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Three-dimensional Fracture Distribution of Overlying Strata During Coalbed Mining based on 3DEC Simulation

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Abstract

Coal bed methane is an unconventional natural gas associated with coal. The development and utilization of residual coalbed methane in coal mined areas can eliminate potential safety hazards and increase the supply of clean energy, while also helping to reduce greenhouse gas emissions. The fractures in the goaf are the storage space and seepage channel for the occurrence and migration of coalbed methane. The study of its distribution characteristics has important theoretical value and practical significance for the coalbed methane drainage in the goaf. This paper takes the mining area of Yuecheng Coal Mine as the background, and the 3DEC software based on the discrete element method studies the distribution characteristics of fracture field during and after the coal mining (goaf). The results show that with the advance of the excavation step, the stress field, displacement field and fracture field of the overlying rock in the mining area show dynamic changes. The height of the overburden caving zone formed after 200m excavation along the advancing direction of the working face is 7.49-10.49m, and the height of the fracture zone is 21.84-29.84m. The three zones in the goaf have strong anisotropy. The anisotropy values of the curved subsidence zone, the fracture zone and the collapse zone are 0.15, 0.21 and 0.38, respectively, and the curved subsidence zone has the strongest anisotropy. The connectivity of the three belts is 0.014, 0.055 and 0.233 respectively, and the connectivity of the collapse zone is the best. The fracture rates of the three belts are 1.87%, 6.02% and 23.43%, respectively. The distribution of fractures in different regions of the fracture zone is different. The number of fractures in the range of 0-40m from the incision is the most, and the number of fractures in the range of 80-120m from the incision in the middle area is less than that of the two ends. The fracture rate within 20m at both ends of the working face is 10%-15%, and the fracture rate in the middle area is 8%-10%. Two areas with relatively developed fissures were identified, namely, the lateral distance from the cut 26.7m, the vertical distance from the coal seam floor 40m, the lateral distance from the end of the working face 32.5m, and the coal seam floor vertical 40m. The results can provide a theoretical basis for CBM extraction in mining area and goaf.

Keywords

Mining Area; Goaf; Coalbed Methane; Stress Field; 3DEC; Fracture.

1. Introduction

Long-term and high-intensity coal mining has produced a large number of abandoned mines and abandoned goafs. According to estimates[1,2] at present, the residual coalbed methane resources in my country's coal goafs (abandoned mines) are nearly 500 billion m3, and the coal seams in the goafs Gas has considerable potential for development and utilization, and if it is used reasonably, it can produce huge economic benefits. Fractures are the channels for the occurrence and migration of coalbed methane. Studying the stress of the overlying strata in the goaf and the distribution characteristics of the fissures is of great significance for the optimization of the well location and the extraction of coalbed methane in the goaf of abandoned mines.

With the development of computer technology, numerical simulation methods have been widely used in the analysis of geotechnical engineering problems. Numerical simulation methods can well analyze the distribution characteristics of stress, strain and displacement in the process of underground mining. The simulation software specially used to solve geotechnical engineering problems mainly includes FLAC, PFC, UDEC, 3DEC and so on. FLAC3D is a finite difference program capable of simulating the mechanical properties and plastic flow of 3D structures of soils, rocks and other materials. PFC is an analysis based on the discrete element method mainly used to study the particle body or the system that can be reduced to the particle body, including PFC2D and PFC3D. UDEC[3,4] is a two-dimensional computational analysis program for simulating discontinuous systems based on the discrete element method theory and this software is particularly suitable for simulating the response of jointed rock systems or discontinuous block aggregates under static or dynamic loading conditions. 3DEC is a computational analysis program based on the discrete element method to describe the mechanical behavior of discrete media. It inherits the basic core idea of UDEC and is essentially the result of extending UDEC from two-dimensional to three-dimensional space.

