characteristics of Macroscopic Stress Field in Gob-Side Entry Retaining by Roof Cutting

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Abstract Non-pillar mining technology plays an important role in sustainable exploitation of coal resources. Gob-side entry retaining by roof cutting (GERRC) is a new technique regarding a non-pillar mining method based on the “cutting cantilever beam theory”. In order to study the distribution and evolution characteristics of macroscopic stress field of surrounding rocks in GERRC, and find out differences from traditional pillar retained mining method (PRMM), some key issues about abutment pressure and stress concentration shell were analyzed by numerical simulations. Results show that: (1) distribution characteristics of lead abutment pressure for the two mining methods are basically the same during the primary mining stage; (2) during the secondary mining stage, peak stress in front of mining face of the two modes is close, while the abutment pressure can be transferred more evenly to coal and rock mass far away from goaf when using GERRC, and that is more likely to cause high stress concentration in the coal

mass near the goaf when mining with PRMM; (3) for the PRMM, lateral abutment pressure will produce a higher stress concentration in section coal pillar and a high residual stress will be maintained in it when coal masses on both sides of the pillar are extracted; (4) adjacent goafs can be connected to form a wide range of pressure relief region when using GERRC, and shape of distribution of the maximum principal stress appears a semi-space ellipsoidal shell in three-dimensional space, and it is a single arch shape in the section perpendicularly to the mining direction, however, it looks like a “m” shape in that section when mining with PRMM because of the high stress concentration in the coal pillar.

Keywords Roof cutting and pressure relief · Non-pillar mining method · Macroscopic stress field · Abutment pressure · Stress concentration shell · Evolving characteristic

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1 Introduction

PRMM, as a conventional longwall mining method with section coal pillars, is currently the most commonly used method for underground mining. Through extensive research and exploration by mining scientists and engineers from all over the world, this mining technology is becoming more and more mature.

However, with the increase of mining depth, large deformation and failure of surrounding rocks become more and more prominent when using this traditional method (Yuan et al. 2018; Wang et al. 2017b). Besides, the remaining section coal pillars lead to serious waste of coal resources. According to statistics, the recovery rate of coal resources in China is only 30–40% on average, and it is even less than 10% in some small coal mines (Yuan 2017). Thus, increasing the recovery rate is one of the key issues that coal mines need to solve, and it is also one of the fundamental tasks that the coal industry confronts (Wang et al. 2016; Qian et al. 2018). In addition, because of the existence of coal pillars left in the goaf, once the pillars suddenly lose stability, it is easy to cause serious dynamic disasters such as rock burst (Wang et al. 2017a; Liu et al. 2018).

In the 1950s, a non-pillar mining technology, the gob-side entry retaining by filling (GERF), was introduced into China, which is of great significance in reducing the roadway excavation and increasing the coal recovery rate. In recent years, many scholars have carried out lots of researches on this mining method, and have achieved fruitful research results, which promoted the development of the gob-side entry retaining technology (Zhang et al. 2015, 2018; Wang et al. 2014, 2015; Li et al. 2018). While this technology is realized by the high strength artificial filling bodies beside the gob-side entry, it can achieve good application results in eliminating section coal pillars. However, the complicated filling system, high labour intensity and low efficiency of the filling body have gravely restricted the popularization and application of these techniques (Luan et al. 2018).

In 2009, a new non-pillar mining method based on the “cutting cantilever beam theory” was proposed by professor He et al. (2015, 2017 and 2018). Through presplitting the roof in front of the working face and using the mine pressure to cause the roof caving, the entry side wall is automatically formed after the roof collapses in the goaf. At the same time, making full use of the dilatancy characteristics of the rock mass makes the coal gangue quickly form a cushion support for the overlying rocks. As the presplitting weakens the mechanical constraints of the roof between the roadway and the goaf, the stress environment of the surrounding rocks is improved (Sun et al. 2014). In recent years, lots of researches on the key parameters of roof cutting, the caving effect of gangue in goaf, the

deformation law and stability control of roadway surrounding rocks, and the deformation mechanism and control technology of side wall were carried out, which are of great significance for the promotion and application of this non-pillar mining technology (Guo et al. 2016, 2017, Gao et al. 2017, 2018; Zhu et al. 2018).

In this paper, based on the geological conditions and mining technical conditions of Ruineng Colliery, distribution of the abutment pressure and evolution characteristics of the macroscopic stress concentration shell for GERRC will be studied by numerical simulation method, compared with the PRMM.

2 Principle of GERRC

The GERRC is different from traditional mining technologies. It does not need section coal pillars or artificial filling bodies to support the gob-side entries. Using the GERRC, a new mining gateway can be formed automatically in its original position, through a series of pragmatic technologies such as the directional presplitting technology, the high prestressed anchor cable supporting technology, and the gangues protection technology. Some differences among the three typical mining technologies can be shown in Fig. 1.

The generation process of the automatically formed entry can be shown in Fig. 2. Firstly, the roof of the entry should be supported by the high prestressed anchor cables and then blasted through the directional presplitting technology in designed location. What needs special attention is that the two tasks should be completed sequentially before the coal is mined. Secondly, when the coal is mined by the shearer, the temporary supporting structures for the roof and the protection structures against the gangues in the gob should be set in time. The gangues supported by the protection structures will form the side wall for the new entry. The mechanical constraints of the roof between the entry and the gob will be weakened to a great extent because of the directional presplitting. As a result, the rock strata in the gob will collapse in time and fill the mined-out area when the mining face is pushed over. Within a certain distance behind the mining face, the gangues are pressed to dense and form supports for overlying strata. At this moment, the

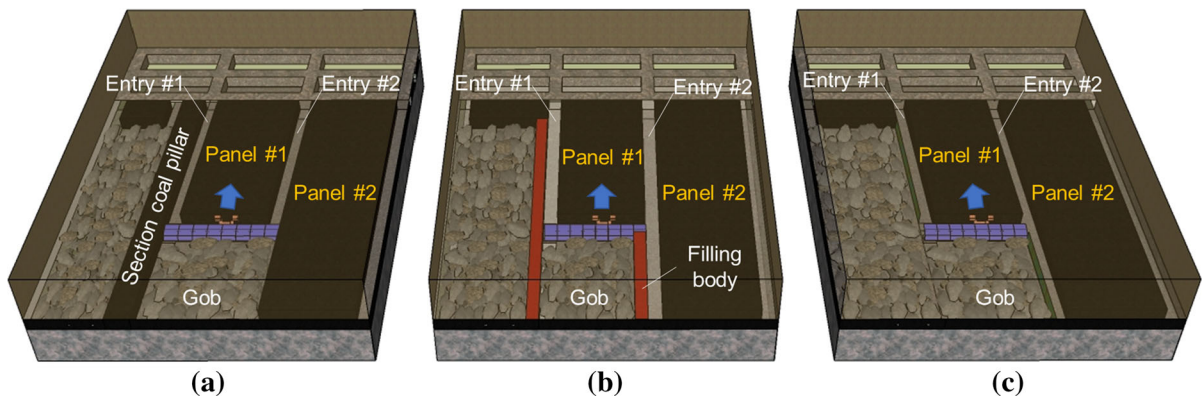


Fig. 1 Schematic diagrams of the three mining technologies. **a** PRMM; **b** GERF; **c** GERRC

