Research Article

Research on Formation Mechanism and Evolution Pattern of Bed Separation Zone during Repeated Mining in Multiple Coal Seams

Jianshuai Ji,1,2,3 Zhihua Li,1,2,3 Ke Yang,1,2,3 Guanghua Zhou,4 Guojun Ma,4 Cheng Liu,1,2,3 and Peng Zhou1,2,3

1Key Laboratory of Coal Mine Safety and Efficient Mining of Ministry of Education, Anhui University of Science and Technology, Huainan 232001, China
2School of Mining Engineering, Anhui University of Science and Technology, Huainan 232001, China
3Institute of Energy, Hefei Comprehensive National Science Center, Anhui, Hefei 230031, China
4National Energy Group Ningxia Coal Industry Co., Ltd, Yinchuan, Ningxia 750011, China

Correspondence should be addressed to Zhihua Li; lizhihua81@126.com

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Mastering the formation mechanism and dynamic evolution pattern of bed separation zone during repeated mining is the key to the success or failure of separation grouting injection technology. Taking a mine in Ningdong as the engineering background, using the research methods of theoretical analysis, numerical simulated, and field measurement, four overburden structure models of single or multiple key strata with repeated mining and single or multiple key strata without repeated mining were constructed. The evolution pattern of bed separation zone was studied from four aspects: bed separation zone development mechanism, formation position, development form, and change of clearance. The results showed that when a single key stratum of repeated mining exists between coal seams, it is difficult to form a large separation area because there is no key stratum during the upper coal mining, and a separation area will be formed below the key stratum when mining the lower coal. When the key stratum exists above all coal seams, a large separation zone will be formed under the key stratum when the upper coal is mined. When mining the lower coal, when the coal seam spacing is less than 4 times of the mining height of the lower coal, the crack will penetrate the upper coal floor. If the key stratum is not completely broken, secondary separation may occur. When multiple key strata are all located above all coal seams, there will be bed separation zone under the high-level key stratum. When multiple key strata and coal seams are distributed at intervals, the separation below the high-level key stratum during upper coal mining and the separation below the low-level key stratum during lower coal mining are formed. Because the high-level key stratum bends and sinks after being affected by the mining of coal 1, the clearance of bed separation during mining coal 2 is slightly less than that during mining coal 1, which is contrary to the pattern that the greater the bed separation clearance increases with the increase of mining height.

1. Introduction

It is inevitably the surface subsidence in mining area due to the coal mining. According to the statistics, the mining subsidence area in China has reached 20000 km², which has seriously affected the people’s life and ecological environment in the mining area [1]. Changing the traditional mining mode is the key to the sustainable development of coal. Fluidization mining is a way to protect the environment. In situ fluidization mining of coal is a fluidization mining technology system that converts deep coal in situ into gaseous, liquid, or gas-solid-liquid mixed substances and realizes in situ mining, beneficiation and charging, thermal, and electric transformation. It can make coal like oil and gas development, to achieve the green mining goal of “no coal on the ground and no one in the mine” [2, 3]. Filling mining is another green mining method. It can not only deal with solid waste but also control surface subsidence and protect surface buildings [4, 5]. However, fluidization mining has not yet entered the industrial stage, and filling mining
is still the mainstream way to protect the environment. Filling mining can be divided into gravity flow filling, wind filling, hydraulic filling, and mechanical filling according to filling power. According to the filling materials, it can be divided into gangue filling, hydraulic sand filling, paste filling, and high-water filling. According to the filling amount, it can be divided into full filling and partial filling. According to the filling position, it can be divided into gob filling, bed separation zone filling, and caving zone filling [6].

