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ORIGINAL PAPER

Research on Correlation Between Abutment Pressure and Gas Drainage Flow of Coal Seam

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Abstract In this paper, based on the field test of No.S3012 working face of Shan Mushu Coal Mine in Sichuan Coal Group, monitoring the abutment pressure and gas drainage flow during the mining process, studying the change law of the abutment pressure and gas drainage flow of the coal seam, and using the numerical simulation method research on the evolution of abutment pressure and displacement of coal seam during the mining process. The results shown that: with the advance of coal mining face, the abutment pressure of coal seam can be divided into stress decreasing area, stress increasing area and original stress area, and the stress state of coal seam and the pore, crack structure and permeability of coal body are obviously changed. With the advance of the mining face, the abutment pressure in front and back of the coal mining face is the moving abutment pressure, and the coal mining face to be in the pressure relief area, the front abutment pressure peak value deep into the coal body 5–10 m, the influence scope reaches the front coal mining face to 90–100 m, this area is the stress increasing area. And the evolution law of the roof displacement of goaf is similar to the elliptical with the axial ratio changes, when the ratio is close to 1, the roof subsidence affected area is similar to the shape of “O”.

Keywords Abutment pressure · Gas drainage flow · Correlation · Numerical simulation

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1 Introduction

With the increase of coal mining depth in our country, the mine gas emission gradually increased (Hu et al. 2008, 2011), which seriously restricts the safe production of coal mine. Therefore, the coal seam gas extraction is an important means to prevent gas disasters. But the coal seam has some characteristics of high plasticity and low permeability, and in the process of coal mining, the gas migration and the deformation of coal seam interaction, which lead to the permeability of coal seam is complex and changeable.

Domestic and foreign scholars have carried out a series of researches on coal and gas co-mining and achieved many achievements. Qin et al. (2012) research the relationship between lead abutment pressure and gas drainage quantity for different mining speeds was analyzed. Solid–gas coupling during pressure unloading was experimentally examined for different unloading speeds and different unloading initial axial pressure. Xie et al. (2014) research the gas pressure and mining stress coupling effect were researched by using the integrated research methods of field measurement, numerical simulation, mathematical and mechanical analysis. Tu and Fu (2009) aiming at the occurrence condition of soft coal seam with high gas and low permeability, building a dynamic model for coal seam deformation and gas migration through theoretical analysis, and it effectively reveals the objective essence of the gas migration law. Liang et al. (2014) studied the mechanism of gas flow during gas extraction, the correlation between deformation and gas seepage in coal seam. Jiang et al. (2011a) aiming at the problem of reasonable decorate of coal gas extraction drilling, combining with the initial and boundary condition of borehole extraction, the solid and gas coupling mathematical model of gas seepage of bore hole extraction is deduced based on established control equations of seepage field and deformation field. Lu et al. (2015) to determine the reasonable distance of gas drainage boreholes in coal seam being mined, established the solid and gas coupling mathematical model of gas seepage in drilling extraction. Zhang et al. (2015) studied the coupling effect of coal-seam mining fissure, stress and methane flow, revealed the permeability of cracked coal mass under mining is related to fissure width, connect situation, unevenness, spacing, normal stiffness and mining stress; methane flow in cracked coal mass is intimate to fissure development; and methane permeability is positively correlated to fissure width and negative to fissure spacing. Yin et al. (2011) and Jiang et al. (2011b) studied the characteristics of coal and rock gas seepage in stress–strain process. It is shown that the gas flow is closely related to the damage and deformation process of coal sample, the gas flow decreases with the compression of coal sample and decreases with the increase of confining pressure. Zhou et al. (2016) using the hollow inclusion strain cells measurement technique, the evolution of mining dynamic pressure is monitored based on original rock stress measurements. Liu et al. (2015) put forward the longwall face was influenced by both dynamic and static abutment pressure. The formation and variation of the dynamic abutment pressure were resulted from the movement of the strata in fractured zone of roof, the formation of the static abutment pressure was resulted from the load transfer of the strata above the fractured zone of roof, and was characterized by the load transfer of key strata. Kong (2014) based on the close spacing layout method of high-density geophones and near-field location principle of microseismic network, combined with mining theory, analyzed the relationships between overburden strata movement and strata fracture, overburden strata movement and abutment pressure distribution, microseismic events and abutment pressure distribution, et al. Wang et al. (2015) studied the whole process of abutment pressure evolution and micro-seismic activities at the lateral strata of goaf, stress and microseismic monitoring devices by using the outer roadways of two-lane layout face.

