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Research Article

Analysis of Collapse Mechanism and Anti-collapse Support of Borehole in Deep Tectonic Coal

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Abstract

To solve the collapse problem of borehole in tectonic coal, based on the actual collapse and plugging characteristics of the borehole, the numerical model of anti-collapse and support of borehole with borehole-sieve tube was built by using FLAC^{3D}. The collapse mechanism of borehole was revealed, the support scheme of full-length support with setting sieve tube and sealing device from the drill pipe inside was proposed. Combining with field tests of collapse prevention and support of boreholes, the deformation and support characteristics of boreholes in tectonic coal were revealed. Results show that the stress is redistributed after the borehole being completed, and the stress concentration occurs on both sides of the borehole due to the tectonic stress. The stress variation range of the coal around the borehole supported by the screen pipe is smaller. The vertical displacement around the borehole is reduced by 38% and the plastic damage area of that is reduced by 34%. The full-length support and deep borehole sealing technology can significantly improve gas extraction concentration and pre-pumping time. The conclusions obtained in this study can provide the reference to the collapse prevention of the borehole in the tectonic coal.

Keywords: Tectonic coal, Borehole collapse, Numerical simulation, Collapse prevention

1. Introduction

With the increasing consumption of coal resources, coal mines in many countries have stepped into the deep mining [1, 2]. As the mining depth continues to increase, the gas influence becomes more and more significant [3-5]. The increase of gas content and gas pressure can easily induce coal and gas protrusion accidents. Since these accidents cannot be effectively avoided, it is important to reduce the gas content and gas pressure in coal during deep mining.

At present, the gas pre-pumping according to the characteristics of the coal in deep mining is widely used in China, the gas extraction effect of underground drilling is obviously good. In the process of gas extraction, the damage state of the coal rock body around the borehole cannot be practically controlled, and the problem of low gas extraction concentrations that cannot be solved well [6]. The factors that induce borehole collapse increase with the depth of mining. For the different factors affecting particle slip and separation in the surrounding rock of the borehole, a strain energy and stress relationship model were derived by Hashemi & Melkoumian, which is a guide to the design of boreholes [7].

The use of bedding borehole for gas pre-pumping is of great significance to reduce gas outburst accidents and improve mining efficiency [8]. The stress environment in deep tectonic coal seams is complex and variable. There are many factors that affect the stability of the borehole after drilling and forming. Borehole collapse and plugging are frequent, the utilization rate of drill holes is low, and the efficiency of gas extraction is low [9]. Therefore, it is an urgent problem to be solved to improve the stability of the borehole, to increase the utilization rate of borehole and to improve the efficiency of gas extraction.

2. State of the art

Stress redistribution after borehole being completed in the coal seam can satisfy the theory of deeply buried cavities in rock mechanics. Willis and Willis derived the elastic stress solution for the borehole wall by elastic theory [10]. The elastic stress solution is too idealized for the complex geological conditions of the coal seam. Therefore, many scholars have developed relevant theoretical models of borehole mechanics based on strength criteria such as Mohr-Coulomb, Drucker-Prager, and Hoek-Brown criteria to study the destabilization damage mechanism of boreholes [11-13]. Gholami et al. evaluated the damage characteristics of the rock by three damage criteria and analyzed the stress distribution and mechanical characteristics of the rock formation [14]. Westergaard studied the stability of the borehole wall based on the Mohr-Coulomb criterion and obtained the elastic-plastic stress solution around the borehole wall [15]. The anisotropic characteristics of deep rocks are also important factors in inducing borehole deformation. Aadony & Chenevert used the Chenvert test to investigate the effect of the difference in properties of different strata in each direction in slanting wells on the stability mechanism of boreholes [16]. It is of interest to use different materials to arrange simulated boreholes to study the microscopic change mechanism during borehole deformation and collapse [17-19]. Based on the study of time lag effect, Qu et al. proposed that the important reasons

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for the deformation of the surrounding rock were pore pressure variation and cuttings [20]. Meier et al. concluded that size effect was the main factor leading to hole collapse in boreholes by analyzing the effect of hole diameter on the deformation mechanism of boreholes [21].

