Simulation and Experimental Validation of Mining Induced Bed Separation of Overlying Strata with Realistic Failure Process Analysis （RFPA）*

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Abstract

In the mining process of underground coal, the bed separation of overlying strata is inevitable. The developing process of the bed separation has an important influence on mining subsidence. It is very significant to study the developing regular patterns of the bed separation for understanding and perfecting the mining subsidence theory further. In this paper, Realistic Failure Process Analysis (RFPA) is used to research the distributing patterns of mining induced bed separation of overlying strata. The strata are sedimentary coal strata. And the similar material simulation experiments are used to test the results. The study shows that the growing height of bed separation is increasing as the advance of working face. At the beginning of coal mining, the height of bed separation increases slowly. As the distance of advance increases, the growing rate of separation height becomes faster gradually. After the working face advances a certain length, the growing rate of separation height decreases and closes to zero. After arrive a limit height, the growing height of bed separation will not increase after arriving a limit height. At last, the bed separation will distribute in a range of trapezoid with a 60 degree bottom angle above the goaf.

Keywords: Rock Fracture, Computation Method,Coal Mining,Bed Separation,Developing Regular Pattern.

Introduction

As deeply researched the theory of mining subsidence, people have realized that there is a bed separation phenomenon in the mining induced damage process of overlying strata. Many scholars have discussed the existence, forming cause, growing process, distributing patterns of the mining induced bed separation in the overlying strata with different method. They have also researched all kinds of factors influencing the development of bed separation. Germany scholar, H.Kratzsch, introduced the bed separation phenomenon in his book of “Mining Damage and Protection”[1]. In 1984, based on the pressure arch theory, American scholar S.S Peng explained the unload state of direct roof of coal seam and the bed separation phenomenon[2]. In 1986, based on many similar material simulation experiments, Chinese scholar, Zhao Deshen, researched the distribution regular patterns of bed separation and put forward the ‘Arch Beam Balance Theory’ of mining induced bed separation in the overlying strata. In this theory, the mechanics structure of bed separation in the overlying strata is defined in macroscopic view[3]. In 1990, Russian scholar, В.Л.Самарин [4], invested the cause of bed separating, place of bed separation and related factors of influencing bed separating in the fracture zone, etc. In 2011, Chinese scholar, Dai Huayang, researched the distribution discipline of rock fractures after coal mining with numerical simulation and probability integral method. And the distribution of bed separation in the overlying strata in the process of mining is determined [5].

In summary, for the question of mining induced bed separation, scholars have got a lot of research results. But, as a nonlinear damage phenomenon, the growing of bed separation in the overlying strata has a certain space complexity [6]. From begin to finish, the bed separation is changing with time. Because the rock layer properties and places are different, the change rates are different in the whole growing process of bed separating. To the questions of different growing rate and spatial variations in the mining process, more work will be done in the future.

So, in this paper, Realistic Failure Process Analysis (RFPA) is used to discover the mechanics mechanism of mining induced bed separating and different growing rate in the overlying strata which are sedimentary coal strata and to research the time and spatial distribution patterns of bed separations. Furthermore, the relationship between the distribution patterns and mining subsidence is studied. The research results about mining induced bed separation will be applied perfectly to control the mining subsidence.

Introduction of Realistic Failure Process Analysis (RFPA)

In 1995, based on the algorithm idea of basic theory of finite element and new material damage process, professor Tang Chun'an put forward the new numerical simulation method 'RFPA' (Realistic Failure Process Analysis). He fully considers the nonlinear, non-uniformity and anisotropy characters in the rupture process of rock or concrete. This theory which is based on the finite element and statistics damage theories is used to analyze the rock rupture process with elastic damage theory and amended Coulomb failure criterion.

The basic principle of RFPA is to discrete the material into a large number primitives their mechanics properties are supposed to obey some statistical distribution. Then the stress and strain state of the material can be got with responding solve methods. Through analyzing the phrases of these primitives and with related failure criterions and damage principles, the material rupture process can be clear [7].