Many researchers use numerical simulation methods based on continuum mechanics, such as finite element method and finite difference method, to study the changes of stress and displacement caused by underground mining. Wang et al. [5] used the FLAC3D software based on the finite difference method to simulate the stress and plastic zone distribution characteristics of the overlying strata. Chao et al. [6] used FLAC3D simulation to analyze the vertical stress distribution and plastic zone of goaf caused by rheology and blasting. Gao et al. [7] used UDEC software to simulate brittle fracture and the consequent roadway failure. Cao and Li[8] used discrete element method UDEC and COMSOL to simulate the distribution of fracture network and gas migration in goaf. Regassa et al. [9] used 3DEC software based on the discrete element method to simulate the rock movement and damage caused by open-pit mining of the Zhanshan Iron Mine. Regassa et al. [9] used 3DEC software based on the discrete element method to simulate the rock movement and damage caused by open-pit mining of the Zhanshan Iron Mine. Ju et al. used the continuum-based discrete element method (CDEM) to simulate the evolution of stress and fracture induced during the excavation and mining of roadways in multi-layer heterogeneous rock formations. Wang et al. used 3DEC software to simulate and analyze the movement law of the overlying strata in the shallow buried coal seam.

Most of the existing studies on the numerical simulation of goafs use the finite element method and the finite difference method. These two methods are mainly based on continuum mechanics and have their limitations in studying the characteristics of fracture distribution. At present, the discrete element method is mostly focused on the numerical simulation of the two-dimensional fracture field, while the research on the simulation of the three-dimensional fracture field based on the discrete element method is far from enough. 3DEC is developed on the basis of the two-dimensional discrete element software UDEC. In terms of geotechnical mechanics, the discrete element method can more realistically express the geometric characteristics of the jointed rock mass, which is convenient for dealing with rock mass failure problems where nonlinear deformation and failure are concentrated on the joint surface, especially the simulation of rock mass movement, separation and caving patterns. 3DEC has strong adaptability, so this paper takes Shanxi Yuecheng Coal Mine as the research object, and uses 3DEC software to study the mining process and the distribution characteristics of the overburden fissure field.

2. Geological Background

Yuecheng Coal Mine is located in the southeast of Qinshui County, at the junction of the eastern and northern districts of the Sihe mining area, and is administratively subordinate to Zhengcun Township,

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Qinshui County. Its landform area is a denuded mountain, dominated by low mountains and hills. The northern boundary of the mine field is the boundary of the large mining height working face planned for the Sihe Mine, the western boundary and the southern boundary are the boundary lines connecting the four local small mines, and the eastern boundary is the boundary of the Chengzhuang Mine. The mine field area is 13.806km2, and the goaf area is about 10.96km2, mainly located in the east of the coal mine. The main mineable coal seam is No. 3 coal, the mine recoverable reserves are 46.082 million tons, the coal seam burial depth is 130~450m, the coal seam thickness is 5.04m-7.16m, the average thickness is 6.11m, and the mineable coal coefficient is 7.11%. The dip angle of the coal seam is 4 to 13 degrees, with an average of 7 degrees. It belongs to the near-horizontal coal seam, and the horizon and thickness are relatively stable. It is an independent peat swamp developed on the basis of the tidal delta front. The mine adopts the inclined shaft development method, adopts the long-wall mining method to mine coal, manages the roof by the caving method, and adopts the fully mechanized excavation method. The roof is mainly mudstone, silty mudstone, siltstone, and partly fine and medium-grained sandstone. The siltstone is mainly developed in the southeast and northwest corner of the mine field, the floor is mainly siltstone and mudstone, and the local part is fine-grained sandstone.

3. Numerical Simulation Method and Model Construction

3.1 Numerical Simulation Method

3DEC is a computational analysis software that describes the mechanical behavior of discrete media based on the discrete element method. The modeling method is joint modeling, and the model block adopts the Moore-Coulomb plastic constitutive model. This model considers that the shear stress causes the material to yield, and the yield stress only depends on the maximum and minimum principal stress, and the intermediate principal stress has no effect. Block parameters include tensile strength, cohesion, friction angle, bulk modulus, shear modulus, and density, among others. The model joint constitutive adopts the joint region contact-Coulomb-slip constitutive model, which simulates the weakening of joint displacement due to the loss of bond strength and tensile strength at the onset of shear or tensile failure. Joint parameters include normal stiffness, tangential stiffness, joint tensile strength, joint cohesion, and joint friction angle. The mesh adopts tetrahedral mesh, which is divided by 3DEC adaptive mesh.