The research on the bed separation zone was first used to prevent and control floods. The bed separation zone flood is a common disaster in the mine. Until the 1980s, China introduced the bed separation zone grouting method from Poland [7]. The bed separation zone grouting technology refers to the use of the separation space formed in the overburden during the movement of the rock stratum to drill holes from the ground and transport the filling materials to the separation area formed in the mining process to support the overburden, thus prevent the development of mining space. The advantage is that it does not interfere with the normal production of the panel [8], as shown in Figure 1. Whether it is bed separation flood or bed separation zone filling, it is necessary to master the development position of the bed separation zone. The development position of bed separation is distinguished and predicted from the perspective of theoretical analysis [9–11]. Literature [12–15] monitors the development of fracture zone and bed separation development position on site through borehole television and other methods. Gui et al. [16] studied the lithology of roof rock stratum, coal seam inclination, water source and coal seam separation, roof management method, mining face size, and the restriction of geological and mining factors such as mining progress on the formation of coal seam separation water disaster; Xu et al. of China University of mining and technology has conducted a lot of research on the separation grouting filling, and proposed the overburden isolation grouting nonvillage mining technology [17, 18]. For example, the formation mechanism of filling horizon, the filling bearing structure model, the supporting effect of filling on key strata, and the formation mechanism of filling compaction zone are studied [19–22]. At the same time, Xu et al. [23, 24] proposed the cumulative effect of unloading expansion of mining overburden and studied its influence on the development of bed separation zone. The research showed that this effect has different degrees of influence on the amount of separation under the key overburden stratum, the height of penetration and fracture of the key overburden stratum, and the surface subsidence coefficient under different mining conditions; a few geological conditions are that there is no obvious key stratum, and multistratum grouting can be implemented. Ma et al. [25, 26] studied the separation grouting under no obvious key stratum through similar simulation test and field test. The research shows that the multistratum separation grouting method can form grouting fillings with different diffusion radius in the mining overburden and jointly stack and support the overburden, which can effectively reduce the damage degree of overburden; Ning et al. [27] studied the grouting timing through similar simulation method. The results show that the development height of bed separation zone is close to 0.4 – 0.6 times of the advancing distance of panel. The generation of bed separation zone is between the initial pressure and periodic pressure, and the best time for bed separation zone grouting is after periodic pressure; Xu et al. [28] through the field test in Xuzhuang Coal Mine, it is concluded that under the condition of repeated mining, the stiffness of the overlying strata decreases due to the influence of repeated mining, showing an overall sinking trend, unable to form separation, and grouting cannot be implemented; literature [29–33] studied the feasibility of separation grouting with or without repeated mining from the field test. The results show that when there is repeated mining, the rock stiffness decreases, the overall subsidence after mining, and separation cannot occur; Xuan et al. [34] introduced the theoretical and physical model of injection filler distribution, quantified the injection thickness at different positions along the main injection horizon, and also studied the stiffness and distribution of grouting body in the overburden after injection and its influence on surface settlement control through field measurement [35, 36].

Numerous studies on bed separation zone have been concluded and favorable results. However, there are few studies on the development pattern of bed separation during repeated mining. This paper mainly uses theoretical analysis and numerical simulation to study the evolution characteristics of bed separation during repeated mining, in order to find out the bed separation zone development position and evolution pattern and provide some reference for the implementation of separation area filling.

2. Engineering Background

The mine field is located in Ningxia Province, China. The mine field location map is shown in Figure 2(a). There are 3 minable coal seams in the coal mine. The thickness of coal 1 is 1.39 to 6.17 m, with an average of 3.32 m. The average thickness of coal seams in the first mining area is 3.0 m; the thickness of coal 2 is 2.17 to 11.51 m, with an average of 6.03 m. Generally, the structure is simple. The average thickness of coal seams in the first mining area is
approximately 5.42 m. The test panel is panel A, the adjacent panel is panel B under mining, and the overlying coal 1 and coal 2 have been mined. Because panel A has not been stopped, the location of rock stratum activity in the measured mining process is selected in panel B. The location map of the panel is shown in Figure 2(b). There is a long distance between coal 2 and coal 3, and the distance is approximately 70 m. There is a hard rock stratum between the two coal seams. Coal 2 and coal 1 are close, and the distance is approximately 30 m. There is no hard stratum between coal 2 and coal 3, and there is a hard stratum above coal 1. The average thickness of coal seam in panel a is 4.2 m. The immediate roof of the coal seam is almost entirely limestone. The top stratum of gangue is relatively stable, but its thickness and lithology change greatly, generally fine sandstone, medium sandstone, and siltstone.

3. Theoretical Analysis on Spatiotemporal Evolution of Bed Separation Zone in Multicoal Seam Mining

3.1. Formation Mechanism of Bed Separation Zone. The generation of bed separation zone is based on interstratum dislocation. From the shear strength of the stratum, the criterion of dislocation along the stratum can be obtained, as shown in Eq. (1). The roof rock is sedimentary rock, because the period is different, the lithology is different, and the mechanical properties are different. There is relatively weakness plane between rock strata. After the coal seam is mined, the roof is hanging. When the span exceeds its limit span, the roof deformation, instability, and caving stratum by stratum. At the position of the relatively weakness plane, the deformation of the upper and lower strata is out of synchronous, and a sudden change occurs between the middle of the lower strata and the upper strata, this is bed separation zone [37]. The key strata theory considers that there are one to several thick and hard strata above the immediate roof, which control the partial or whole strata movement of the overlying strata in the stope [38]. According to the definition of key stratum, the deformation of the overlying stratum and its lower stratum will be out of sync, which is the same as that caused by bed separation. In a word, it is easy to produce bed separation zone under the key stratum.

\[ \tau \geq C + \sigma \tan \phi, \quad (1) \]

where \( \tau \) is the stratum shear stress; \( C \) is the stratum cohesion; \( \sigma \) is the stratum compressive stress; \( \phi \) is the friction angle in stratum.