The functions of RFPA are following: (1) To simulate the rock rupture process. Especially to study the influence of the local damage induced stress re-distribution to further deformation and damage process. (2) To simulate the acoustic emission in the process of rock rupture in order to invest the omens of the rock failure and the relationship between the frequency of acoustic emission and the magnitude. (3)Consider the non-uniformity distribution of material mechanics parameters (strengths, elastic models), the nonlinear deformation of rock can be tested basically through all kinds of statistical functions in the software, such as Weibull distribution and normal distribution. (4)Micro faults and macro fault such as joints and fractures can be simulated. (5)Damage process induced by loading and failure process induced by weight can be simulated. (6)To simulate the tunnel digging process, mining subsidence and coal seam roof falling, etc. [8]

Simulation Design of mining induced bed separation with RFPA

The simulation background is the sedimentary coal strata. The time-space distribution laws of bed separation in the mining process are tested in this part.

Mining Geological Conditions

The mechanics parameters of rock in the strata and the geological conditions used in the numerical simulation are in the Table 1. And considering the difference of mechanics parameters of different layers and the change of mechanics parameters of rock in the falling zone, weak planes are set between two different planes. The parameters of these planes are in the Table 2.

Table 1. Rock Mechanics Parameters of the Model

Layer	Elastic Modulus */MPa*	Compressive strength */MPa*	Bulk Density */(KN/m^3)*	Angle of internal friction /(°)	Poisson's ratio	Thickness */m*
Sandstone	6000	60	26.5	30	0.25	30
Fine Sandstone	4000	55	25.5	35	0.30	42
Sand-shale	1500	30	25.0	37	0.30	8
coal	1000	20	14.0	38	0.35	4
Floor sandstone	10000	100	28.0	30	0.25	16

Table 2. Mechanics Parameters of Weak Planes

Elastic Modulus */MPa*	Compressive Strength */MPa*	Bulk Density */(KN/m^3)*	Poisson's ratio
500	10	20.0	0.25

Numerical Mode

The mechanics parameters of rock in the strata and the geological conditions used in the numerical simulation are in the Table 1. And considering the difference of mechanics parameters of different layers and the change of mechanics parameters of rock in the falling zone, weak planes are set between two different planes. The parameters of these planes are in the Table 2.

A two-dimensional model of RFPA is made. Its length is 190*m*, height 100*m*. There are 200 horizontal split lines and 100 vertical split lines to make 20000 units. According to the geological conditions of prototype strata, the depth of coal seam is 80*m* and the thickness of coal seam is 4*m*. The load is strata weight. Five steps are set to simulate the mining process. Every step of digging is 10m. The mining width is 50*m*. It is 70*m* from the cup open to the left side of model. Figure 1 shows the numerical model.

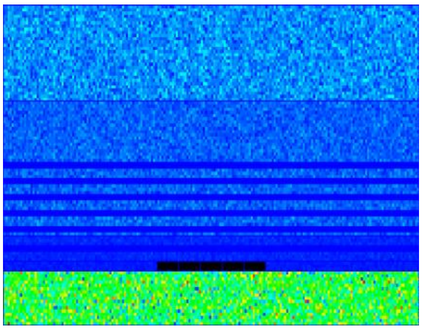

Fig. 1 Numerical model

Results analysis of RFPA

Five steps are simulated in the model, every step is 10m. From figure 2 to figure 6 are the simulating results of bed separating process in the overlying strata.

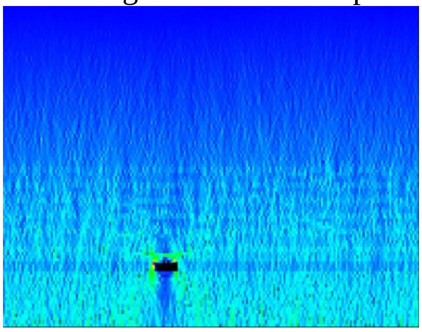

Fig.2 Develop state (10*m*)

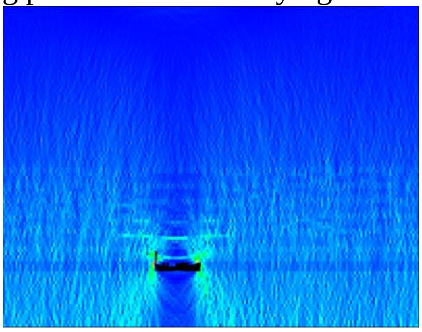

Fig.3 Bed Separation State (20*m*)

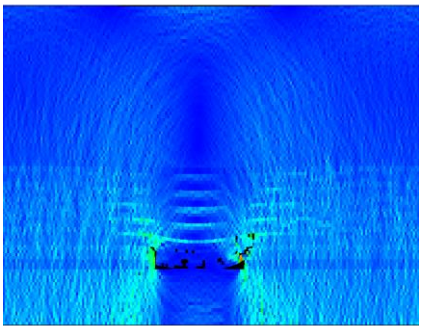

Figure 4. Bed Separation State(30*m*)