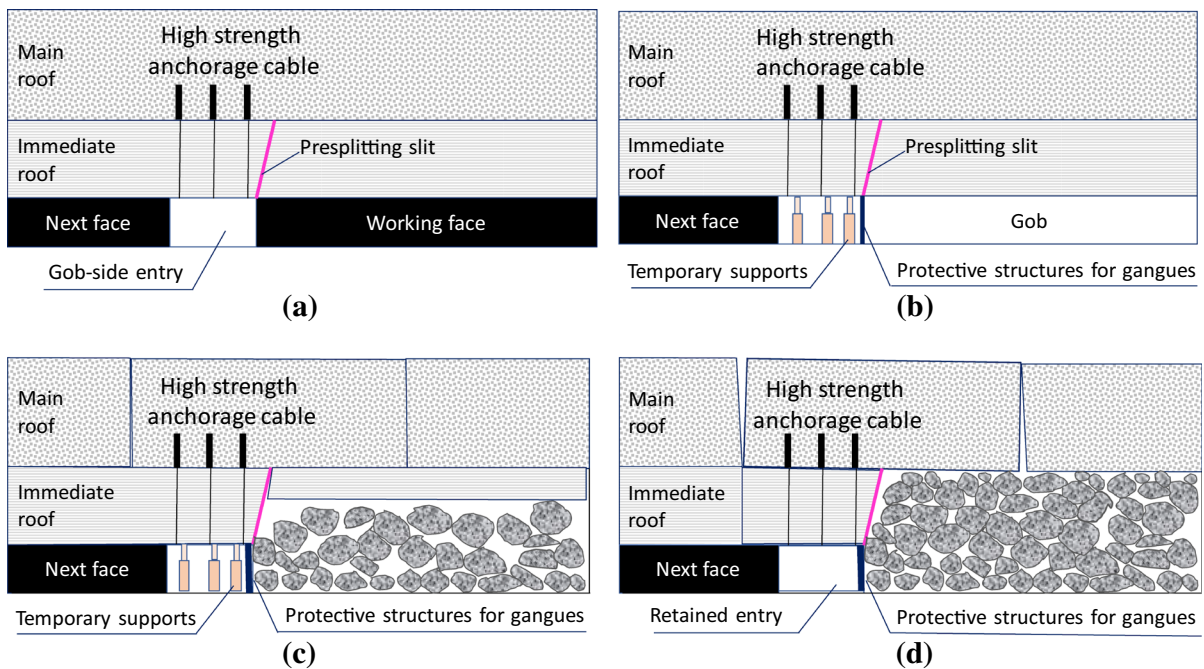


Fig. 2 Principle of the GERRC. **a** Supporting and blasting the roof; **b** supporting the roof and the gangues; **c** roof collapse; **d** forming the entry

surrounding rocks tend to be stable, and finally a new roadway is formed.

3 Numerical Calculation Model

3.1 Engineering Situation

The FLAC3D numerical calculation model was established based on the engineering geological conditions of 121 panel of Ruineng Colliery, which

located near the city of Yanan, China, as shown in Fig. 3. The 2# coal seam is the only minable coal seam in this coalmine, and its thickness is about 0.8–2.2 m with a dip angle ranging from 0° to 3° and an overburden ranging from 140 to 260 m. The roof stratum of this panel is mainly composed of fine sandstone and mudstone, and the floor of the coal seam is mainly composed of sandy mudstone and fine sandstone. Each working face of this panel is approximately 150 m wide along dip and 1000 m long along strike, mined by fully mechanized mining method.



Fig. 3 Engineering site

The first mining face is the F117 which located in the north of the panel. When the F117 is completely mined out, its tailgate retained for F115 that located on the south of the F117.

3.2 Numerical Simulation Scheme

A numerical calculation model with 440 m in length, 400 m in width, and 120 m in height was established according to the mining conditions and geological conditions, to simulate the mining of F117 and F115. Both of the two working face are 150 m wide along dip and 300 m long along strike. Border coal pillars with a width of 50 m were set up around the model whose horizontal displacement on the side and vertical displacement at the bottom were limited. Also, the vertical stress of 3 MPa is used to simulate the weight of overburden. According to the mine geological data, the lateral pressure coefficient is 1.0. For comparison, another model with the same dimensions mining with PRMM was established, and the width of the section coal pillar is 16 m according to the previous mining method of this coal mine. The model for GERRC has 788,406 elements and 733,800 nodes, and the model for PRMM has 817,779 elements and 761,600 nodes. The schematic diagrams of the two numerical calculation models are shown in Fig. 4, and the 3D mesh models generated by computer are shown in Fig. 5.

3.3 Material Parameters

The Mohr–Coulomb yield criterion is used to describe the failure of the rock mass. According to the field

data, the mechanical parameters of the rocks are shown in Table 1. However, in order to reflect the characteristics of the coal seam's residual strength decreasing with the increase of deformation during the yielding process, the coal is simulated using the strain softening model.

Considering that the gangues in the goaf will produce irreversible volumetric compression deformation, also, the strength and the modulus are gradually increased during the process of compaction, the double yield constitutive model is used to simulate the loose rock mass in the goaf. The material mechanical parameters are shown in Tables 2, 3 and Fig. 6 according to the method introduced in the literature (Wang et al. 2017c).

4 Distribution Characteristics of the Abutment Pressure

Over the past few years, many scholars have carried out lots of researches on distribution characteristics of the abutment pressure when mining with traditional mining method (Yao et al. 2015; Xia et al. 2011; Chang 2011; Zhang et al. 2013, 2014; Yang et al. 2018a, b). However, there is no section coal pillar or artificial filling body between working faces when mining with GERRC, and the side of the entry near the goaf filled by gangues from the goaf. As a result, the supporting pattern of overlying stratum and the distribution of abutment pressure will be very different from conventional mining method. According to the different mining progress of F117 and F115, the abutment pressure around the worked-out area can be obtained. In the same way, the support pressure in the section coal pillar can also be acquired when mining with PRMM.