3.2. Identification of Key Stratum

3.2.1. Height Calculation of Overburden "Two Zones." According to the lithology histogram, most of the overlying strata are sandstone, so it is calculated according to medium hard rock, and the calculation formula is shown in Eqs. (2) and (3) [39].

(a) Caving zone height

The calculation formula of caving zone height is

\[ H_c = \frac{100\sum M}{4.7\sum M + 19} \pm 2.2. \quad (2) \]

(b) Fracture zone height

The calculation formula of fracture zone height is

\[ H_f = \frac{100\sum M}{1.6\sum M + 3.6} \pm 5.6, \quad (3) \]

where \( M \) is the mining height; \( H_c \) is the caving zone height; \( H_f \) is the fracture zone height. 

\( M_1 = 4.0 \text{ m}, M_2 = 5.4 \text{ m}, M_3 = 2.7 \text{ m} \) substitution Eq. (2), (3) to get

\( H_{c3} = 8.83 \text{ to } 12.78 \text{ m}, \quad H_{c2} = 9.97 \text{ to } 14.37 \text{ m}, \quad H_{c1} = 5.84 \text{ to } 10.24 \text{ m}, \quad H_{f3} = 34.40 \text{ to } 45.60 \text{ m}, \quad H_{f2} = 38.52 \text{ to } 49.72 \text{ m}, \quad H_{f1} = 28.49 \text{ to } 39.69 \text{ m}. \)
3.2.2. Key Stratum Calculation. The key stratum needs two conditions. The first condition is shown in Eq. (4), and the second condition is shown in Eq. (5) [38]:

\[(q_{n+1})_1 < (q_n)_1,\]

\[lj < lj + 1(j = 1, 2, 3, \ldots k),\]

where \((q_{n+1})_1\) is that when considering the effect of the \(n+1\) stratum on the stratum 1, the load of the stratum 1, KN; \((q_n)_1\) is that when considering the effect of stratum \(n\) on stratum 1, the load of stratum 1, KN; \(lj\) is the breaking distance of stratum \(j\); \(k\) is the number of strata of hard stratum determined by Eq. (4).

\[qn = \gamma nhn,\]

\[(q_m)_n = \frac{Enh^3_s(\gamma_n h_n + \gamma_{n+1} h_{n+1} + \ldots + \gamma_m h_m)}{E_n h_n^3 + E_{n+1} h_{n+1}^3 + \ldots + E_m h_m^3},\]

where \(n\) is the load of the nth stratum; \((q_m)_n\) is that when considering the effect of stratum \(m\) on stratum \(N\), the load of stratum \(N\), where \(m > n\); \(\gamma\) is the volume force of rock stratum; \(h\) is the thickness of rock stratum; \(E\) is the elastic modulus.

Based on the data in Table 1 calculated according to the above formula, it can be seen that no. 3 is the first key stratum, no. 7 is the second key stratum, no. 16 is the third key stratum, and no. 21 is the fourth key stratum.

3.3. Mechanical Model of Temporal and Spatial Evolution of Initial Development of Bed Separation Zone

<table>
<thead>
<tr>
<th>No.</th>
<th>Lithology</th>
<th>Legend</th>
<th>Buried depth (m)</th>
<th>Thickness (m)</th>
<th>Bulk density (KN/m³)</th>
<th>Elastic modulus (GPa)</th>
<th>Tensile strength (MPa)</th>
<th>Remarks</th>
</tr>
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<td></td>
<td>297.0</td>
<td>4.2</td>
<td>14.35</td>
<td>3.24</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Limestone</td>
<td></td>
<td>295.1</td>
<td>1.9</td>
<td>24.00</td>
<td>5.53</td>
<td>2.06</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Mudstone</td>
<td></td>
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<td>9.6</td>
<td>25.50</td>
<td>3.05</td>
<td>1.57</td>
<td>KS1</td>
</tr>
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<td>9.09</td>
<td>6.40</td>
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<tr>
<td>5</td>
<td>Medium sandstone</td>
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<td>277.5</td>
<td>4.7</td>
<td>24.70</td>
<td>13.25</td>
<td>4.00</td>
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</tr>
<tr>
<td>6</td>
<td>Fine sandstone</td>
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<td>274.7</td>
<td>2.8</td>
<td>24.80</td>
<td>16.45</td>
<td>4.65</td>
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<td>6.2</td>
<td>25.50</td>
<td>3.05</td>
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<td>7.8</td>
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<td>16.45</td>
<td>4.65</td>
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</tr>
<tr>
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<td>Coarse sandstone</td>
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<td>6.0</td>
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<td>10.84</td>
<td>3.26</td>
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</tr>
<tr>
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<td>8.0</td>
<td>25.50</td>
<td>3.05</td>
<td>1.57</td>
<td></td>
</tr>
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<td>4.0</td>
<td>24.90</td>
<td>9.09</td>
<td>6.40</td>
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<tr>
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<td>3.0</td>
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<td>4.24</td>
<td>0.14</td>
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<td>25.00</td>
<td>9.12</td>
<td>6.40</td>
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<td>4.0</td>
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<td>3.05</td>
<td>1.24</td>
<td></td>
</tr>
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<td>24.90</td>
<td>9.09</td>
<td>6.58</td>
<td></td>
</tr>
<tr>
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<td>Fine sandstone</td>
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<td>184.3</td>
<td>8.0</td>
<td>24.80</td>
<td>16.45</td>
<td>4.56</td>
<td></td>
</tr>
<tr>
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<td>Medium sandstone</td>
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<td>180.3</td>
<td>4.0</td>
<td>24.70</td>
<td>14.24</td>
<td>4.54</td>
<td></td>
</tr>
<tr>
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<td>165.3</td>
<td>15.0</td>
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<td>9.09</td>
<td>6.95</td>
<td>KS4</td>
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</table>