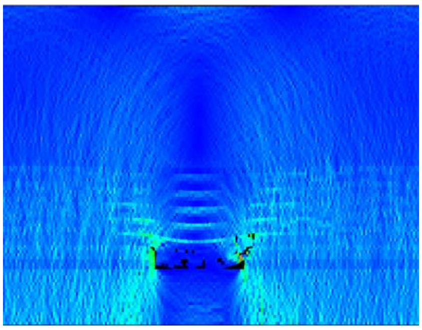

Fig.5 Bed Separation State (40*m*)

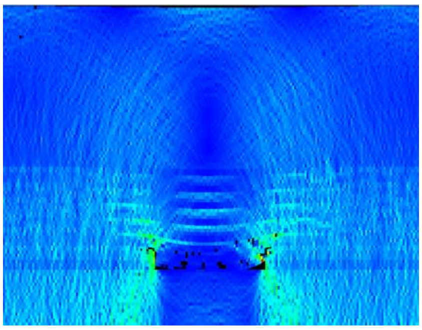

Fig.6 Bed Separation State (50*m*)

Analyzing figures from 2 to 6 shows that the plate girder structure of seam roof bends under the vertical load applied by overlying strata and weight when work face advanced 10*m*. When the face moves 20*m*, bed separation will appear in overlying strata as the range increase of naked roof and increasing bend of layers. The most growing height is 8.03*m* in this digging step. When the work face moves 30m, the most growing height of bed separation is 12.7*m*. When moving 40*m*, the height is 21.9*m*. When moving 50*m*, the height is 26.6*m*. The distribution zone of bed separation is a trapezoid with the bottom angles are 63 degrees (left) and 61 degrees (right) after mining stop, as figure 7 shows. The corresponding relationships

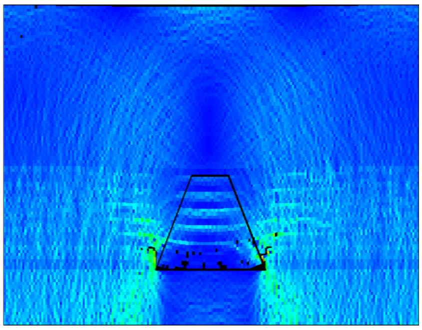

Fig.7 Distribution of bed separation numerical simulation

between work face movement and the most growing height of bed separation are in table 3.

Table 3. The corresponding relationships

Work face movement /(m)	20	30	40	50
The most growing height of bed separation /(m)	8.03	12.7	21.9	26.6

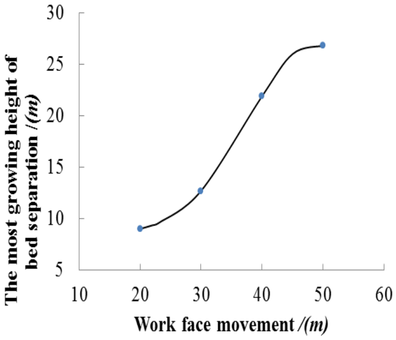

Fig.8 Relationship curve between work face movements and bed separation heights

According to the table 3, the relationship curve between work face movements and the most growing height of bed separation is shown in figure 8.
The equation of relationship curve between work face movements and bed separation heights is:

$$H=-0.0015D^3+0.1581D^2-4.5785D+48.4 \qquad (1)$$

In the formula, H represents the bed separation height, D represents the distance of the work face movement.
According to the analysis, the growing height of bed separation increases as the work face moves. At the beginning of coal mining, the height of bed separation increases slowly. As the distance of moving increases, the growing rate of separation height becomes faster gradually. After the working face advances a certain length, the growing rate of separation height decreases and closes to zero. After arrive a limit height, the growing height of bed separation will not increase after arriving a limit height. In the coal mining process, the growing rates of bed separation height are different in different periods.
In summary, the main conclusions obtained by numerical simulation of bed separation in overlying strata with RFPA are following. The bed separation constantly grows forward and upward as the work face moves. At last, the bed separation distributes in a trapezoid zone with the bottom angles about 60 degrees above the goaf. The height of bed separation grows slowly at early stage and grows faster at later stage until the limit height. At the end, the height doesn’t grow. At different stages, the increase rates are different. The limit height of be separation is sixty percent of the work face moving distance.