4.1 The Lead Abutment Pressure

4.1.1 Influence of the Primary Mining Stage

When F117 is mined by 230 m, the overall distribution of the abutment pressure of surrounding rocks are shown in Fig. 7, where the X axis represents the direction of the working face, the Y axis indicates the mining direction, and the vertical stresses S_{ZZ} are expressed on Z axes. It clearly shows from the figures that the pressure of the rock masses in the

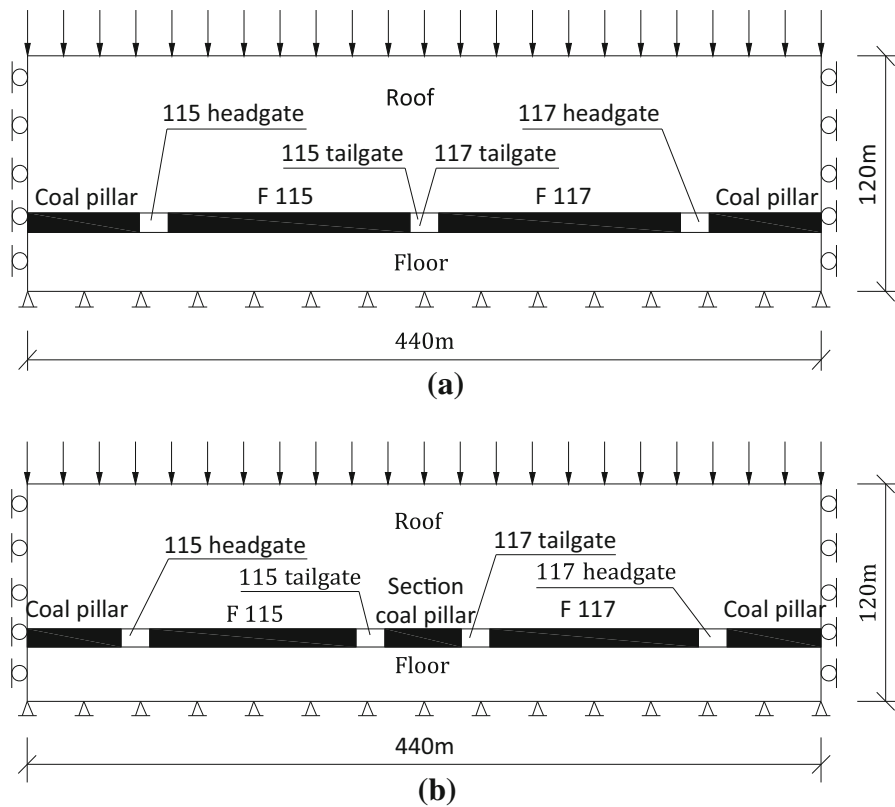


Fig. 4 Schematic diagrams of the two mining methods. **a** GERRC; **b** PRMM

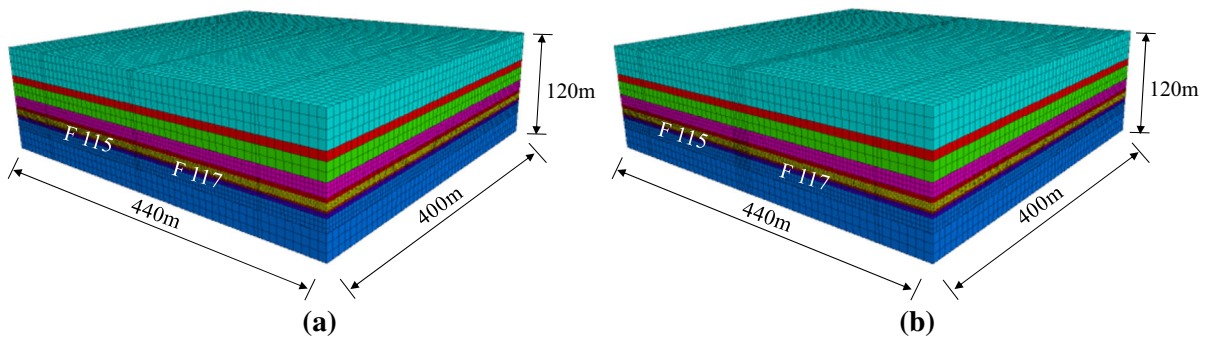


Fig. 5 3D mesh model generated by computer. **a** GERRC; **b** PRMM

goaf has been released, which resulting in stress concentration around the mined-out area, after the coal seam is mined. However, in general, the degree of the stress concentration for the two mining methods are not serious, with a peak value of 17.89 MPa and 18.67 MPa respectively.

Three longitudinal observation lines along the mining direction are set in front of the mining face, where the first line lies in the upper part of the mining

face, 6 m away from the 117 headgate; the second one lies in the middle part of the mining face; and the third one lies in the lower part of the mining face, 6 m away from the 117 tailgate. Therefore, the lead abutment pressure along the three survey lines can be obtained, as shown in Fig. 8. It can be seen from the figures that the distribution and peak value of the lead abutment pressure for the two mining methods are basically the same during the primary mining stage. And, the lead

Table 1 Material mechanical parameters for coal and rock masses

Rock strata	Volumetric weight γ (kN m ⁻³)	Bulk modulus K (GPa)	Shear modulus G (GPa)	Cohesion c (MPa)	Internal friction angle φ (°)	Tensile strength σ_t (MPa)
Roof						
Coarse sandstone	25.3	7.55	5.11	1.46	28	1.47
Fine sandstone–mudstone	25.1	4.16	3.05	1.85	27	1.01
Medium sandstone	25.8	5.68	3.93	2.28	30	1.38
Fine sandstone–coarse sandstone	26.3	4.58	3.22	1.91	33	1.23
Fine sandstone–mudstone–coal	25.1	4.16	3.05	1.85	27	1.01
Fine sandstone–mudstone	23.6	4.75	3.40	1.66	25	0.91
Coal						
2# coal	14.5	2.41	1.63	0.85	20	0.77
Floor						
Sandy mudstone	23.5	5.09	3.13	1.23	23	0.89
Fine sandstone	26.6	7.05	6.35	3.45	35	1.56

Table 2 Cap pressure for double yield model

Strain	Stress (MPa)	Strain	Stress (MPa)	Strain	Stress (MPa)	Strain	Stress (MPa)
0.01	0.4984	0.07	4.7916	0.13	14.197	0.19	51.287
0.02	1.0442	0.08	5.8393	0.14	16.973	0.20	71.532
0.03	1.6444	0.09	7.0359	0.15	20.437	0.21	111.27
0.04	2.3074	0.10	8.4155	0.16	24.880	0.22	224.81
0.05	3.0439	0.11	10.023	0.17	30.786	0.23	3290.4
0.06	3.8666	0.12	11.922	0.18	39.017		

Table 3 Material parameters of gangues

Density (kg m ⁻³)	Bulk modulus (Pa)	Shear modulus (Pa)	Dilatancy angle (°)	Friction angle (°)
1700	90e9	120e9	8	1

abutment pressure is distributed within 65 m in front of the mining face, with a peak value of 16.54 MPa in the middle part of the mining face. While the value of the abutment pressure in the lower part of the mining face is slightly larger when mining with PRMM because of the existence of the section coal pillar and the 115 headgate. Besides, the figures also indicate that the lead abutment pressure in the upper or lower part of the working face is larger than the in situ rock stress, even at a distance from the working face. Obviously, it just caused by the excavation of the

roadway which can lead to slight stress concentration in the rocks around the roadway.