Theoretical studies of stress distribution for the borehole are relatively well established. With the development of numerical simulation techniques, some scholars have applied this combination to the study of stress and fracture distribution around boreholes [22, 23]. The study of stress distribution characteristics and fracture distribution law around the borehole is of guiding significance to the borehole sealing [24, 25]. Gentis used physical tests and numerical simulations to investigate borehole stability, and predicted the stability of horizontal boreholes in the overbalanced to underbalanced range with STABView [26]. Zhang et al. studied the characteristics of deformation mechanisms of intact, collapsed and plugged holes under creep characteristics, and they found that plugging caused the formation of a continuous medium between coals which reduced the gas extraction efficiency [27].

The above theoretical studies on the deformation mechanism of the borehole show that the geological conditions of the coal seam and the stress distribution around the borehole have an important influence on the stability of the borehole, but substantive field experimental studies on the collapse prevention support of the borehole are still lacking. Proper pre-supporting of coal gas extraction boreholes can not only effectively protect the stability of the borehole and increase the service life of the borehole, but also improve the efficiency of gas extraction. By filling the borehole with expansion material, the active expansion force generated by the material itself can be used to support the borehole wall and resist the deformation damage of the borehole to maintain its stability [28]. Spraying foam concrete slurry on the borehole wall can provide a better support effect to the borehole [29]. There are many ways to support the borehole, and in the borehole setting the support tube is also a commonly used form of support. Different support materials can provide a variety of support effects.

The above mentioned studies of borehole stability mechanism were more idealized. The stability model of the borehole based on numerical simulation did not consider the actual field conditions of the borehole. The diameter of the borehole in the construction site is usually larger than the diameter of the support sieve tube to make it easier to put the sieve tube into the borehole. Compared to the assumptions in the theory of deeply buried circular chambers, the differences in borehole and sieve tube diameters can change the force and deformation characteristics of the borehole. The wall collapse of the borehole often occurs in the first time, and the sieve tube can provide support effect afterwards. Therefore, the study of the collapse mechanism of the borehole based on the actual state of borehole and sieve tube is of the practical guidance for engineering practice.

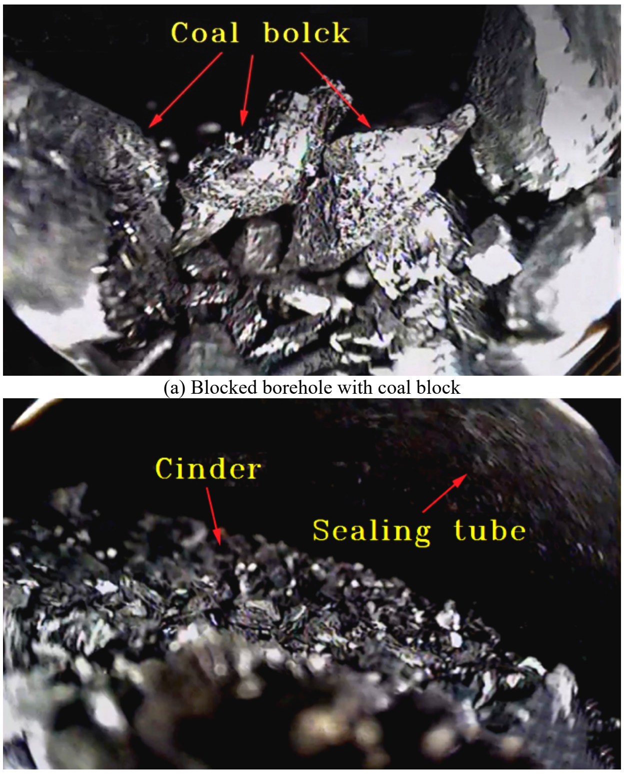
To solve the collapse problem of the gas extraction borehole and improve the utilization rate of the borehole, taking Yuxi coal mine in Shanxi Province in China as the research background, the collapse mechanism of the gas extraction borehole was analyzed, and the whole borehole support scheme with setting the sieve tube and sealing device in the drill pipe were proposed. The results of this study can provide the guide to the site operation and industrial testing of the collapse prevention and support of the borehole. The rest of this study is organized as follows. Section 3 gives the relevant background and analysis methods. Section 4 describes the results and discussion, and finally, the conclusions are summarized in Section 5.

3. Methodology

3.1 Engineering background

The Lanhua Branch Yuxi coal mine is located in Hudi Township, Qinshui County, Shanxi Province, China. The coal mine is mainly mining $3^{\#}$ coal, the coal thickness is 5.12-7.20 m. The coal-bearing coefficient of the coal seam is 7.73-14.99%, with an average of 11.67%, of which the recoverable coal-bearing coefficient is 11.31%. This coal seam is a pumpable coal seam.

