Numerical Simulation Study on Height Evolution Laws of Overlying Gas Flow Paths with Discrete Element Method

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Abstract—In order to study height of overlying gas flow paths of a certain mine, Shanxi province, China, this paper studied the formation mechanism of overlying fractures induced by mining operation with the method of material mechanics, and the optimization arrangement of high-located borehole in working face through discrete element simulation software-UDEC and field gas extraction monitoring. The results showed that: the key stratum has controlling effects on the evolution of mining induced fractures, which depend on the development level of vertical fractures in the stratum. Instead of linearly develop, the height of mining induced fractures behaves a leaping develop with the advancing process of working face, and the height of development relates to the controlling height of the key stratum. The optimization height of borehole gas extraction is located in the third key stratum of roof, namely with 43-51m position in the roof.

Keywords-gas flow path; mining induced fracture; gas extraction; key strata; discrete element method

I. INTRODUCTION

Security problem of coal mine gas has become one of the important problem of coal mine safety production. In 2014 47 gas explosions in Chinese coalmine had killed 266 workers, death toll of significant gas accident accounted for 70.7% of major accidents happened in our country [1]. One of the effective measures to decrease gas accidents is to arrange gas extraction systems reasonably, thus contribute to optimize energy structure and increase resource utilization.

Overlying fractures, induced by mining operation, are the main paths for gas migration [2-3], therefore, studies on laws and distribution of mining induced fractures should be a priority for arranging reasonable gas extraction systems, and also has the great significance in decreasing gas accidents.

II. EVOLUTION MECHANISM OF MINING INDUCED FRACTURES

Rock in hypogynous overlying strata broken completely, falls and fills the goaf after coal mining, however this situation usually does not occur in upper strata but rotation and deformation instead, which lead to two types of typical fractures.

The first one is bed-separated fractures, because there are differences on properties of each overlying strata which result in different sagging deformation when rotation and deformation happens, namely incompatibility caused by strata subsidence that lead to bed-separated fractures among strata and provide flowing space for gas desorption. The conditions of incompatibility sagging are shown in equation (1) [5, 6].

$$y_i = \frac{q_i L^4{}_i}{32 E_i h_i{}^3}, \; y_{i-1} > y_i \tag{1}$$

Where hi denotes thickness of i stratum; qi denotes permissible stress of i stratum; yi denotes deflection of i stratum; Ei denotes elastic modulus of i stratum; Li denotes span of i stratum.

The second type of fracture is vertical and broken fractures. When span length of strata reaches a certain degree, that is rotations and deformations develop to a certain degree, vertical fractures will appear in strata. If they run through all strata and connect upper bed-separated fractures to the lower, the paths that can make gas move up and down form. The span length that lead to strata fracturing is shown in (2) [4, 5].

$$[L_i] = 2h_i \sqrt{\frac{\sigma_i}{3q_i}}, \; L_i > [L_i] \tag{2}$$

Where [Li] denotes ultimate span of i stratum; σi denotes uniaxial tensile strength of i stratum.

The paths composed of holes and fractures more than 10-1mm in diameter are sections that mixture of relieved gas with laminar and turbulent flow permeate. The sections are migration and accumulation paths for relieved gas [6]. Therefore, these fractures around rock mass under mining are called flowing paths of gas.

III. NUMERICAL SIMULATION WITH UDEC

A. Geological overview of panel 4314

Working face 4314 being mined in the mine belongs to coal seam 3# with average buried depth of 560 m, variation coefficient of seam thickness is relatively small. Thickness of coal seam is 4.60-6.35m, an average of 5.91m with stable distribution in the whole region. Coal seam 3# is a high gas mine with a relative gas burst quantity of 6.77 m^3/t, absolute gas gushing quantity of 61.45m^3/min, coal dust is unexplosive. Roof lithology is shown in Fig. 1.

Based on the key strata theory [7,8], key strata play a very important role in the process of overlying strata movement. Therefore, it also has important function in the forming process of gas flow paths [9,10]. Thus, according to characteristics of inconsistent deformation between key strata and lower layer, key strata carry their own loads. Analysis and calculation has been done on overlying key strata, they must meet the formula (3) [11].

$$q_{n+1} < q_n \tag{3}$$

Where q_{n+1}, q_n denotes load of n+1 stratum and n stratum respectively.