4.1.2 Influence of the Secondary Mining Stage

When F117 is mined out and F115 mined by 150 m, the overall distribution of the abutment pressure of surrounding rocks are shown in Fig. 9. The results indicate that the adjacent goafs can connect to form a large pressure relief zone when mining with GERRC, while the remaining section coal pillar in goaf still

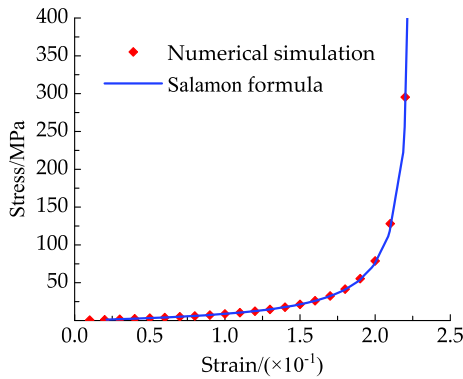


Fig. 6 Comparison of numerical simulation with Salamon formula

retains high residual stress when mining with PRMM. Besides, it can be seen that, for the two mining methods, the difference of the peak stress in front of the mining face is not obvious, with a value of 30.16 MPa and 32.49 MPa respectively.

Similarly, three longitudinal observation lines along the mining direction and two transversal observation lines perpendicular to the mining direction are set in front of the mining face. The relative position of the longitudinal lines is similar to the previous observation lines, and the first transversal line is 10 m away from the mining face and the second one is 20 m away from the mining face. Thus, the lead abutment pressure along the observation lines can be obtained, as shown in Figs. 10 and 11.

It can be seen from the figures that the distributions of the lead abutment pressures in the middle and lower part of the mining face for the two mining methods are

basically the same during the secondary mining stage, but the value of the pressure is slightly larger when mining with GERRC. However, when mining with PRMM, the value of the pressure is obviously larger than that with GERRC within 100 m away from the mining face in the lower part. Besides, in the direction parallel to the working face, the pressure in GERRC is slightly larger than that in PRMM, but the location of the peak stress is farther from the coal wall when mining with GERRC. All of these indicate that the abutment pressure can be transferred more evenly to the coal and rock masses far away from the goaf when using GERRC, and that is more likely to cause high stress concentration in the coal mass near the gob when using PRMM.

4.2 The Lateral Abutment Pressure

In order to get the distribution characteristics of the lateral abutment pressure, a transversal observation line towards the direction of F115 was set in the middle of the goaf, when F117 was mined out. The lateral abutment pressure along the observation line is obtained as shown in Fig. 12. The figure expresses the important information that the stress will be concentrated in the coal pillar, with a peak value of 23.23 MPa, when the coal seam was mined out if mining with PRMM, while the stress in the next working face is relatively small with a peak value of 17.01 MPa. However, when mining with GERRC, the distribution curve of the abutment pressure is relatively gentle and the peak value is about 18.25 MPa.

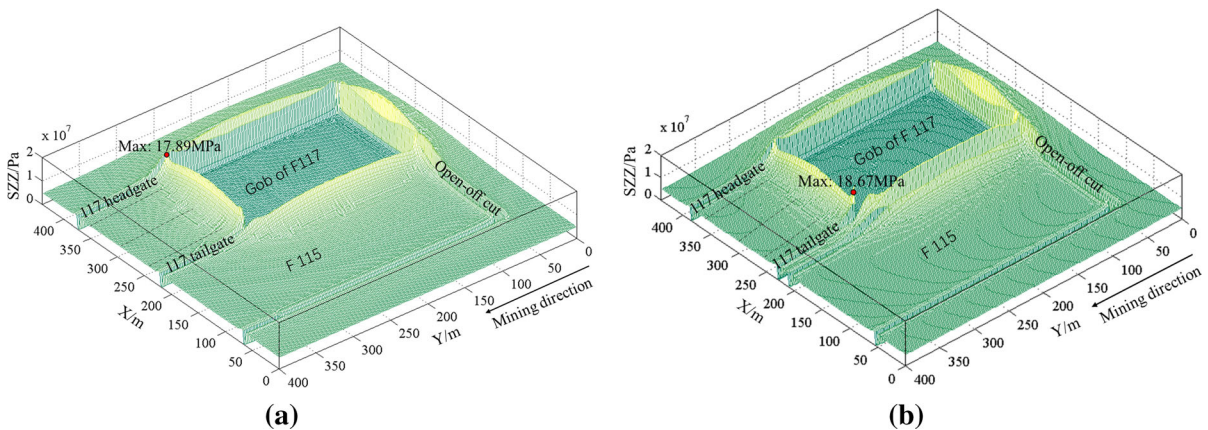


Fig. 7 Vertical stress field as the F117 is mined by 230 m. **a** GERRC; **b** PRMM