3.2 Numerical Model Construction

Based on the geological data of Yuecheng Coal Mine, a numerical model is established. The model is 300m long, 150m wide, and 120m high. It is divided into 9 layers from bottom to top, and 50m of coal pillars are left on both sides of the working face. A coal pillar of 45m is left laterally, and the model is shown in Figure 1. In 3DEC, displacement boundary conditions cannot directly constrain displacement because displacement does not play a role in the calculation process. The boundary is constrained by the boundary command and the boundary speed is set to be zero. The speed in the x and y directions of the sides of the fixed model is zero, and the speed in the x, y, and z directions of the bottom is fixed to zero. Since the top part that does not reach the ground is 432m, an equivalent load of 6.5MPa is applied to add the z-gravity acceleration in the vertical direction of the top boundary zz to be -9.8m/s2. Based on the actual geological conditions, the stress values in the positive directions of x, y, and z at the model origin are -7.827MPa, -5.358MPa, -8.038MPa, respectively. Gradient stress is set, and the stress changes with depth according to gravity. The average density of the rock formation is 2600kg/ m3. The block parameters and joint surface parameters are shown in Table 1 and Table 2. The model is distributed excavation, the excavation step is 10m, and the excavation is 20 times for a total of 200m. A monitoring line is set in the stratum, and 100 monitoring points are set on one monitoring line, and the monitoring points are spaced at 3m intervals to monitor the changes of stress and displacement after each excavation and calculate the balance.

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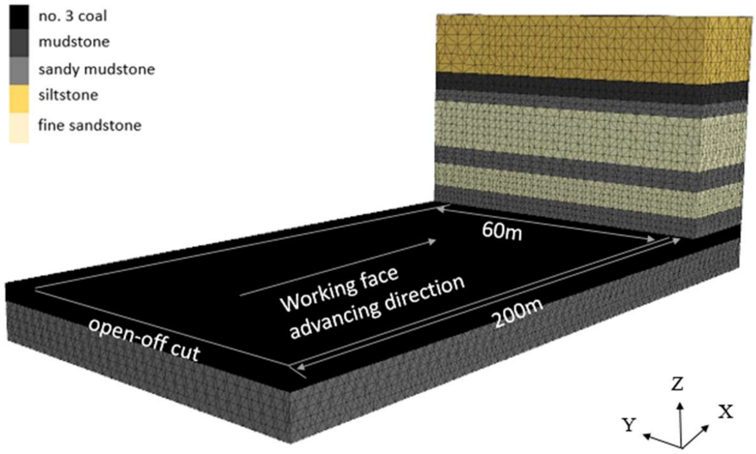

Fig. 1 Schematic diagram of geological model of the study area

Table 1. Model block mechanical parameters

rock formation	thickness (m)	lithology	tensile strength(MPa)	cohesion(MPa)	friction angle (°)	bulk modulus(GPa)	shear modulus(GPa)	natural test weight(kg/m^3)
1	15.0	sandy mudstone	3.0	3.4	36	16.3	10.3	2300
2	6.5	3# coal	0.9	1.5	32	6.6	3.1	1460
3	9.0	sandy mudstone	3.0	3.4	36	16.3	10.3	2300
4	12.0	fine sandstone	4.8	4.3	38	27.9	20.9	2600
5	9.0	sandy mudstone	3.0	3.4	36	16.3	10.3	2300
6	24.0	fine sandstone	4.8	4.3	38	27.9	20.9	2600
7	6.0	sandy mudstone	3.0	3.4	36	16.3	10.3	2300
8	9.0	mudstone	2.6	2.0	35	13.3	8.0	2250
9	29.5	siltstone	3.4	2.25	37	18.6	12.3	2800