In the mining process, the working area will inevitably lead to the collapse, bending subsidence of the overlying strata in the goaf, thus forming caving zone, fissure zone and bending subsidence zone for the overlying strata. And the overlying strata of the caving belt and fissure zone lead to rock cracks, through, as water and gas and other seepage channel. The fissure increases the fluid through enhanced ability, and the fracture closure fluid passing capacity decreases. In the process of coal mining face, in the front of the working face can be divided into stress decreasing area, stress increasing area and original stress area. The stress decreasing area caused the increase of the coal-rock fissure and the fluid through the stress enhancement; the stress increasing zone makes the coal-rock fissure closure, compaction, resulting in reduced fluid through capacity. Therefore, it is necessary to study the stress state of the gas in the coal and rock in migration law.

In this paper, based on the field test of No.S3012 working face of Shan Mushu Coal Mine in Sichuan Coal Group, monitoring the abutment pressure and gas drainage flow during the mining process, studying the change law of the abutment pressure and gas drainage flow of the coal seam, and using the numerical simulation method research on the evolution of abutment pressure and displacement of coal seam during the mining process. It provides reference value for coal and gas safety, it provides reference value for coal and gas safety co-mining.

2 Description of Field Observation

2.1 Survey of Working Face

The No.S3012 mining face is in the merge area 2 + 3# coal of the Shan Mushu coal mine is operated by the Sichuan FuRong Group Industrial Co. Ltd, the working coal face strike length is 752 m, and the slope length is 136 m, the average dip angle is 4°, the thickness about 0.8–4.4 m, the average thickness is 3.1 m. The immediate roof is sandy mudstone with a thickness of about 3.0 m. There is a false roof of about 0.4 m between the coal seam and the immediate roof, the false roof is a thin layer of mudstone-argillaceous limestone, fragile, and it can fall with the mining. The main roof is sandstone-carbonaceous mudstone with an average thickness of 6 m. The immediate floor is clay-stone, soft and water swelling, with an average of 2.8 m. The main floor is sandy mudstone, sandstone, with an average thickness of more than 5 m. The 2 + 3# coal seam is coal and gas outburst coal seam, coal seam gas content is 17.37 m^3/t, gas pressure is 1.32 MPa. The mining method is longwall retreating mining on strike, the ground control is total caving method, U type ventilation. The No.S3012 working face near the strata is Table 1, the working face of the roadway layout as shown in Fig. 1.

2.2 Test Program

2.2.1 Gas Drainage Flow Monitoring

The head gate and the tail gate constructed the bedding hole in the S3012 working face, drilling diameter of 120 mm. The drilling distance of a single row is 1.0 m of the head gate, the drilling dip angle of − 18° to − 19°, the hole depth of 50 m. The drilling distance of a single row is 1.0 m of the tail gate, the drilling dip angle of − 2° to − 9°, the hole depth of 66 m, and in the No.1# exploring coalway, No.2# exploring coalway, No.2# interconnection construct the bedding drainage hole pre-drainage methane. Due to encounter the geological structure, fault and other reasons in the course of construction the working face bedding hole, the head gate to the north of 55–85 m in the direction of the slope of some bedding pumping construction is not in place to produce mining blind, then the water injection hole is injected before the extraction of the working face everyday. At the same time, the interval prediction hole is reduced during outburst prediction every time. When there are abnormal cases Construct the unloading drilling or other measures to eliminate the drainage blind spot. The coal seam gas drainage drilling potency through the optical interference type