The effective support length of the gas extraction bedding borehole is 18 m, of which 12 m is the sealing section and 6 m is the sieve tube support length. The borehole collapse and plugging of the borehole is occurred frequently. As shown in Fig. 1, the collapse phenomenon inside the borehole can be divided into two types. Fig. 1(a) shows that when the deformation damage occurs in the borehole, the coal block of the borehole wall is fall out to block the borehole, thus affecting the normal use of the borehole. The second form of the blockage is the blockage of gas extraction channel caused by broken cinder, as shown in Fig. 1(b). This form of blockage destroys the patency of the gas extraction tube and leads to the failure of the gas extraction channel, which results in the gas extraction concentration going to zero. The gas extraction borehole plugging phenomenon is frequent. There is low utilization rate of borehole, too fast decay of gas extraction concentration, and low stope efficiency in Yuxi coal mine.



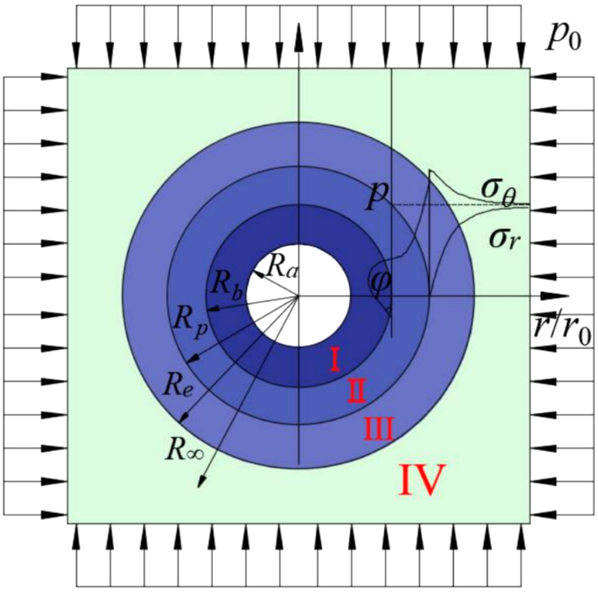
(a) Blocked borehole with coal block

(b) Cinder blocking the borehole

Fig. 1. Borehole blockage condition.

3.2 Theoretical analysis of borehole collapse mechanism

After the borehole being done, the cavity effect is formed in the coal seam, the original stress balance of the coal seam is out of balance, and the stress around the borehole is redistributed. The coal can be divided into crush zone, plastic zone, elastoplastic zone and elastic zone along the central axis of the borehole and outward [23], as shown in Fig. 2.



I-Crushing zone, II- Plastic zone, III-Elastic zone, and IV-Original stress zone. R_a-Radius of the borehole , R_b-Radius of the crushing zone, R_p-Radius of the plastic zone, R_e-Radius of the elastic zone, and R_∞-Original coal seam.
Fig. 2. Stress distribution around of coal borehole.

Under the influence of drilling tool disturbance, macroscopic fissures of the coal of the borehole wall are developed, and the coal body around the hole is relatively broken and distributed in bulk. The coal is less stable under the effect of pressure release from the hole. The coal in the crush area is affected by many factors to show block fall, thus causing the hole collapse and blockage in the borehole. Analysis of the causes of collapsed can be summarized in the followings:

(1) The mechanical properties of coal are changed. After the borehole being completed, the surrounding coal is broken, the integrity of the coal is damaged and the strength is sharply reduced, and the collapse phenomenon occurs with poor stability.

(2) The stress balance in coal seam is disrupted. The coal seam is in the unloading state after the borehole being completed, and the coal around the unloading deformation of the borehole is collapsed and plugged with the effect of time under the action of tectonic stress.