Meanwhile, the key strata must meet strength conditions shown in equation (4) [11], which is interval of roofing breaking of lower hard stratum must be smaller than the upper stratum.

$$l_i < l_{i+1} \tag{4}$$

Where l_i, l_{i+1} denotes interval of roofing breaking of i stratum and i+1 stratum respectively.

According with the geological column of mine with the above equations of key strata and inputting data, the result showed that there are 3 key strata in the mine located at 8.0m, 28.9m and 43.2m above coal seam, respectively.

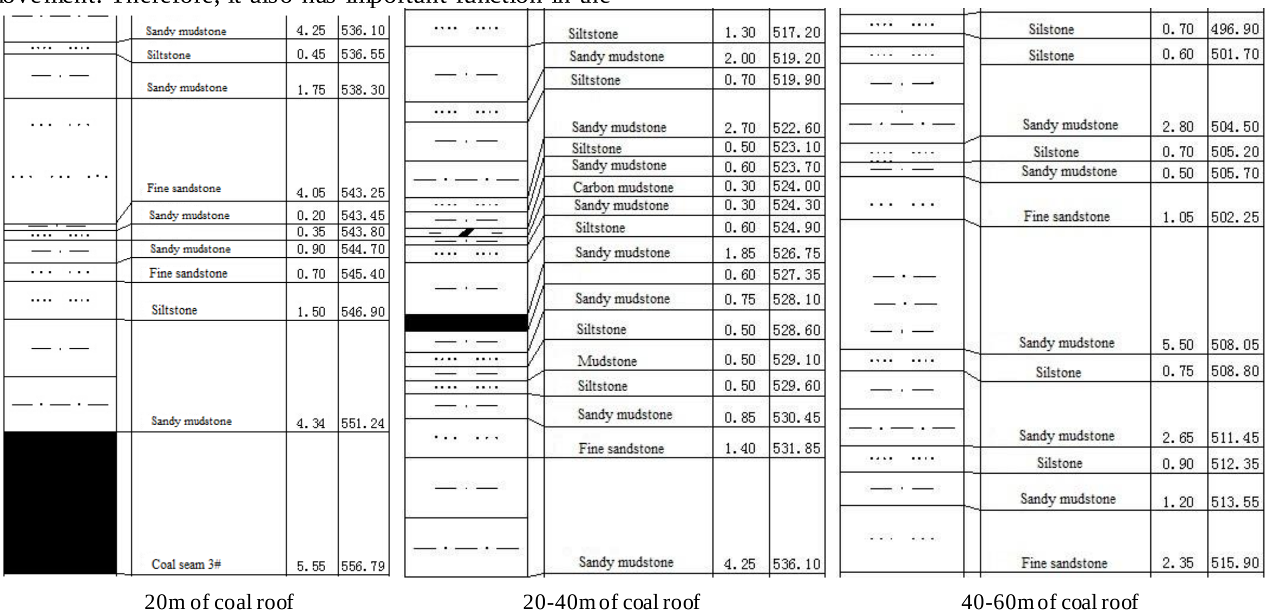


Figure 1. Geological column

B. Numerical model

According to the geology data from the mine, the two-dimensional UDEC numerical model is built along with the advancing direction of working face. In order to simplify the model, the strata with the similar lithology and small thickness are combined. To better study the function of key stratum on overlying fractures induced by mining operation, the relatively weak rock layers between the direct roof of coal seam and the key stratum in overlying rock employ the Voronoi block type joint generator to create random joints. Other rock layers and key stratum used Jet joint generator to create rectangle joints. This model has a length of 200m and a height of 106m. The overlying load condition is simulated by employing a vertical of 12.1MPa to the top of the model. Constitutive model of Mohr-Coulomb is used for all rock layers. .The UDEC numerical model and the physical mechanics parameters used in simulation was showed as Fig. 2 and Table I.