Table 1 The working face near the strata

Main lithology	Thickness (m)	Bulk modulus (GPa)	Shear Modulus (GPa)	Cohesion (MPa)	Friction angle (°)	Tensile strength (MPa)	Density (kg/m^3)
Mudstone	> 15	3.61	1.86	1.46	25.4	1.2	2540
K9 limestone	0.7	7.55	6.64	3.2	42.0	2.17	2600
1# coal seam	0.65	2.05	1.02	1.7	18.5	1.05	1400
Sandstone-clay stone	8.5	3.6	1.8	1.1	32	1.48	2580
C2 coal seam	0.42	2.05	1.02	1.7	18.5	1.05	1400
Mudstone	10	3.61	1.86	1.46	25.4	1.2	2540
K8 muddy limestone	0.5	4.03	3.54	1.65	24.5	1.65	2400
Sandstone-carbon mudstone	6	6.27	4.7	1.77	22.8	1.85	2450
Mudstone-mud limestone	3	3.50	3.1	1.6	30	2.48	2550
2 + 3# coal seam	3.1	2.05	1.02	1.7	18.5	1.05	1400
Clay-stone	2.8	3.98	2.17	1.8	25	0.3	2460
Sandy mudstone	> 5	8.9	8.4	4.3	40	3.5	3020

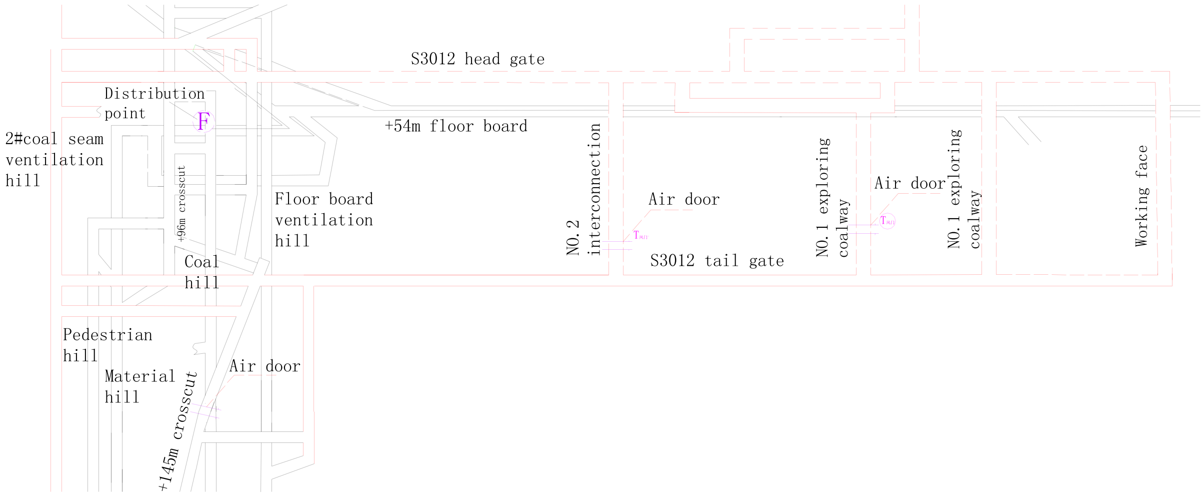

Fig. 1 Layout of roadway in No.S3012 working face

methane analyzer, drilling flow through the gas meter (gas flow indicator).

2.2.2 Abutment Pressure Monitoring

The abutment pressure of the coal seam is monitored by the drilling stress gauge installed in the tail gate of the No.S3012 working face. The drilling stress gauge layout method: from the 2# coal exploration roadway 45 m, and arranging drilling holes along the coal seam at the tail gate, the spacing between boreholes is 5 m, height 0.8 m, depth 8 m, and arranged a total of 5. Then, the drilling stress gauge is installed. In the process of mining face, monitoring the change of abutment pressure of the coal seam in real-time. The schematic diagram of drilling stress gauge and extraction borehole layout as shown in Fig. 2.