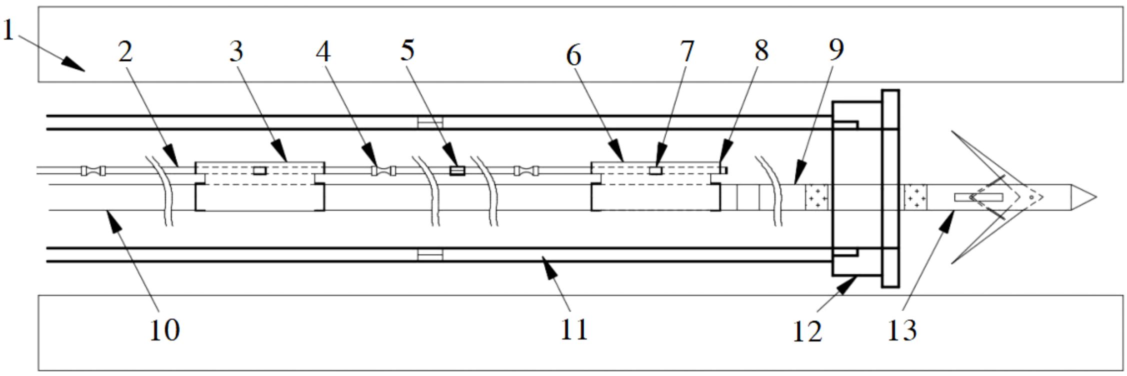
(3) The nature of the coal is changed. The water used for drilling construction intrudes into the internal structure of the coal seam, causing phenomena such as softening and swelling of the coal. The cohesive force decreases and the coal becomes soft, and the borehole is prone to collapse under long time bare hole condition.

3.3 Support scheme design of borehole

By analyzing the causes of borehole collapse and the phenomenon of collapse and plugging in Yuxi coal mine, it is known that the inability to effectively support the borehole after completion of construction will result in the failure of the gas extraction channel. Therefore, the use of full-length support for large-span bedding boreholes can effectively improve the borehole plugging and ensure gas smooth extraction.

Setting the sieve tube and sealer device into the borehole from the drilling pipe inside to accomplish full-length support for borehole, this solution puts the support sieve tube and sealer device into the hole along the inside of the drill pipe before exiting the drilling tool in sequence after the construction of the hole being completed. Even if the hole collapses after the drilling tool being withdrawn, the sieve tube is already present in the borehole and can play a supporting role for the hole. Therefore, the integrity of the gas extraction channel is ensured, which can effectively improve the gas extraction efficiency.

The construction equipment includes large diameter drill pipe, large diameter drill bit, small diameter borehole sealing device and some auxiliary equipment. The design length of the borehole is 100 m, the length of the sealed section is set at 20-25 m, and the length of the PVC sieve tube support section is 25-100 m. The construction process is shown in Fig. 3. This construction process can timely and effective support and sealing of the borehole, ensuring the integrity of the borehole.



1-Coal wall, 2-Grouting pipe, 3-Second grouting bag, 4-Straight fitting, 5-Burst valve, 6-First grouting, 7-One-way valve, 8-Buckle, 9-PVC sieve tube, 10-Gas extraction tube, 11-Drill pipe, 12-Drill bit, 13-Fixture.
Fig. 3. Construction process diagram of borehole.

3.4 Numerical simulation method

Numerical simulations is used to analyze the feasibility of the full-length support of the borehole [30]. The coal seam gas is pre-pumped by bedding borehole, and the coal of the hole wall is strong disturbed during the drilling construction process.The coal of the hole wall is broken leading to a significant decrease in the stability of the borehole. The numerical calculation model of borehole was bulit for the anisotropy characteristics of coal. The “Extrusion” in FLAC^{3D} software was used to construct an irregular mesh to characterize the crush properties of the coal around the borehole. The outer coal mass was built using a regular grid. The model of borehole is shown in Fig. 4.

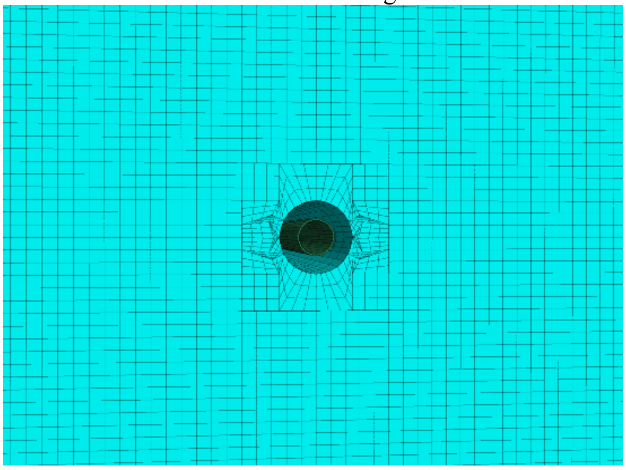


Fig. 4. Numerical model of the borehole.