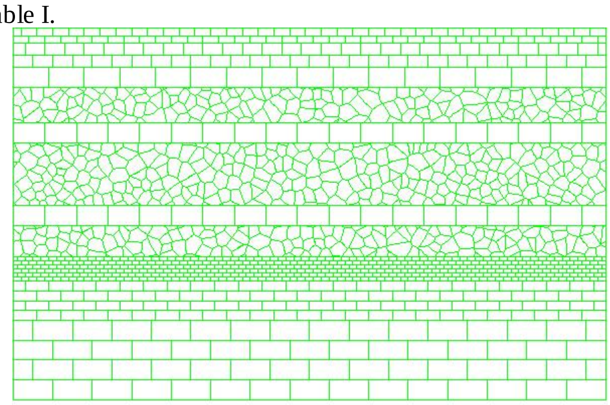


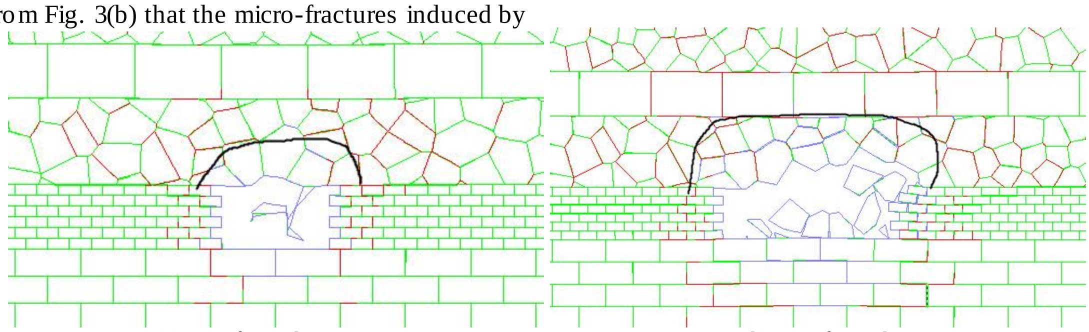
Figure 2. Diagram of numerical model

TABLE I. PHYSICAL AND MECHANICAL PARAMETERS OF ROCK

Lithology	Density ρ/(Kg/m^3)	Bulk modulus B/GPa	Shear modulus S/GPa	Internal friction angle φ/(∘)	Cohesion C/MPa	Tensile Strength σ_t/MPa
sandy mudstone	2500	5.8	5.4	29	5.2	3.8
fine sandstone	2500	7.6	7.1	34	4.2	5.2
coal	2400	2.1	1.7	28	2.0	1.8
mudstone	2500	6.7	6.5	25	3.0	5.6
siltstone	2500	7.2	6.4	29	4.2	6.2