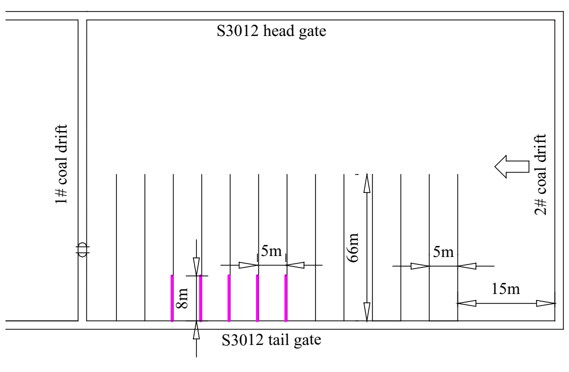

Fig. 2 Drilling stress gauge and extraction borehole layout

The coal seam abutment pressure measurement method: after the drilling operation are constructed, push the drilling stress gauge into the bottom of the hole with a coarse push rod and ensure that the stress gauge cylinder face up; rotate the rod make the drilling stress gauge cylinder extend to the hole wall, and then connect the measuring instrument to record the initial value of the drilling strain gauge. The drilling stress gauge used the ZLG-40 type vibrating wire sensor, the maximum initial support force up to 40 MPa. Before installing the drilling stress meter, connect the drilling stress gauge to the detector, enter the initial frequency f_0 and the sensor A, B constant for each drilling stress gauge, the drilling stress gauge are numbered, the

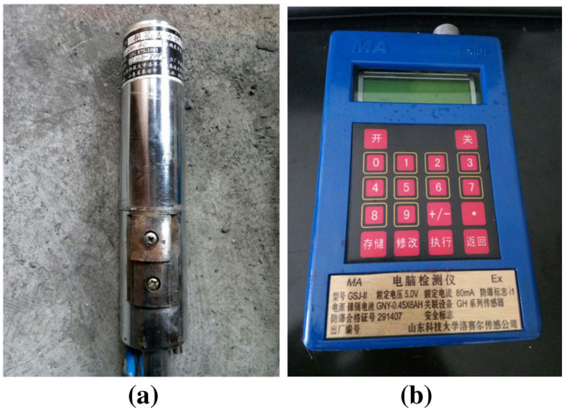

Fig. 3 Monitoring device of mining stress. **a** Drill stress gauge, **b** data acquisition instrument

drilling stress gauge and instrument are shown in Fig. 3.

3 Evolution Law of Coal Seam Abutment Pressure and Gas Drainage Flaw

The drilling stress stations of No.S3012 working face is designed with the drilling rig of 45, 50, 55, 60, 65 m, and the nearby gas drainage drilling in the 2# coal roadway respectively. Based on the field measurement data, obtained the distribution law of abutment pressure and gas drainage flow in the S3012 working face mining process. Figure 4 shows the abutment pressure curve and the gas drainage flow curve of the coal seam at different working face advanced distances.

It can be seen from Fig. 4 that the abutment pressure of coal seam can be divided into stress decreasing area, stress increasing area and original stress area with the mining face from No.2 exploring coalway along strike propulsion. In the working face of the front 15–25 m to reach the peak value. When the immediate roof of the working face to collspse, The weight of the overlying rock mass one side is borne by the coal wall and the side is borne by the collapsed rock stratum. With the advanced of the working face, the gas drainage flow varies with the abutment pressure of the coal seam, and the stress decreasing area, stress increasing area and original stress area show different permeability characteristics, and there is a negative correlation. In the vicinity of the working face, the coal body is affected by mining, the strength is reduced, the stress is released and transferred to the deep coal body. The stress state of the coal is changed from three directional load to two directional unloading confining pressure, and the unloading zone is formed. The unloading expansion deformation of the coal body makes the pores and fissures open in the coal seam, the development of the new fractures is penetrating, the permeability of the coal seam increases, and the gas extraction flow increases, resulting in the pressure relief and flow increasing effect. With the continuous advance of the working face, the abutment pressure of the coal seam gradually increases and greater than the original stress, that is the stress increasing area. In this area the coal seam is compressed, the new cracks and the original pores closure in the coal seam, the gas migration channel is closed, the permeability of the coal seam is reduced, the gas drainage flow is reduced, and reach the minimum near the abutment pressure peak value, the area is called a pressure drop flow area, but the area of gas drainage flow is still slightly higher than the original seepage area of the gas pumping flow. With the continuous advance of the working face, the influence of the coal seam by the mining gradually weakened, the abutment pressure gradually restore to the original stress state in coal seam, the original pore, crack and the new fractures form under the action of mining stress in coal seam change little, the permeability of the coal seam does not change much, the gas drainage flow tends to be stable, and the area is the original seepage area.