The borehole diameter of the model is 100 mm and the PVC sieve tube diameter is 50 mm, which assumes the role of support borehole. The coal is defined as Mohr-Coulomb model and the PVC screen pipe is defined as Elastic model. The overlying rock pressure is 17.7 MPa and the tectonic stress is 21.4 MPa. Assign the corresponding calculation parameters and enable large strain in FLAC^{3D} for borehole collapse prevention support calculation. The material parameters of the model are listed in Table 1.

3.5 Industrial testing

The 1302 working face in Yuxi coal mine was selected for borehole collapse prevention and support test. According to the difference of coal integrity at the working face, different areas of coal were selected for testing. The test was divided into two groups, each group constructed 10 boreholes with an interval of about 3 m. The borehole location layout is shown in Fig. 5. The gas extraction was carried out after the completion of borehole construction and gas extraction data was monitored and recorded. Then, the comparative analysis with gas extraction data was done from older boreholes in adjacent areas.

Table 1. Physical and mechanical parameters of coal and sieve tube.

Name	Unit weight (kN/m^3)	Elastic modulus (GPa)	Poisson' ratio	Cohesive strength (MPa)	Tensile strength (MPa)	Frictional angle (°)
Coal	16.5	1.52	0.25	0.38	0.73	45.1
Sieve tube	13.8	3.20	0.32	-	-	-

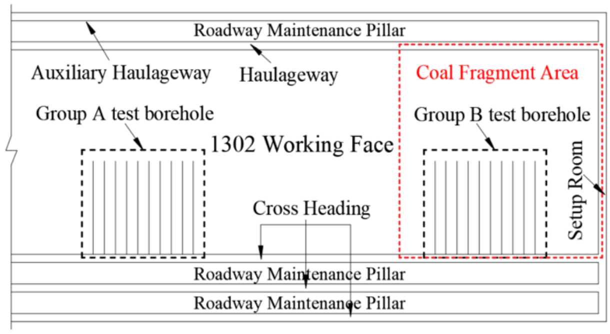


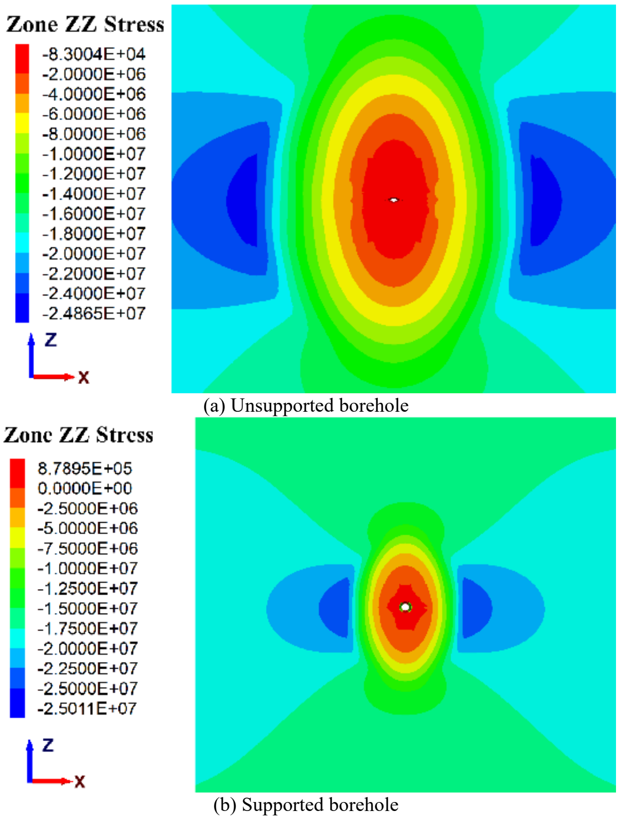
Fig. 5. Borehole arrangement.

4. Results analysis and discussion

4.1 Vertical stress characterization

The working face at y=1.25 m in the model was selected and the vertical stress about the borehole is shown in Fig. 6. The stress distribution around the borehole shows a gradual diffusion from the center to the outside, and the upper and lower sides and the left and right sides are symmetrical. The stress variation is "saddle-shaped", and the stress areas are connected for upper and lower sides. Under the influence of tectonic stress, the stress concentration occurs in the left and right sides of the borehole. The coal stress variation range around the borehole with sieve tube support is small.