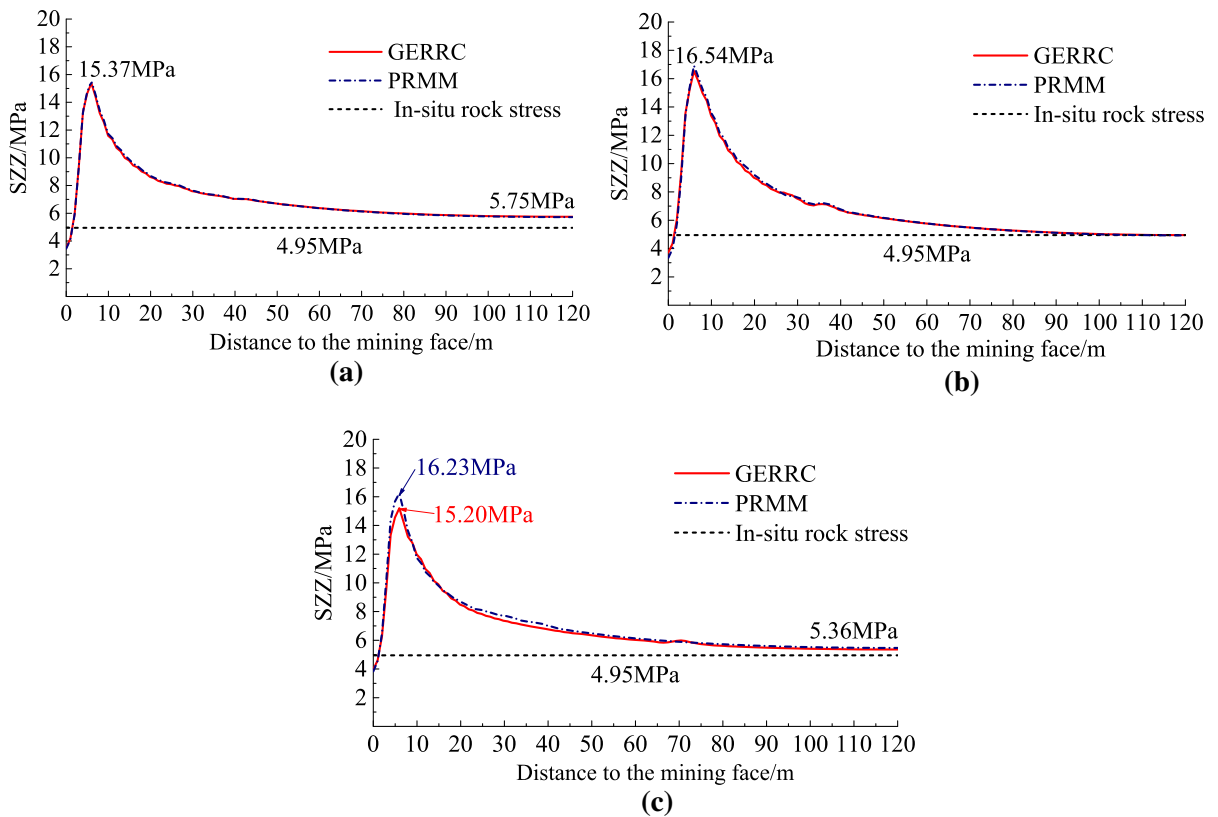


Fig. 8 Distribution of lead abutment pressure as the F117 is mined by 230 m. **a** Upper part of the mining face; **b** middle part of the mining face; **c** lower part of the mining face

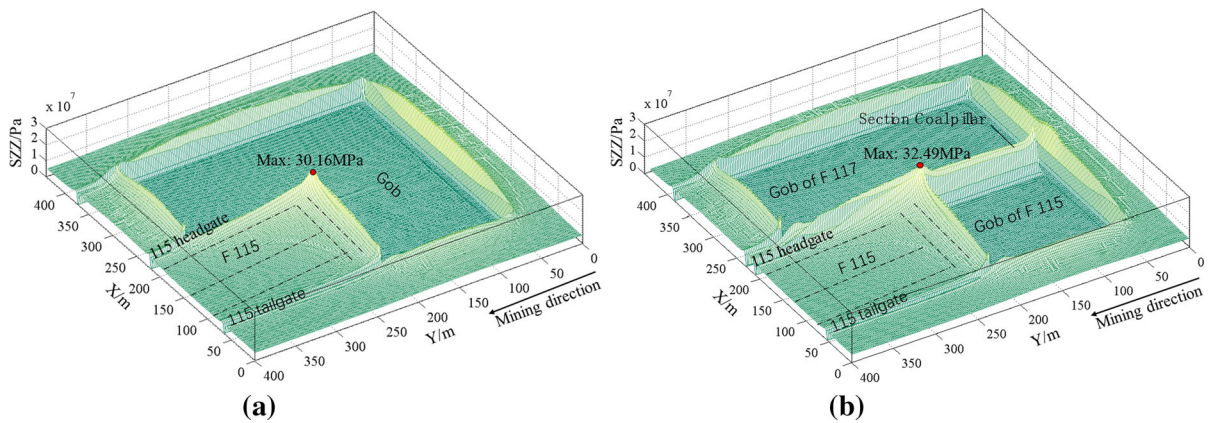


Fig. 9 Vertical stress field as the F115 is mined by 150 m. **a** GERRC; **b** PRMM

4.3 The Maximum Vertical Stress of Section Coal Pillar

During the two mining stages, the evolving process of the maximum vertical stress for the section coal pillar

can be shown in Fig. 13 when mining with PRMM. From the curves appeared in Fig. 13, some conclusions can be drawn easily. Obviously, with the mining of the panels, the peak value of the maximum vertical stress in the section coal pillar nearby the open-off cut

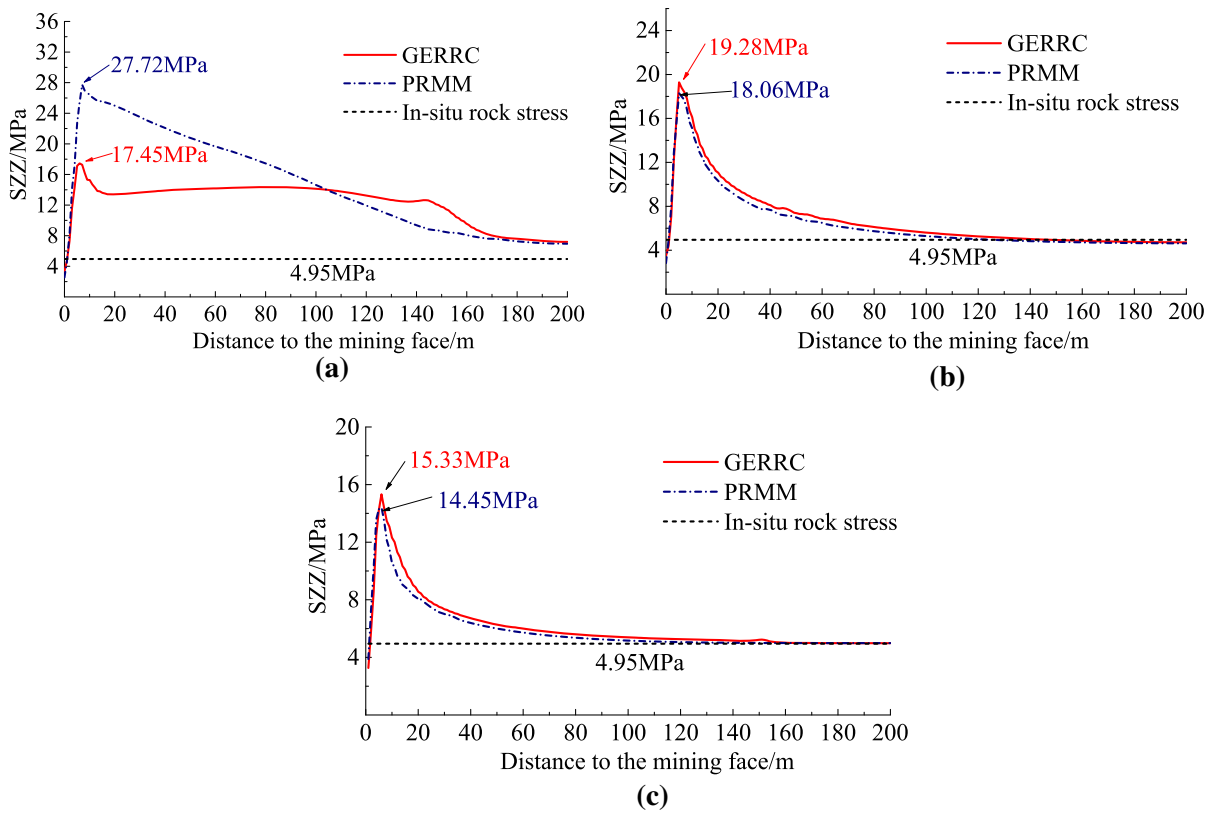


Fig. 10 Lead abutment pressure along mining direction as the F115 is mined by 150 m. **a** Upper part of the mining face; **b** middle part of the mining face; **c** lower part of the mining face