Verification on similar material experiment based on the results of numerical calculation for bed separation in mining overburden

Simulation conditions of the model and experimental purposes

In order to verify the numerical simulation results of bed separation in mining overburden based on the calculation method of rock failure process (RFPA for short), the similar material simulation experiment is adopted. Parameters of the model material are same between numerical simulation experiment and similar material simulation experiment. Coal seam dip angle is 0 °. The depth of coal seam is 80m under the ground. Mining width is 50*m*. Mining thickness is 4*m*. The coal bulk density is 1.4×10^{-3}*kg/cm*^{3} and the uniaxial compressive strength of coal is 20*Mpa*. The average bulk density of overlying strata is 2.5×10-3*kg/cm*^{3}. The uniaxial compressive strength of overlying strata is 40*Mpa*.

Selection of similar constants of simulation experiment

The ratio between the physical quantities corresponding to the experimental model (m for short) and the prototype (P for short) is called the similarity constant (c for short). The similarity constants in the simulation experiment must be determined reasonably. So the deformation and failure of the whole simulation mining process is more close to the actual situation. Similar constants in this experiment can be shown as followed.
Geometric similarity constant can be calculated by Eq. (1).

$$a_l = l_m / l_p = 1:100 \tag{1}$$

Time similar constant can be calculated by Eq. (2).

$$a_t = t_m / t_p = \sqrt{a_l} = 1:10 \tag{2}$$

Speed similar constant can be calculated by Eq. (3).

$$a_u = u_m / u_p = \sqrt{a_l} = 1:10 \tag{3}$$

Acceleration of gravity similar constant can be calculated by Eq. (4).

$$a_g = g_m / g_p = 1:1 \tag{4}$$

Displacement similar constant can be calculated by Eq. (5).

$$a_s = a_l = 1:100 \tag{5}$$

Bulk density similar constant can be calculated by Eq. (6).

$$a_r = r_m / r_p = 3:5 \tag{6}$$

Strength elastic modulus bond force similar constant can be calculated by Eq. (7).

$$a_R = a_E = a_C = a_l \cdot a_r = 3:500 \tag{7}$$

Internal friction angle similar constant can be calculated by Eq. (8).

$$a_f = f_m / f_p = a_g \cdot a_r \cdot a_l^3 = 0.6\times10^{-6} \tag{8}$$

Selection and mix ratio of similar materials

Model is mixed with different types and properties of materials in order to meet the mechanical properties of coal seam overburden. Similar materials usually consist of cementing material and filler. Different mechanical properties of overburden strata will be obtained by adjusting the ratio of the different materials
In this experiment, similar materials with quartz sand, barite and mica are used as filler. Lime and gypsum are used as cementing materials. Borax is used as retarder. Bulk density of similar materials is shown as Table 4.

Table4. Bulk density of similar materials

Material name	quartz sand	barite	Mica	Gypsum	Lime
Bulk density（g/cm^3）	1.4	4.0	0.5	0.8	0.8

The bond force of the model can be controlled by adjusting the ratio of lime and gypsum. Internal friction angle of the model can be controlled by changing the structure of quartz sand. The material mix ratio is shown as Tab.5 according to similar constants and overburden property.

Table5. The material mix ratio

Material name	binder-aggregate ratio	aggregate ratio	Compounds ratio
		quartz sand: mica: barite	Gypsum- lime ratio
Sandstone	1:4	2:1:1	1:1
coal	1:6	6:1:1	3:7

Model dimension and model making

Coal is mined with the roof all Collapsed. The width of mining is 0.5*m*. The Thickness of mining is 0.04*m*. The dimension of the model is shown as Figure 9.

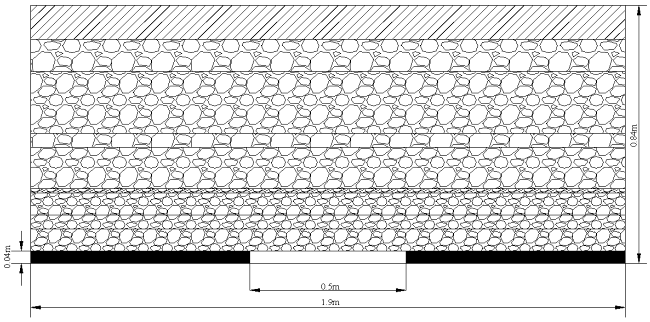

Fig.9 The dimension of similar material model **Fig.10 Model for similar simulation experiment**