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Table 2. Table of mechanical parameters of joints

rock formation	thickness(m)	lithology	normal stiffness(GPa)	tangential stiffness(GPa)	joint tensile strength(MPa)	Joint cohesion(MPa)	joint friction angle(°)
1	15.0	sandy mudstone	5.0	4.0	2.6	3.3	17
2	6.5	3# coal	4.3	4.3	2	2.5	16
3	9.0	sandy mudstone	5.0	6.3	2.6	3.3	17
4	12.0	fine sandstone	5.5	4.6	3.5	3.8	21
5	9.0	sandy mudstone	5.0	4.0	2.6	3.3	17
6	24.0	fine sandstone	5.5	4.6	3.5	3.8	21
7	6.0	sandy mudstone	5.0	4.1	2.6	3.3	17
8	9.0	mudstone	5.1	4.1	2.8	3.4	18
9	29.5	siltstone	5.3	4.3	3.2	3.6	20

4. Analysis and Discussion of Simulation Results

4.1 The Distribution Characteristics of the Fracture Field

In the process of coal mining, two types of cracks are mainly formed in the overlying strata of the goaf, one is the separation layer crack, and the other is the vertical fracture crack. Separation fissures are interlayer fissures that appear between layers, and vertical breaking fissures are interlayer fissures formed with the subsidence and breaking of rock layers.

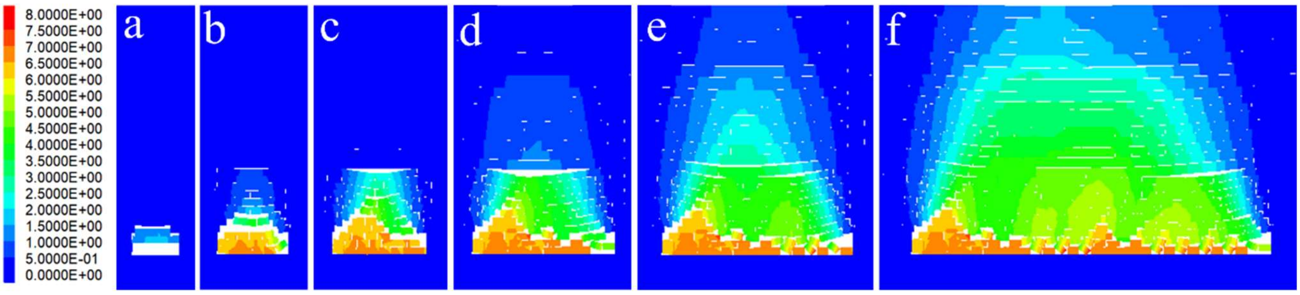

Fig. 2 Displacement field distribution

a excavation 20m; b excavation 30m; b excavation 40m; d excavation 60m;e excavation 80m; f excavation 150m

In the process of coal seam mining, the overlying strata move and break, and the displacement field is shown in Figure 2. With the increase of the overhang area of the direct roof, when the working face advances by 20m, the direct roof settles and the displacement is up to 1.25m, but it does not completely collapse. When the coal seam was excavated for 30m, the direct roof collapsed in a large area and contacted the bottom plate. By reducing the excavation step distance to 5m/time, the coal seam began to collapse when the coal seam was excavated at 25m, and it was judged that the initial pressure step was about 25m. Through the analysis, it can be concluded that the displacement of each monitoring line is relatively close and large when the distance is less than 25m, and it is judged that