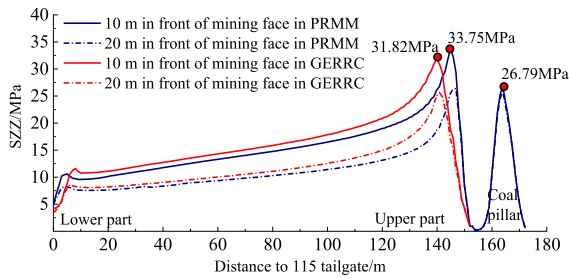


Fig. 11 Lead abutment pressure perpendicularly to mining direction as the F115 is mined by 150 m

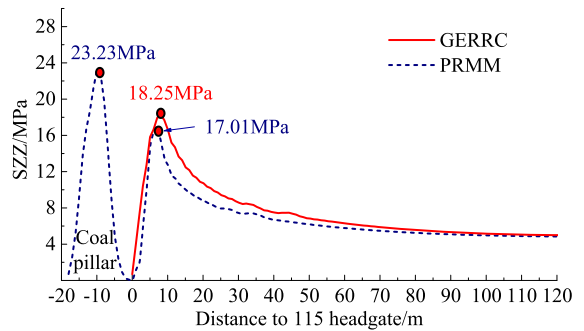


Fig. 12 Distribution of lateral support pressure as the F117 is mined by 300 m

gradually increases, and the position of the peak is gradually away from the coal wall. Also, almost anywhere in the section coal pillar, the maximum vertical stress increases with the extraction of the coal seam. While when the two panels on both sides of the section coal pillar are mined out completely, the maximum vertical stress in the middle part of the pillar begin to decreased, which indicates that all of the coal masses in this region are in plastic state and the

strength has been greatly weakened. However, even if the coal masses are completely yielded, the residual stress in the yield region is still very large and is far larger than its original rock stress, with a maximum value of 25 MPa in this project. The high residual stress will transfer to the floor and cause high stress concentration in the area near the pillars, which will

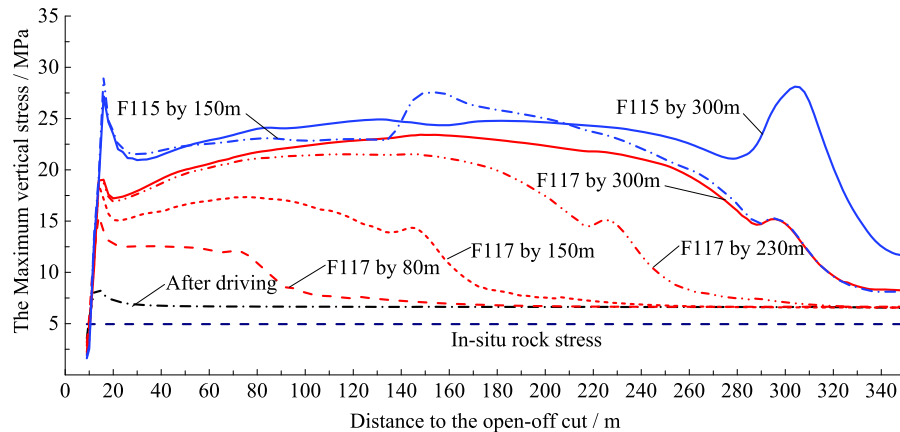


Fig. 13 Evolution of the maximum vertical stress in the section coal pillar

seriously affect the mining of the coal seams under the section coal pillars.

5 The Stress Concentrated Shell and Spatial Morphology of Pressure Relief Body

The coal mining causes stress redistribution in surrounding rocks and deflects the direction of the principal stress, which leads to the generation of stress concentration area and pressure relief area (Luo et al. 2018). Xie et al. found that macroscopic stress shell composed of high stress beams exists in surrounding rocks when mining by fully mechanized caving mining method, through numerical simulation and similar material test research (Xie 2005, 2006; Xie and Wang 2008, 2013). And, they hold the view that rocks in the macroscopic stress shell was the main bearing body to support overburden loads. In addition, they have carried out detailed researches about the effects of mining height, length of mining face and lithology on mechanical characteristics of stress shells. Based on the above research results, the stress concentrated shell and spatial morphology of pressure relief body will be studied in this section by comparison of two mining methods.

5.1 Mining with GERRC

The distribution characteristics of the maximum principal stress along the mining direction are basically the same when F117 or F115 is mined. During the mining of F117, the maximum principal stress field

of surrounding rocks can be obtained as shown in Fig. 14. It can be seen from the figure that stress arch that composed of high stress beams exists in surrounding rocks after the coal is produced. The front and the rear arch feet located in the unexploited coal seam at the goaf boundary along the mining direction respectively, where local high stress concentration exist. The figures also show that the stresses of rocks in the arch are obviously higher than that upper or lower of the arch. The rock mass above the arch is in its original stress state, but that lower of the arch is in a pressure relief state. The front arch foot can move along the mining face while the rear arch foot remains stationary. When the mining face is moving forward, the concentrated stress increases, and the area of stress concentration is expanding. If the space occupied by the rock in pressure relief state is called “Unloading Space”, the “Unloading Space” will gradually extend along the mining direction following the mining face.

When F117 is mined by 230 m, the maximum principal stress field of surrounding rocks at different distances from the mining face can be obtained as shown in Fig. 15. It can be seen from the figure that there is a large range of stress concentration in the coal seam in front of the mining face, which caused by the stress concentration of the front arch foot. When the mining face is moving forward, the stress arch and the “Unloading Space” will be gradually formed. The retained entry located in “Unloading Space”, which makes it easy to maintain stability.