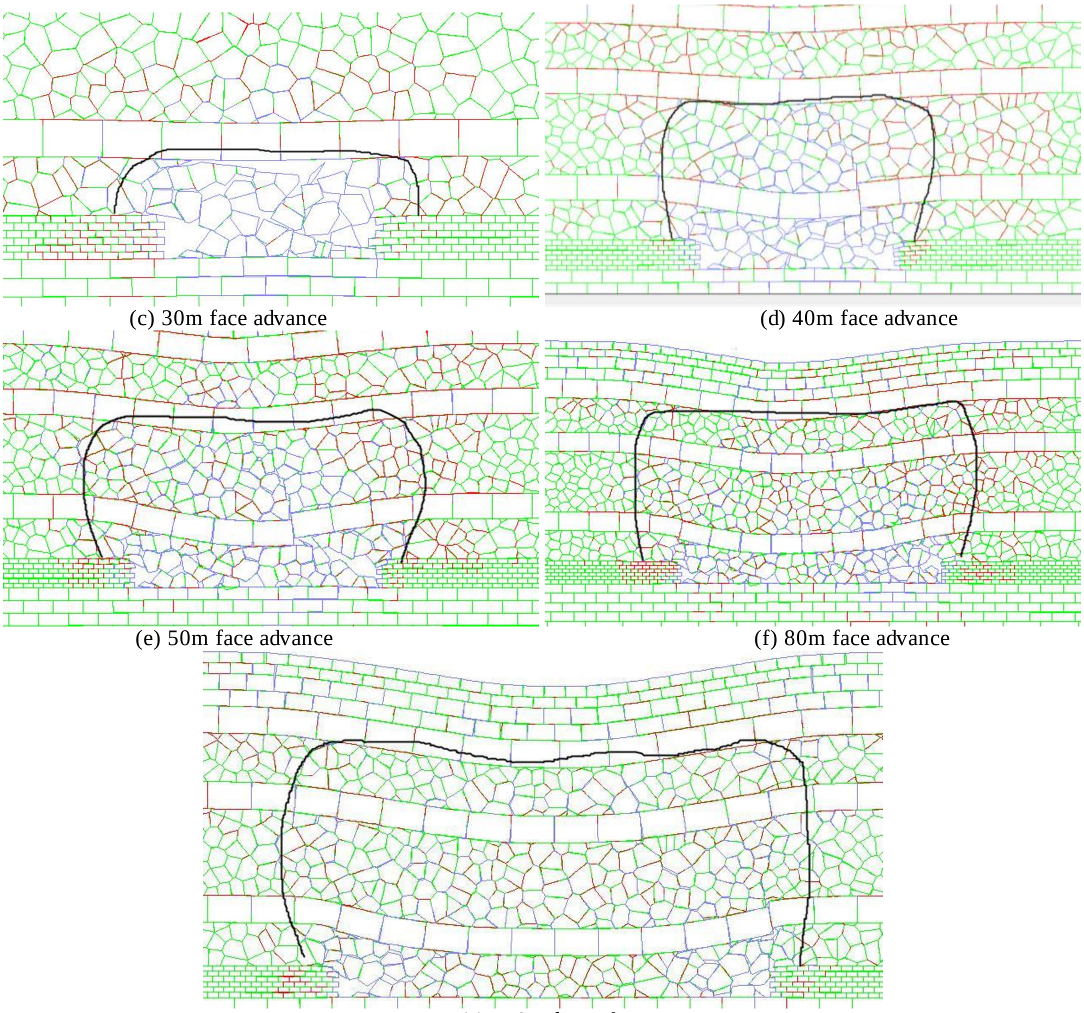
C. Simulation results and analysis

1) Fractures evolution laws with mining process: During the process of simulation, the blue represented the fractures induced by mining operation with a diameter larger than 10^{-1}mm. The flow state of gasgas in this type of fracture mainly is the mixture of laminar and turbulence, called macro-fractures induced by mining operation. The red reflected the fractures induced by mining operation with a diameter less than 10-1mm. The flow state of gas in this type of fracture mainly is seepage, called micro-fractures induced by mining operation. The height of macro-fractures induced by mining operation, namely the flow path of gas, was marked by black line.In order to eliminate the influence of boundary effect, the boundary of 40m is reserved in one side of the model. Excavation starts at 40m position in one side of the model, excavation advancing 5m each step, 110m in all. In the process of advancing the work face, the horizontal monitoring lines are set in the three key strata monitor the vertical displacement within 5m back and forth in the corresponding working face of key strata. Representative figures are selected from the results shown in Fig. 3. It can be seen from Fig. 3(a) that the direct roof collapsed partly at that time, but the first key stratum has not collapsed. The first key stratum has only micro-vertical crack growth, without macro-vertical crack growth. The Micro-fractures induced by mining operation, namely the gas flow path, developed at the height of the first key stratum. Meanwhile, the height of the Micro-fractures induced by mining operation, namely the gas flow path, is 4.2m.It can be seen from Fig. 3(b) that the micro-fractures induced by mining operation have developed to the first key stratum but not went through the entire key strata. Therefore, the height of the gas flow path is 8.0m. It can be seen from Fig. 3(c) that the macro-fractures induced by mining operation still have not gone through the first key stratum. So, the height of the gas is still at the position of first key stratum, namely the 8.0m. It can be seen from Fig. 3(d) that the first key stratum broke obviously. The macro-fractures already went through the first key stratum, and evolved to the second key stratum but not went through. The gas flow path ended at the second key stratum, namely the 28.9m. It can be seen from Fig. 3(e) that the evolution of macro-vertical fractures still ended at the second key stratum but not went through. The height of the gas flow path is still 28.9m.It can be seen from Fig. 3(f) that the macro-vertical fractures went through the whole rock layer. The evolution of gas flow path broke through the second key stratum, and reached at the third key stratum but not went through. The height of the gas flow path is 43.2m. It can be seen from Fig. 3(g) that vertical fractures still don't go through the third key stratum. The evolution of gas flow path ended at the third key stratum and the shape of gas flow path is saddle. The height is 43.2m. After that, the evolution height of macro-fractures induced by mining operation is almost unchangeable. So, the gas flow path is stable. For the convenience, the value of the above analysis adopted the lower boundary height of the key stratum. In fact, the height of the gas flow path should also take account with the height of the vertical macro-fractures in the key strata.