Based on the analysis, it can be seen that the permeability is closely related to the abutment pressure of the coal seam. The change of the stress state of the coal seam makes the structure change, and changes the permeability of the coal seam, which leads to the change of the coal mining gas with the change of the mining stress, In the pressure relief area of the coal seam, the porosity and the fissure are permeated and

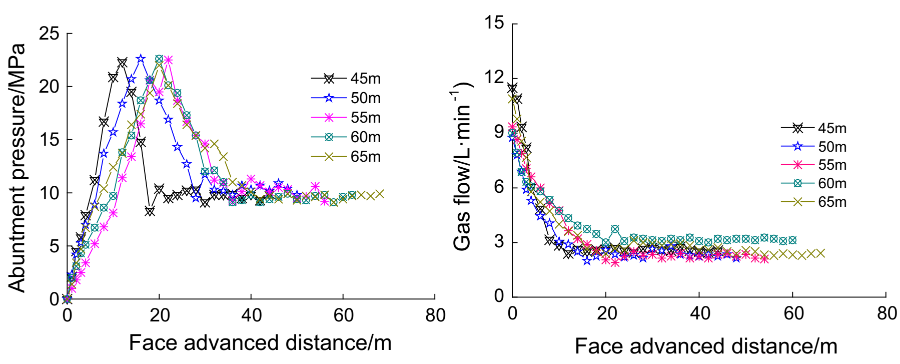

Fig. 4 Gas drainage flow and abutment pressure curve of coal seam with the advanced different distance of the mining face

the permeability increases, and the gas extraction flow increases. In the stress increasing area of coal seam, the stress is increased and the fissure shrinkage is closed in the coal seam. Compared with the pressure relief area, the permeability of the coal seam is reduced and the gas drainage is also reduced, but the gas drainage rate is still slightly higher than the original seepage area in this area. In the original stress area, the permeability of the coal seam does not change much, the gas drainage flow tends to be stable.

4 Numerical Analysis of Mining Face

4.1 Numerical Model Setup

According to the geological conditions of No.S3012 working face, $FLAC^{3D}$ was used to establish three-dimensional models, the model parameters were 400 m × 200 m × 150 m (length × width × heigth), as shown in Fig. 5. In the implicit solution stage, the roller support border is adopted for the bottom and the sides of the model, and the upper part of the model is applied with an overlying load of $\sigma_\gamma = \gamma H$, that's the overburden pressure for z direction, the x-direction lateral earth pressure coefficient is the x-direction principal stress and vertical stress ratio, the y-direction lateral earth pressure coefficient is the y-direction principal stress and vertical stress ratio. The coefficient of lateral earth pressure for x and y direction in 3-D condition is 1.5, 2.0, respectively, which γ is the average unit weight of the upper stratum ($\gamma = 24$ kN/m^3), H is the laneway depth (m). The Mohr–Coulomb yield criterion was used in the computation of the model (Zhao 2011; Baghbanan and Jing 2007; Li et al. 2015). The working face advanced distance of 50 m every time, the total length of 250 m.

$$f' = \sigma_1 - \sigma_3 \frac{1+\sin\varphi}{1-\sin\varphi} - 2c\sqrt{\frac{1+\sin\varphi}{1-\sin\varphi}} \quad (1)$$

where f' is the shear yield function; σ_1 and σ_3 are the maximum and minimum principal stresses (MPa), respectively; c is cohesion (MPa); and φ is the internal friction angle of the rock (°).

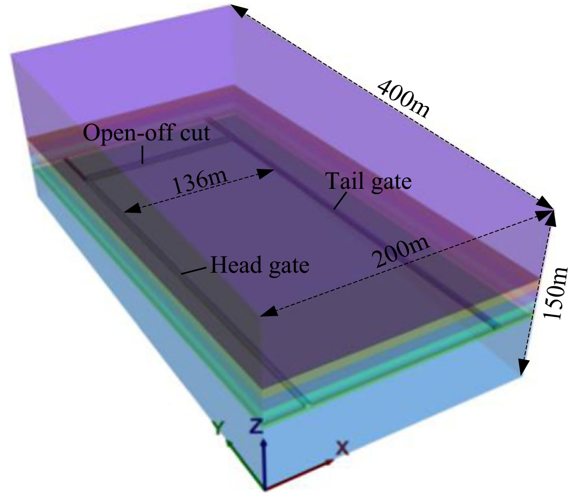

Fig. 5 $FLAC^{3D}$ three-dimensional model

4.2 Result Analysis

4.2.1 Variation Regulation of Abutment Pressure

When the working face is advanced at different distances, the abutment pressure curve is extracted along the roof of the coal seam is shown in Fig. 6.