When F117 is mined out and F115 is mined by 150 m, the maximum principal stress field of surrounding rocks at different distances from the mining

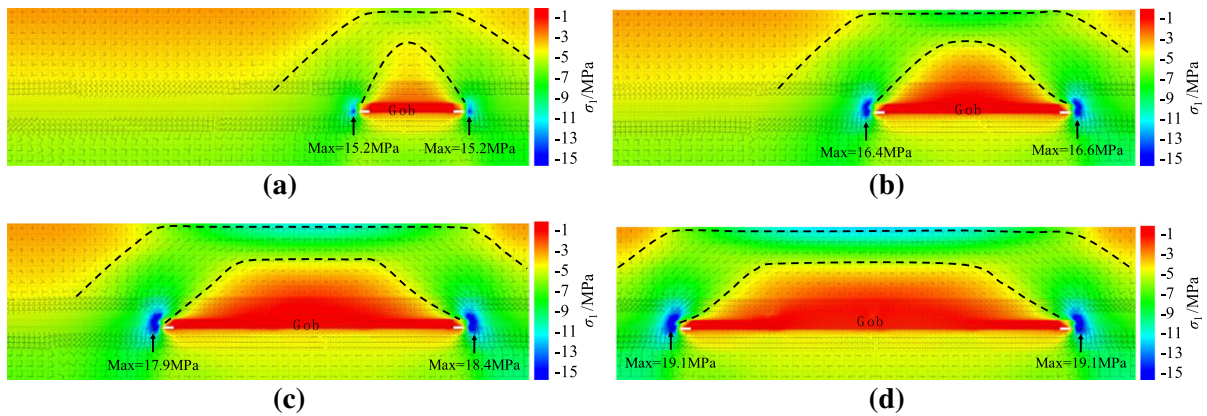


Fig. 14 Maximum principal stress field along mining direction when F117 is mined with GERRC. **a** Mined by 80 m; **b** mined by 150 m; **c** mined by 230 m; **d** mined by 300 m

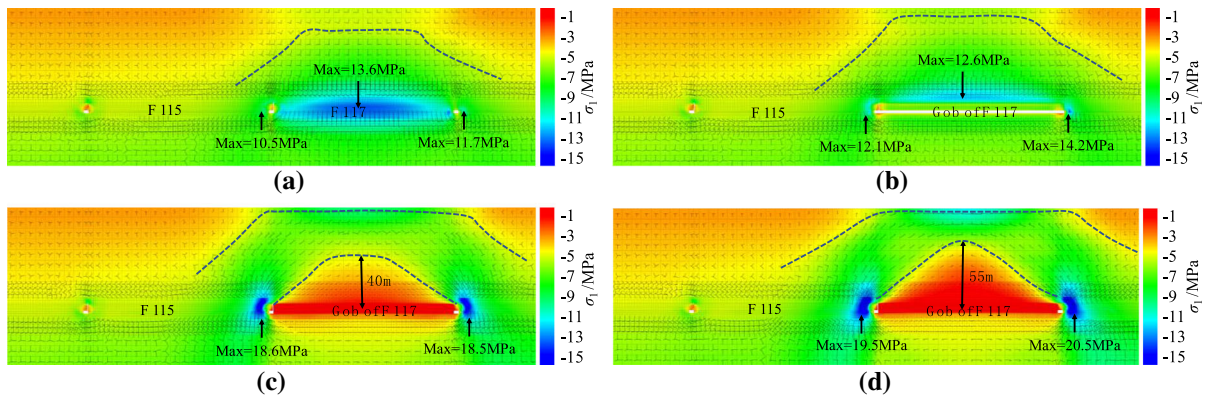


Fig. 15 Maximum principal stress field perpendicular to mining direction when F117 is mined with GERRC. **a** 10 m in front of the mining face; **b** in the mining face; **c** 50 m behind the mining face; **d** 115 m behind the mining face

face can be obtained as shown in Fig. 16. It can be seen from the figure that the stress concentration range and extent of the surrounding rock increased significantly in front of the mining face, with the maximum value of 33.2 MPa. In addition, the “Unloading Space” of F115 expands gradually along the height direction and finally expands to be level with that of F117. Eventually, the new stress arch and new “Unloading Space” will form.

In fact, the actual shape of stress concentration zone in three-dimensional state is a semi-space ellipsoidal shell, whose lower area is a large “Unloading Space”. And, the shell transmits relatively high stresses from overburden. The maximum principal stress field of the surrounding rock of the whole stope is shown in Fig. 17, when F117 and F115 are mined out.

5.2 Mining with PRMM

When mining with PRMM, the distribution characteristic of the maximum principle stress along mining direction is similar to that with GERRC, but it is very different perpendicular to mining direction. When F117 is mined by 230 m, the maximum principle stress fields at different distances from the mining face along mining direction are shown in Fig. 18. It can be seen from the figure that the stress arch and the “Unloading Space” are gradually formed with the advance of the mining face. Also, high stresses concentrate on two sides of the working face, but it tends to concentrate in section coal pillar if the pillar exists.

When F115 is mined by 150 m, the maximum principle stress fields at different distances from the mining face along mining direction are shown in

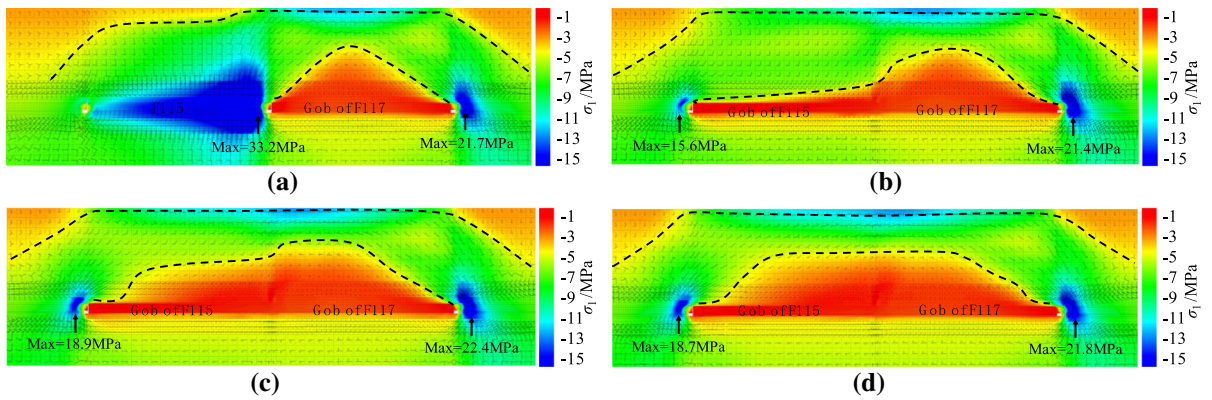


Fig. 16 Maximum principal stress field perpendicular to mining direction as the F115 is mined with GERRC. **a** 20 m in front of the mining face; **b** 20 m behind the mining face; **c** 50 m behind the mining face; **d** 80 m behind the mining face

Fig. 17 Three dimensional diagram of the maximum principal stress field when mining with GERRC