(a) 10m face advance

(b) 20m face advance



(c) 30m face advance (d) 40m face advance

(e) 50m face advance (f) 80m face advance

(g) 110m face advance

Figure 3. Fracture distribution in face advance

2) Effect of key stratum in fracture evolution: A graph showing the height of the gas flow path changes with the advance of working face is shown in Fig. 4, the conclusions from the diagram show that the height of the gas flow path increases with the advancing of the work face before the height reaching the first key layer, and it presents linear growth; when the height of the gas flow path reaches the first key stratum, the height stabilizes around the first key stratum for a period of time, and increase to the second key stratum suddenly, then stabilizes around the second key stratum; the same change occurs in the second key stratum until the third key stratum. The height of the gas flow path does not increase linearly with advancing of working face, its development is controlled by the key stratum. The ability that vertical macro fractures in key layer run through the whole key strata is the control function. After the expansion of the mining-induced fracture breakthrough key stratum, the height of gas flow path suddenly increases to its upper key stratum. Before vertical macro fractures are linked up in the upper key stratum, the height of gas flow path remains at the position of key stratum with the working face advancing. As working face advance to a certain degree, the height of overlying fractures no longer changes, the scope of the mining-induced fractures presents a distribution like a "saddle".

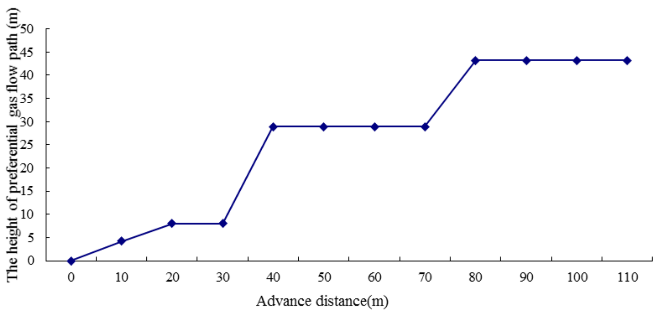


Figure 4. The development of the gas flow path with the advancing of working face

IV. Design of Borehole Drilling and Effect of Gas Extraction

A. Design of borehole drilling

There are four directional high holes designed in 8# chamber across the drilling filed, and the hole depth is not less than 400m, which is in order to test the borehole extraction effect different locations of face and different horizons of roof.

There are four holes in the design(1#, 2#, 3#, 4#), the effective periods are 55.5m, 43.5m, 31.5m, 19.5m from the 4314 the return airflow roadway respectively. The drilling horizontal interval are 12m. And effective period of 1# is 59m from the coal seam roof, which is equivalent to the top interface of K8 sandstone (the 3th key layer), while 2# is 44-51m from coal seam roof, which oblique crossing the K8 sandstone, then 3# is 43m, namely the bottom interface of K8 sandstone, and 4# is 32m.

B. *Effect of gas extraction*

The gas extraction data in January 2015 is obtained by collecting the extraction data of directional high holes in 8# chamber of 3414 face. Sorting gas extraction data, the daily gas extraction concentration is gained at last as shown in Fig. 5

Because of the data lack of 11th, the data statistical analysis of the rest date of January was conducted only. From the Fig. 3.5, we can see the concentration of the gas extraction was small in general before 11th, it mostly was less than 10%, the gas extraction concentration of 12th reached the maximum, which was 18.6%, during the 12th to 23rd, the gas extraction concentration has a tendency to gradually reduce, after 23th, the gas extraction concentration was in a relatively stable range, which was about 14%.

In order to study the best position of gas extraction, the author collected and analyzed the gas extraction data of each borehole. Due to the gas extraction concentration started into the relatively stable period after 23th, the gas concentration contrast was developed among the 1-4# during these days, as you can see from Fig. 6, the change trend of the gas extraction concentration in four gas drilling was the same basically, the concentration of the four holes was basically two separate trends, the gas extraction concentration of 2# and 3# were interaction, so were the 1# and 4#. The gas extraction concentration of 2# and 3# is higher than 1# and 4#, therefore, the best position of gas extraction is the position of 2# and 3#, namely the position is 43-51m far from the roof of K8 sandstone, and it is also the third key layer, which is agreement with the numerical simulation results.