The amount of materials of every layer is calculated according to Table 5 and then the model is made stratified. Mica as joint plane is drop between the two layers. So the model made by this method has a good integrity and the strength of the material is easy to be maintained. The model is made on the model desk. First channel Steel is placed in both sides of model. Then the materials are weighed according to material mix ratio and are stirred evenly by water. The materials are layered hierarchical. The thickness of strata is 0.02m and the thickness of coal layer is 0.01m. It need for 3 up to 5 days to remove template and start test after the materials are compacted uniform. The model is shown as Figure 10.

Analysis of similar material experiment results

Coal is mined with the roof all collapsed in this experiment. The mining process is divided into five steps according to numerical similar experiment. The length of every excavation is 10m. The width of mining is 50m. The morphology of bending, fracture, overburden caving and bed separation in overburden strata are shown from Figure 11 to Figure 15 corresponding to every excavation step. The following figures respectively show the development status of bed separation when the mining face advanced 10m,20m,30m,40m,50m.

Fig.11 the development status(10*m*) **Fig.12 the development status(20*m*)** **Fig.13 the development status(30*m*)**

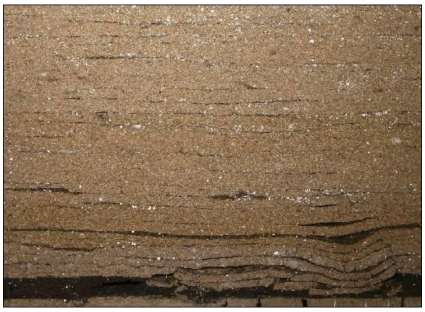

Fig.14 **the development status(40*m*)**

Fig.15 **the development status(50*m*)**

The movement and fracture of overburden strata are not occurred because of stress balance according to from Figure11 to Figure15. Goaf is formed after coal is mined in layers before coal excavation. The roof above goaf forms beam structure because it loses the support when the mining face advanced 10m. The small bed separated fissures are produced because bending is not synchronized between adjacent strata. Then the roof is collapsed rapidly. At this moment the first excavation step is completed. The strata under the initial bed separation are further collapsed and caving zone is developed upward when the mining face advanced 20m. The bed separation space near the coal seam roof experienced a process from generation to quickly disappear. The existence time is very short for the bottom bed separation.

Mining area increased gradually with mining face advanced. The scope of overlying strata bending is also enlarged. Strata are broken after bed separation formation. Caving zone and fractured zone are formed in the lower strata. A large number of bed separations are developed in fractured zone. Bend zone is formed from fractured zone up to the ground. Strata of bending zone are continuous and stable. Mining is over when work face advanced 50m. Most bed separations undergo the process of crack initiation, development and closure and the height of bed separation reaches the maximum. Bed separation are distributed in the area of "eight" shape which is roughly trapezoidal symmetry. The fracture angle of strata at open-off cut of coal is 63 degrees. The fracture angle of strata at stopping line is 62 degrees. The height of bed separation is nonlinear growth with the increase of mining working face advance distance according to the experimental data. The maximum height of bed separation is 0.6 times of the advancing distance of mining face. The above experimental results are same to the numerical simulation results by RFPA for mining overburden separated strata.

Conclusions

In this paper, the bed separation in mining overburden is simulated based on RFPA. The development of bed separation in mining overburden during mining is studied. The conclusions are showed as followed.

Firstly, tensile failure and shear failure occur in weak formation under the joint action of transversal shear and gravity stress during the process of mining. Interlayer dislocation and vertical separation are generated in strata. The separation space is formed.

Secondly, the bed separation is developed forward with the mining face advanced. The growth rate of the bed separation height during different stages is different. Fracture initiation time of bed separation is different. So the growth state of different bed separation is different at the same time.

Thirdly, the distribution laws of bed separation in mining overburden are from below and from back to front with the continuous advance of the mining face. It has a certain timelines for the growth process of bed separation.

Finally, the bed separations are distributed within the scope of trapezoid under the specific conditions. The angle of trapezoid base is 62 °. The bed separations are located just above the goaf. The growth rate of the bed separation is from fast to slow and gradually approach to zero.

Characteristics of different speed for different bed separation are shown in different stages. The maximum height of the bed separation is 0.6 times of the distance of mining face advance.

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