The upper wall stress variation of borehole and sieve tube at this working face is shown in Fig. 7. During the deformation of the borehole without sieve tube support, the upper wall stress is gradually decays and stability when stress fluctuation reaches 2.6 MPa. The stress on the upper wall of the borehole supported by the sieve tube fluctuates widely with the deformation of the borehole. When the screen pipe provides 6.8 MPa support force the borehole stress gradually decays. After the deformation of the sieve tube, its force state gradually changes, and when the vertical stress reaches a peak of 17.3 MPa, it starts to show sinuous decay. The deformation of borehole is gradually stability with support, and the stress in the sieve tube and coal around borehole are gradually stabilization.



(a) Unsupported borehole

(b) Supported borehole

Fig. 6. Vertical stress distribution around the borehole.

4.2 Vertical displacement characterization

The borehole is deformed after the pressure relief of coal seam. The displacement of the upper and lower sides of the borehole wall is the largest and gradually decreases in the form of "mushroom cloud" to the deeper part, as shown in Fig. 8. The deformation of the borehole without sieve tube support is larger and finally appears as "eye shape", as shown in Fig. 8(a). and the distance between the upper and lower walls of the borehole is 13mm. Fig. 8(b) shows the sieve tube support borehole. As the borehole deformation squeezes the sieve tube, the PVC sieve tube gradually tends to oval and provides support for the borehole, which ensures the integrity of the borehole.

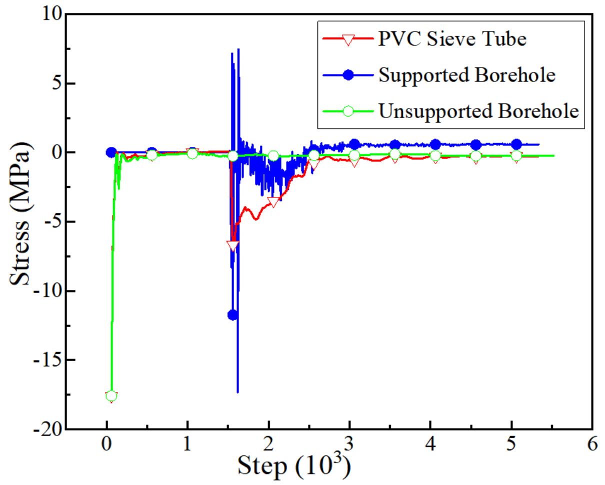
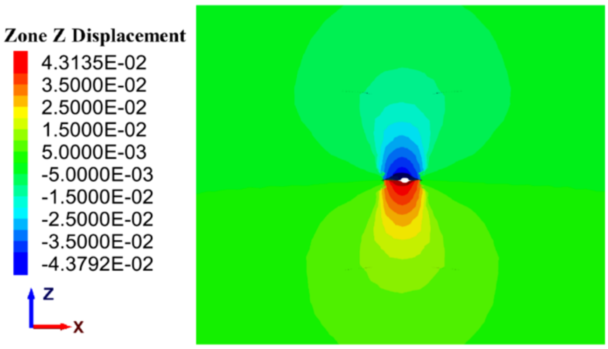
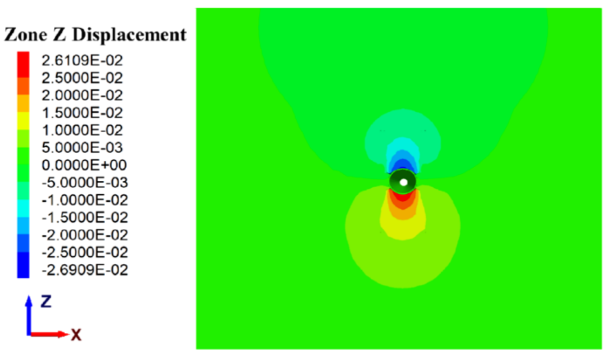


Fig. 7. Vertical stress distribution of the wall around the borehole.



(a) Unsupported borehole



(b) Supported borehole

Fig. 8. Vertical displacement around the borehole.

As shown in Fig. 9, the borehole has a large deformation at earlier stage. The maximum displacement of borehole without screen pipe support is 43 mm. The deformation is a gradual decay process in the borehole supported by the screen tube. When the maximum vertical displacement of PVC sieve tube reaches 1.7 mm, the maximum vertical displacement of the borehole is 26.7 mm. The support force provided by the screen tube at this point can effectively prevent the borehole from continuing to deform.