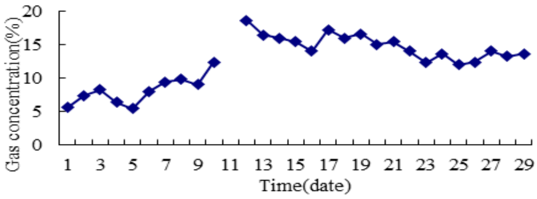


Figure 5. Gas concentration of borehole 8# across gob in January

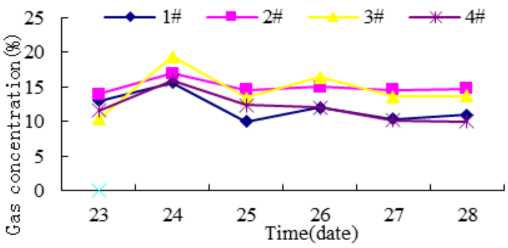


Figure 6. Gas concentration of borehole 1-4#

V. CONCLUSIONS

The coordination of sagging amount and span length of coal seam are the crucial factor for the formation of overlying fractures induced by mining operation, and also the condition of flowing paths for gas. Through the study on development laws of flowing paths for gas, the results showed that key strata had definite control effect on the development of flowing paths for gas which depends on the ability that vertical fractures run through key strata. The optimization height of borehole gas extraction locates in the third key strata of roof plate, the calculated results basically tally with field test data.

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REFERENCES

[1] G. X. Jing. "Law of coal-gas mining accidents in China from2008 to 2013," Journal of Safety and Environment, vol. 14, Oct. 2014, pp.353-356, doi:10.13637/j.issn.1009-6094.2014.05.077.

[2] Y. J. Zhang, G. M. Yu, S. B. Lu, L. Li, D. F. Yang. "Numerical analysis of gas flow law with short distance upper protective layer gas extraction," Rock and Soil Mechanics, vol.31, Aug. 2010, pp.398-404.

[3] H. W. Zhou, T. Zhang, D. J. Xue, J. H. Xue. "Evolution of mining-induced crack network in overburden strata of longwall face," Journal of China Coal Society, vol.36, Dec. 2011, pp.1957-1962, doi:10.13225/j.cnki.jccs.2011.12.004.

[4] H. T. Liu, N. J. Ma, J. Li, W. P. Zhang, S. S. Ping. "Evolution and distribution characteristics of roof shallow fissure channel," Journal of China Coal Society, vol. 37, Sep. 2012, pp.1451-1455, doi:10.13225/j.cnki.jccs.2012.09.012.

[5] Y. Zhang, L, F, Xu, K. M. Liu, Y. J. Li, B. Zhang, W. B. Li. "Formation mechanism and evolution laws of gas flow channel in mining coal and rock," Journal of China Coal Society, vol. 37, Sep. 2012, pp.1444-1450,doi:10.13225/j.cnki.jccs.2012.09.011.

[6] H. Y. Liu, Y. P. Cheng, H. D. Chen, S. L. Kong, C. Xu. "Characteristics of mining gas channel and gas flow properties of overlying stratum in high intensity mining," Journal of China Coal Society, vol. 37, Sep. 2012, pp.1437-1443, doi:10.13225/j.cnki.jccs.2012.09.010.

[7] J. L. Xu, M. G. Qian. "Study on the influence of key strata movement on subsidence," Journal of China Coal Society, vol. 25, Apr. 2000, pp.122-126, doi:10.13225/j.cnki.jccs.2000.02.003.

[8] M. G. Qian, X. X. Miao, J. L. Xu. "Theoretical study of key stratum in ground control," Journal of China Coal Society, vol. 21, Jun. 1996, pp.2-7,doi:10.13225/j.cnki.jccs.1996.03.001.

[9] R. L. Wu. "Effects of key stratum on the scope of the 'three zones' of gas pressure relief and migration in coal seam group mining," Journal of China Coal Society, vol. 38, Jun, 2013, pp.924-929, doi:10.13225/j.cnki.jccs.2013.06.027.

[10] Q. D. Qu, J. L. Xu, M. G. Qian. "Study on influences of key strata movement on gas emissions of adjacent layers," Chinese Journal of Rock Mechanics and Engineering, vol. 26, Jul. 2007, pp.1478-148.

[11] M. G. Qian. "Ground pressure and strata control," Xuzhou: China University of Mining and Technology press, 2010.