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the step distance of the initial pressure is about 25m. When the coal seam was excavated for 40m, there were separation cracks (maximum length 34.45m, maximum height 1.92m) at 35m above the coal seam floor; vertical cracks appeared at 46.7m above the coal seam. When the coal seam is excavated for 60m, the bed separation cracks at the upper 29m will increase with the advancement of the working face. The maximum length of the lateral bed separation cracks is 53.9m, the highest is 2.88m, and the horizontal distribution range of the transverse cracks is up to 67m. When the coal seam was excavated for 80m, the main key layer initially collapsed, and along with the collapse of the main key layer, the development of lateral separation fractures surged, and the maximum height reached 80m above the coal seam floor. Moreover, the layer separation fissures at 80m above are more developed than other positions. The layer separation fissures here are 46.8m long, 0.66m in height, and 91m in vertical fissures. When the coal seam is excavated for 200m, the maximum separation crack occurs at 168m away from the incision hole, and the maximum height of the crack is 1.86m; At 0-149.6m from the incision hole, the layer-separated fissures are closed as the excavation progresses, and the height is between 0-0.45m and the middle area below the main key layer has less fissures developed due to compaction. When the working face is advanced to a certain distance, a typical "O" ring characteristic appears in the horizontal direction above the goaf. The displacement in the middle area is large, which is the compaction area, and the surrounding rectangular area with rounded corners is the fracture area. The failure of the overlying rock in the vertical direction presents a saddle shape, and the failure range decreases with the increase of the vertical direction, which is not a linear relationship, but the degree of reduction increases. Before the main key layer is broken for the first time, the amount of layer separation in the goaf increases with the advancement of the working face, and the maximum layer separation is located in the middle of the goaf. With the rupture of the main key layer, the middle of the main key layer, namely the No. 6 rock layer, tends to be compacted, and there is still a separation zone at both ends. However, the separation zone on one side of the advancing direction of the working face moves forward as the excavation progresses. The maximum height of the separation zone before the initial break of the main key layer is 2.8m, and after the break, the maximum height of the separation zone decreases with the advancement of the working face, and the maximum height is 1.86m. The fractures are mainly distributed at both ends of the goaf in the strike of the working face. The left range is 26.7m long and 40m high, and the right range is 32.5m long and 40m high. The fractures on the side of the gob in the advancing direction of the fissure face are more developed than the opening.

The overlying strata of the goaf are divided into three zones. When excavating 200m, According to the caving characteristics of the overlying strata, the caving zone and the fissure zone are divided. The height of the caving zone is between 8.37-11.22m; the height of the fissure zone is between 27.89-29.63m.

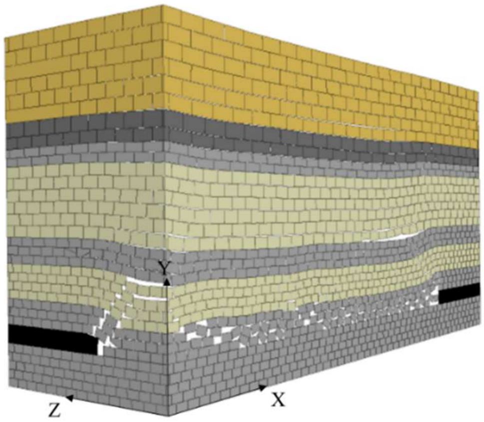

Fig. 3 Three-dimensional fracture model

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The three-dimensional distribution characteristics of cracks were studied, and 1500 slices obtained by slicing the model after 3DEC simulation excavation were imported into AVIZO software, and processed through image cropping, grayscale adjustment, filtering, threshold segmentation, and three-dimensional reconstruction. The 3D model of the gob fissure is obtained, and the 3D fissure model is shown in Figure 3. Statistics of the fracture parameters in different regions of the 3D fracture model, including the number of fractures, average opening, surface area, volume, fracture degree, anisotropy, specific surface area and connectivity.

Table 3. Three zone fracture parameters

		Number of bars (bars)	average opening(m)	total capacity(m3)	total surface area(m2)	specific surface area(m2/m3)	fissure rate(%)	anisotropy	connectivity
curved sinker zone	Lateral fissure	192	6.03	14573.87	105556.81	7.24	1.87	0.15	0.014
	vertical fissure	29	1.11	56.57	442.79	0.13			
fissure zone	Lateral fissure	511	5.21	20185.78	113691.46	5.63	6.02	0.21	0.055
	Lateral fissure	109	4.24	1487.42	5125.44	3.44			
caving zone	Lateral fissure	411	4.45	21888.25	53353.49	2.44	23.43	0.38	0.233
	vertical fissure	157	4.06	6224.94	15932.02	2.56			