4.3 Plasticity zone distribution characteristics

The coal will undergo plastic damage when the stress applied exceeds its itself yield stress, as shown in Fig. 10. The plastic zone is divided into two damage types at inside and outside the borehole. The outer side plastic zone is dominated by shear damage, and the inner side plastic zone is shear and tensile damage. The plastic zone in the inner side of the borehole without screen pipe support is slightly damaged showing "round", as shown in Fig. 10(a). The screen pipe support borehole is an ellipse with the horizontal direction as the long axis, as shown in Fig. 10(b). The coal plastic damage area of without screen pipe support is 1.5 times larger than support borehole. The PVC screen pipe is regarded as elastic calculation with no plastic deformation.

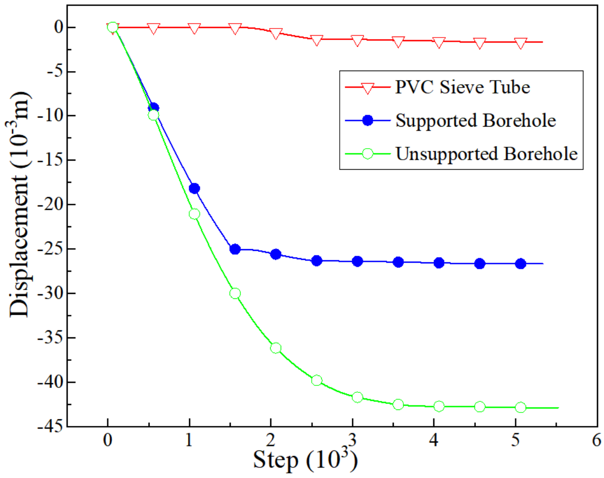
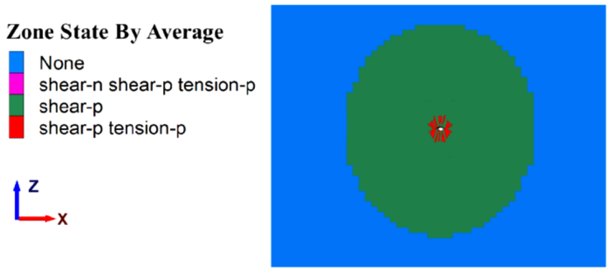
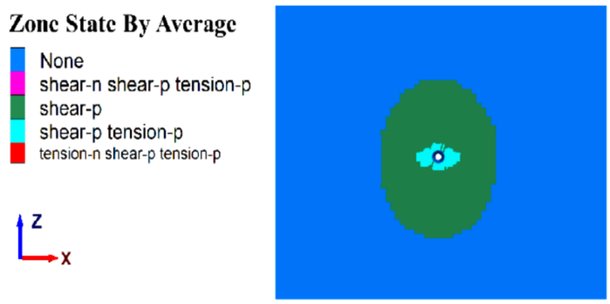


Fig. 9. Vertical displacement distribution of the borehole.



(a) Unsupported borehole



(b) Supported borehole

Fig. 10. Plastic zone distribution around the borehole.

4.4 Gas extraction effect of Group A test

The method of placing sieve tube and borehole sealing device from the drill pipe inside were used to conduct the test of collapse prevention and support for coal gas extraction borehole. Group A tests was conducted in areas with better coal quality. After completing borehole support and sealing processes, the gas extraction was carried out and the gas concentration of the borehole was recorded. The gas concentration data for some of the boreholes are listed in Table 2.

The new and old boreholes were compared for gas extraction concentration decay pattern, as shown in Fig. 11. There are old borehole: 8-3, 8-16, 8-22, 9-4, and 9-14. There are group A test borehole: A3, A6, A7-1, A8, and A9-2. It can be concluded that the gas extraction concentration of old boreholes decayed faster, and most dropped to zero after one month. The borehole cannot continuity extraction. The gas extraction concentration in the Group A test borehole decayed more slowly. The gas concentration was generally maintained at about 30% after extraction 85 days, and the borehole guarantee the continuity of gas extraction. The results show that the scheme used in the test boreholes effectively improve the utilization rate of the boreholes.

Table 2. Gas extraction concentration data of group A borehole.