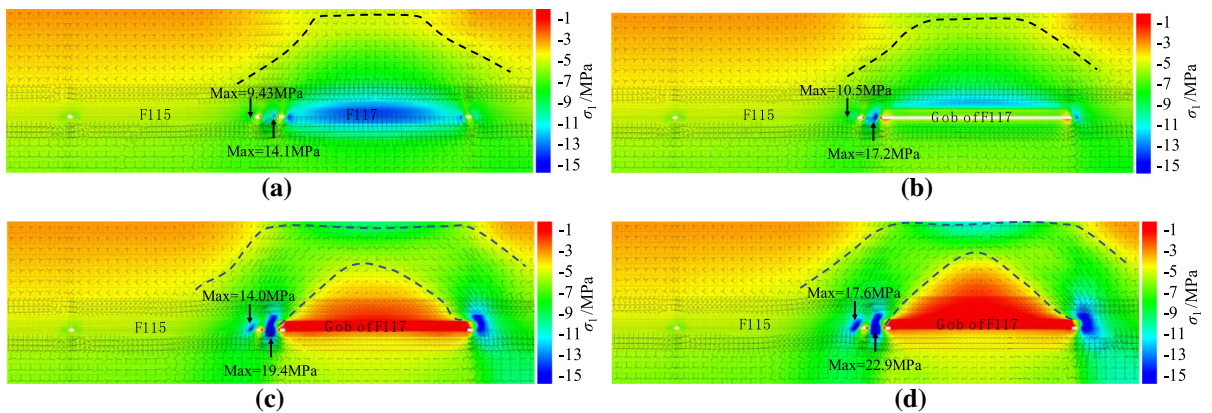
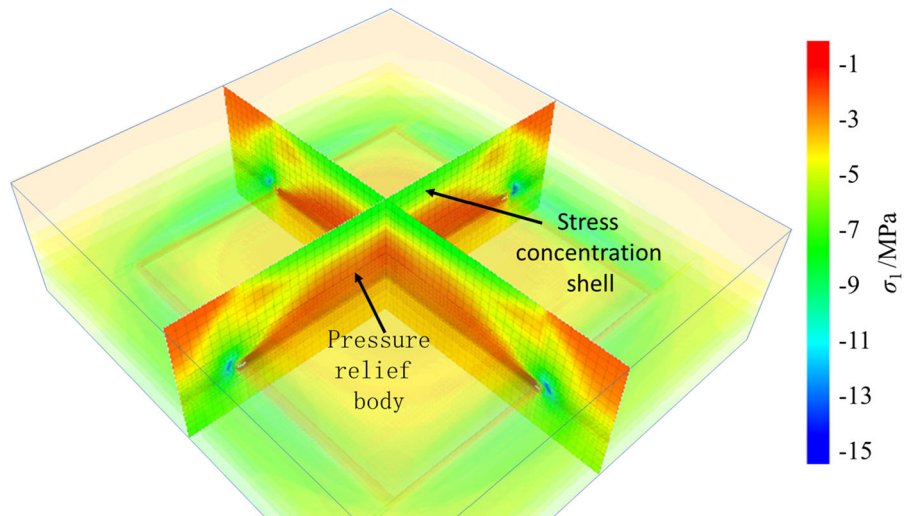


Fig. 18 Maximum principal stress field perpendicular to mining direction when F117 is mined with PRMM. **a** 10 m in front of the mining face; **b** in the mining face; **c** 40 m behind the mining face; **d** 80 m behind the mining face

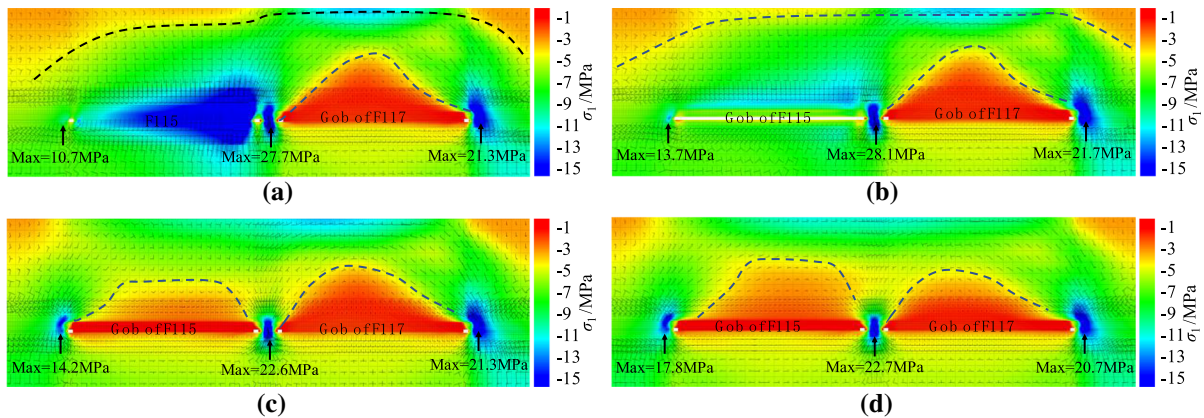


Fig. 19 Maximum principal stress field perpendicular to mining direction when F115 is mined with PRMM. **a** 10 m in front of the mining face; **b** in the mining face; **c** 40 m behind the mining face; **d** 80 m behind the mining face

Fig. 19. It can be seen from the figure that higher stresses concentrate in the section coal pillar as the F117 is mined out. The stress arch and the “Unloading Space” of F115 can be gradually formed with the advance of the mining face, but they can not connect with that of F115. As a result, when the F117 and F115 are mined out, the stress arch appears an “m” shape.

6 Conclusion

1. During the primary mining stage, the distribution characteristics of the lead abutment pressure of GERRC is basically the same with that of PRMM, while the value of the pressure of PRMM is slightly higher than that of GERRC. During the secondary mining stage, the peak value of the lead abutment pressure of the two mining modes is close. However, the pressure can be transferred more evenly to the coal and rock mass far away from the goaf when mining with GERRC, while the pressure tends to concentrate in the coal near the goaf when mining with PRMM.
2. The lateral abutment pressure is easier to concentrate in the section coal pillar when mining with PRMM. And, the maximum vertical stress of the pillar is increasing with the advancing of mining face. Besides, the stress may decrease when the coal seams on both sides of the pillar have been extracted and the whole section of the pillar is in yield state, but it still remains a high residual stress in the pillar.

3. Adjacent goafs can be connected to form a wide range of pressure relief region when mining with GERRC and the shape of distribution of the maximum principal stress appears a semi-space ellipsoidal shell in three-dimensional space. While it looks like a “m” shape in the section perpendicular to the mining direction when mining with PRMM because of the high stress concentration in the section coal pillar.
4. It can be speculated from the above that the stress field of surrounding rocks in PRMM may be involved into the form of that in GERRC when the section coal pillar is fully yielded and unstable, but it may lead to large-scale movement of overlying strata and cause dynamic disasters. Consequently, the long-term strength of section coal pillars is a typical and important issue when mining with PRMM.

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