With the continuous advance of the coal mining face, which leading to stress distribution of rock mass and overlying strata around the working face. The distribution characteristics of abutment pressure in front and back of the working face: the coal wall side bearing the fracture zone above the working face and its most of the overlying strata in front of the coal mining face. The front abutment pressure of the mining face is much greater than the back. Due to the advance of the mining face, the coal wall and the goaf area are moving forward continuously, so the abutment pressure in front and back of the coal mining face is the moving abutment pressure. As the fissure zone formed a half-arch balance with coal wall and goaf caving zone for before and after bearing points, leading to coal mining face to be in the pressure relief area. The maximum value of the abutment pressure formed in front of the coal face occurs in front of the middle of the working face, the peak value reaches 22.08 MPa, the stress concentration coefficient K about 2.3. The front abutment pressure peak value deep into the coal body 5–10 m, the influence scope reaches the coal mining face front 90–100 m, this area is the stress increasing area, and the coal seam is

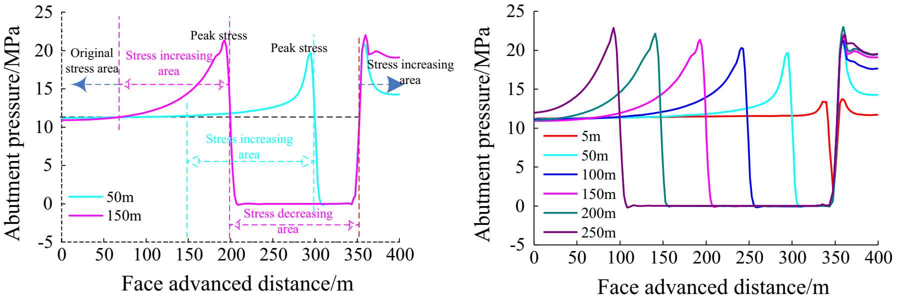

Fig. 6 The abutment pressure distribution in front and back of the working face

unaffected by the mining area is the original stress area. The stress concentration coefficient K is given by (2).

$$K = \frac{\sigma'}{\sigma_{\gamma}} \tag{2}$$

where, σ' is abutment pressure, MPa; σ_{γ} is overlying load, MPa.

The stress concentration coefficient of the abutment pressure in front of the coal face is relatively small after the put-cut off is excavated, which is 1.39. As the working face advanced step distance increase continuously, the stress concentration coefficient of the coal seam changes within the range of 2–2.4, and tends to be stable. The evolution law of stress concentration coefficient in front of working face is close to the law of the concentration in elliptical hole with axial ratio. That is, from the beginning of the work face, the K value increases with the advancing distance, or the K value increases with the increase of the axial ratio, to the working face advanced the within range the main roof the first movement of the rock strata end, the length and short ratio is decided by the span of rock beam and height of the main roof tends to be stable and relatively stable limit.

The results of field measurement and numerical simulation are shown in Table 2, the difference between the two results is small and the error is less than 5%, this result is significant to the extraction of coal mining face, gas treatment and roadway support.

Table 2 Comparison of results of stress concentration coefficients

Field measurement results	2.32	2.35	2.34	2.35	2.29
Numerical simulation results	2.05	2.12	2.22	2.3	2.38

4.2.2 Variation Regulation of Displacement

When the working face advanced different distance, along the top and floor of the coal seam to extract displacement curve are shown in Fig. 7. With the advance of the coal mining face, the roof of the working face is affected by the mining unloading, the roof has a vertical download uploading swelling deformation after mining, resulting in the separation and caving of the roof, and the failure mechanism of the roof is mainly tensile failure. The bottom of the coal seam shows vertical upward unloading and swelling deformation, due to the immediate roof is mudstone, it can be concluded that the top-coal can fall with the mining, resulting in the deformation of coal seam roof is larger than that of the floor.