Borehole / Gas/% / Time/d	A3	A6	A7-1	A8	A9-2
1	58	65	90	65	30
8	60	58	57	65	46
15	37	55	40	35	42
22	37	46	52	60	52
29	50	40	57	50	30
36	42	38	45	40	25
43	30	25	30	40	28
50	25	37	33	55	32
57	0	20	37	50	32
64	0	20	27	40	0
71	32	15	38	45	0
78	30	30	10	25	0
85	30	28	15	40	20

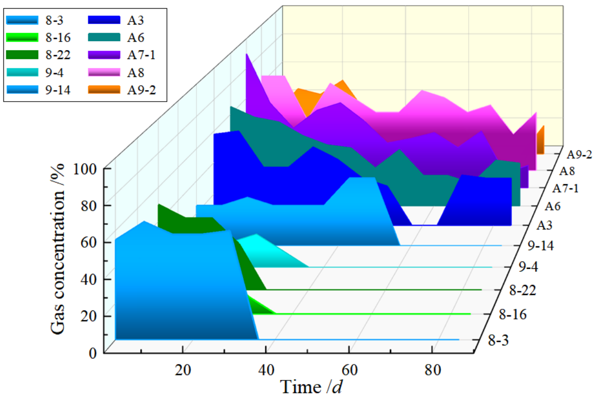


Fig. 11. Decay regularity of gas concentration for group A of tests.

4.5 Gas extraction effect of Group B test

The nature of the coal in the setup room area is more fragmented, and the integrity of the coal is low degree. After the boreholes being completed gas extraction and recorded the gas concentration. The selected borehole extraction concentration data are listed in Table 3.

As shown in Fig. 12, there are the old boreholes data: 13-42, 13-43, 13-49, 18-1, and 21-1. There are the borehole gas data from the Group B test: B1, B2-1, B5, B9, and B10-2. It is clear that the concentration of the old boreholes decayed too quickly, with some concentration of boreholes is zero after 21 days of extraction, and the boreholes is unable to effectively maintain gas pre-pumping. The gas concentration of the test borehole in group B decayed slowly, and the concentration remained at 30% after two months. The results show that the test scheme improved the integrity of the borehole and the efficiency of gas extraction.

Table 3. Gas extraction concentration data of group B borehole

Borehole / Gas/% / Time/d	B1	B2-1	B5	B9	B10-2
1	62	20	40	62	42
8	55	62	25	55	0
15	48	60	25	55	30
22	40	55	18	0	30
29	25	30	18	90	0
36	27	28	25	78	52
43	27	49	27	75	45
50	42	42	32	60	10
57	35	27	30	52	45
64	26	30	25	50	40

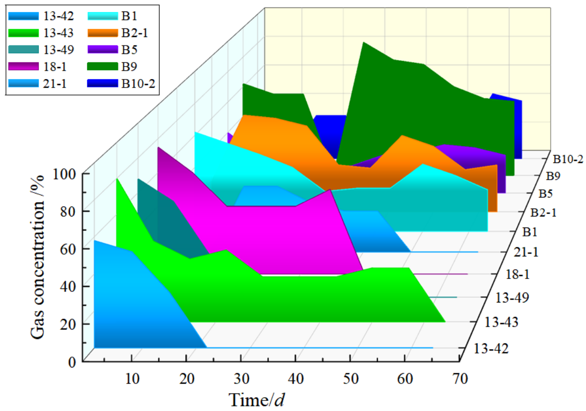


Fig. 12. Decay regularity of gas concentration for group B of tests.

5. Conclusions

Taking Yuxi coal mine in Shanxi Province as the engineering background, the collapse mechanism of coal seam gas extraction borehole was revealed, and the full-length support scheme with setting the screen pipe and sealer device from drill pipe inside to the borehole were proposed. The deformation characteristics of the borehole in tectonic coal were analyzed and the on-site industrial testing of borehole collapse prevention and support was conducted. The main conclusions are obtained as follows:

(1) After the drilling construction being completed, the surrounding stress distribution spreads gradually from the center outward. Under the influence of structural stress, the stress concentration occurs within the left and right sides of the borehole. The coal stress variation range around the borehole with sieve tube support is small.

(2) The deformation occurs when the borehole is unloaded. The sieve tube provides support, and the vertical displacement deformation of borehole can reduce 38%. The shear and tensile damage occurs in the coal around the borehole, and the screen tube is no obvious plastic deformation. Use screen pipe support borehole can reduce the plastic damage area by 38%.

(3) The borehole adopts full-length support and deep sealing technology, which can effectively improve the gas extraction concentration and gas pre-pumping time, and improve the collapse and plugging condition of the borehole.

Ensuring the utilization of the borehole is critical to gas extraction. Due to the complex geological conditions of the coal, the trajectory of the borehole is variable, so the further study is needed for the stability of the borehole in the next step.

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