The research on fracture volume and fracture average opening is carried out by region. In the horizontal direction, the study area is the caving zone and the fissure zone, ranging from the coal seam floor to 40m above it, and is divided into 20 sections every 10m from the opening of the incision.. It can be seen from the figure that the volume of the cracks at both ends of the working face is significantly larger than that in the middle area; The fracture degree within 20m from both ends is 10%-15%, the fracture degree in the middle area is 8%-10%, and the fracture degree at both ends of the working face is larger than that in the middle area, which is the reason for the strong compaction effect in the middle area. From the bottom of the coal seam to the top every 10m, it is counted every 10m in the vertical direction. It is divided into 19 sections starting from the bottom of the coal seam, each section is 5m, to 95m above the bottom of the coal seam. It can be seen from the figure that in the 0-5m and 5-10m sections of the coal seam roof, the fracture volume is more than 13500m3, and in the six sections of 10m-55m, the fracture volume is 2100-8400m3. In other areas, except for the 90-95m area, the fracture volume is 344-1800m3 range. Therefore, according to the fracture volume, it can be vertically divided into three orders of magnitude: 0-10m, 10m-40m, 40m and above from the coal seam floor. From the above, it can be concluded that within the range of 20m at both ends of the advancing direction of the working face, the vertical height of the fracture is most developed within the range of 0-40m from the coal seam floor. Therefore, it is best to extract coalbed methane here.

The fracture connectivity and fracture anisotropy of the three zones were studied respectively. The ratio of vertical fissures to transverse fissures in the overall caving zone of the three belts is 0.38, the ratio of caving zones is 0.43, the ratio of fissure zones is 0.48, and the ratio of bending subsidence zones is 0.28. The ratio of the bending subsidence zone is the lowest, the anisotropy is the strongest, and the anisotropy of the fracture zone is the weakest.. It can be seen that the number of fissures at

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the opening of the incision is the largest in the fissure zone, and the number of 141 fissures within the range of 80-120 m from the incision in the middle area is less than the number of fissures at both ends of the working face. In terms of connectivity, the three-dimensional connectivity evaluation formula is used for evaluation, and the evaluation formula is:

$$C = \frac{v'}{v} \tag{1}$$

C is the connectivity, v' is the volume of connected fractures, and v is the total volume of the study area.

After calculation, it is concluded that the connectivity of cavitation zone, fissure zone and bending subsidence zone are 0.233, 0.055 and 0.014 respectively. Among the three zones, the connectivity of cavitation zone is the best, and the connectivity of bending subsidence zone is the worst. In terms of fracture degree, the fracture degree of the cavitation zone is 23.43%, the fracture degree of the fracture zone is 6.02%, and the fracture degree of the bending subsidence zone is 1.87%. It can be seen that among the three belts, the fracture degree of the caving zone is the largest, and the fracture degree of the bending subsidence zone is the smallest. Anisotropy is represented by the ratio of vertical cracks to transverse cracks. The cavitation zone, fissure zone, and bending subsidence zone are 0.38, 0.21, and 0.15, respectively. According to the number of horizontal and vertical fractures in the three belts in Table 3, it can be seen that the anisotropy of the bending subsidence zone is the strongest, followed by the fracture zone and the fractures in the caving zone are the most developed, and the fractures in the curved subsidence zone are the least developed.

5. Conclusion

Based on the geological conditions of Yuecheng coal mine mining, a 3DEC geological model of the Yuecheng coal mine mining area was established, which revealed the coal seam mining process and the overburden damage characteristics after mining. It is obtained that the height of the caving zone is 8.37-11.22m, and the fissure zone is 27.89-29.63m, which is in good agreement with the theoretical calculation results.

The three zones in the goaf have strong anisotropy, The anisotropy values of the caving zone, fissure zone and bending subsidence zone are 0.38, 0.21 and 0.15, respectively. The bending subsidence zone has the strongest anisotropy, with connectivity of 0.233, 0.055, and 0.014, respectively, and the cavitation zone has the best connectivity, with the three-zone fissure ratios of 23.43%, 6.02%, and 1.87%, respectively. Combined with the size of the three-zone area, it can be seen that the cavitation zone has the most developed fractures, and the curved subsidence zone is the least developed. There are 179 cracks in the range of 0-40m at the opening of the caving zone, and 141 cracks in the range of 80-120m in the middle area of the working face are less than the number of cracks at both ends.

Through the comparative study of various parameters of fractures in different regions, it is concluded that the fractures are most developed within the range of 0-40m above the coal seam floor in the vertical direction and within 20m at both ends of the working face in the horizontal direction.

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