In the process of mining face, the variation law of the roof displacement in the goaf of coal seam are shown in Fig. 8.

At the beginning of put-cut off, with the advance of coal mining face, the evolution law of the roof displacement of goaf is similar to the elliptical with the axial ratio changes. The oblique direction of the working face is elliptical short axis, and the strike direction is elliptical long axis. As the working face continues to advance, the axial ratio continuously increases, and the roof subsidence area of the goaf increases continuously. When the ratio is close to 1, the roof subsidence affected area is similar to the shape of “O”. As the working face advance continues, the axial ratio continuous increase, and area of the roof subsidence in goaf increases continuously along the long axis.

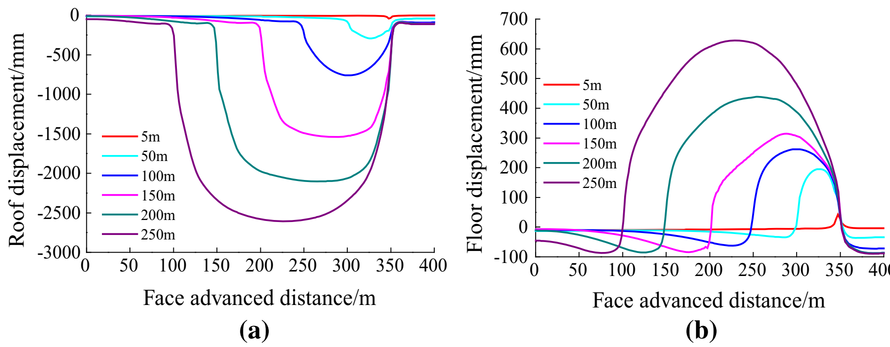

Fig. 7 Displacement curve of roof and floor of coal seam. **a** Roof displacement, **b** floor displacement

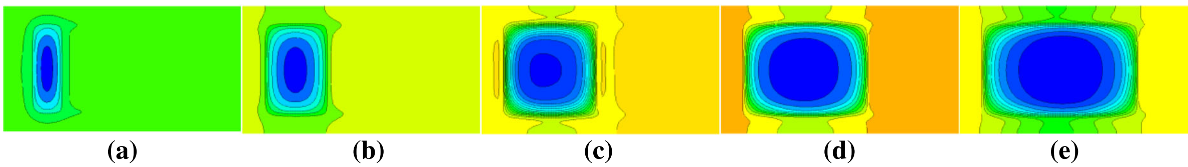

Fig. 8 Variation law of roof displacement "O" in Goaf. **a** 50 m, **b** 100 m, **c** 150 m, **d** 200 m, **e** 250 m

5 Conclusions

1. With the advance of coal mining face, the abutment pressure of coal seam can be divided into stress decreasing area, stress increasing area and original stress area. In the stress decreasing area, the unloading expansion deformation of the coal body, the permeability of the coal seam increases, and the gas extraction flow increases. In the stress increasing area, the coal seam is compressed, the permeability of the coal seam is reduced, the gas drainage flow is reduced. In the original stress area, the permeability of the coal seam does not change much, the gas drainage flow tends to be stable.
2. With the advance of the mining face, the abutment pressure in front and back of the coal mining face is the moving abutment pressure, and the coal mining face to be in the pressure relief area. The front abutment pressure peak value deep into the coal body 5–10 m, the influence scope reaches the front coal mining face to 90–100 m, this area is the stress increasing area.
3. With the advance of coal mining face, the evolution law of the roof displacement of goaf is similar to the elliptical with the axial ratio changes. When the ratio is close to 1, the roof subsidence affected area is similar to the shape of "O". As the working face advance continues, the axial ratio continuous increase, and area of the roof subsidence in goaf increases continuously along the long axis.

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Author Contributions Dongming Zhang had the original idea for this study, all co-authors were involved in data analytics work, as well as Yushun Yang writing and revising all parts of this manuscript.

Compliance with Ethical Standards

Conflict of interest The authors declare no conflict of interest.

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