Table 1: Rock stratum histogram.
Figure 3: The spatial model of bed separation zone.

Figure 4: Mechanical model of initial development of bed separation zone under uniform load.

Figure 5: Mechanical model of bed separation zone periodic development under uniform load.

Figure 6: Repeated mining model and survey line layout.
(1) Establishment of bed separation zone development model

At present, most scholars analyze the development position and space of the bed separation zone through the beam theory mode, but because the rock stratum is a three-dimensional model, it is more accurate to use the plate model. Ma [40] analyzed the initial development and periodic development of the bed separation zone during mining by establishing the plate model, as shown in Figure 3. It is assumed that there are \( n \) strata. Bed separation zone will occur between stratum \( i \) and stratum \( i+1 \).

(2) Initial development of bed separation zone

The mechanical model of initial development of stratified zone under uniform loading is shown in Figure 4. After the coal seam was mined, the stable state of the rock is broken. Before the failure of the rock stratum develops to the initial development of the bed separation zone, the bed separation zone is surrounded by solid rock mass. Therefore, the quadrilateral fixed support mechanical model is used for calculation. Assuming that the thickness of the sheet is "\( h \)”, the lengths of the rectangular sheet in the \( X \) and \( Y \) directions are “\( a \)” and “\( b \)”, respectively, and the rectangular sheet is subjected to a uniformly distributed load \( q_o = yh \), where \( y \) is the unit weight of rock stratum, and \( H \) is the buried depth of rock stratum. It is assumed that when the overburden separation zone is formed for the first time, before the rock plate at the top of the rock separation zone breaks, the small deflection boundary conditions of the rectangular plate with quadrilateral fixed supports are as follows [40]:

\[
\omega|_{x=0,a} = 0, \quad \omega|_{y=0,b} = 0. \tag{8}
\]

Expression of deformation potential energy of rectangular sheet

\[
U = \frac{E}{2(1-v^2)} \int_0^a \int_0^b \left( \nabla^2 \omega \right)^2 + \left( \frac{\partial^2 \omega}{\partial x^2} \right)^2 \, dx 
\]

where \( v \) is the Poisson’s ratio.

Since the deformation potential energy does not change with the change of \( Z \), replace \( D = Eh'/12(1-v^2) \) to get

\[
U = \frac{D}{2} \int_0^a \left( \nabla^2 \omega \right)^2 \, dx - \frac{1}{D} \int_0^a \left[ \frac{\partial^2 \omega}{\partial x^2} \frac{\partial^2 \omega}{\partial y^2} - \left( \frac{\partial^2 \omega}{\partial x \partial y} \right)^2 \right] \, dx. \tag{11}
\]

The above formula is solved according to Stokes formula:

\[
U = D \int_0^a \int_0^b \left( \nabla^2 \omega \right)^2 \, dx 
\]

The work done by uniformly distributed load is

\[
I = \int q_o \omega \, dx 
\]

Substituting Eqs. (11) and (12), the total potential energy of the sheet is

\[
E_p = U - I = D \int_0^a \left( \nabla^2 \omega \right)^2 \, dx - \int q_o \omega \, dx. \tag{15}
\]

The vertical deflection function is assumed to be

\[
\omega = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} A_{mn} \left( 1 - \cos \frac{2\pi m x}{a} \right) \left( 1 - \cos \frac{2\pi n y}{b} \right). \tag{16}
\]

Due to the quadrilateral fixed supports, all boundaries are given displacement boundaries, \( m = n = 1 \) is selected to meet the calculation requirements, and Eq. (15) is substituted into (14):

\[
E_p = 2A_{11} \pi^4 abD \left( 3 \frac{a^4}{b^4} + 2 \frac{a^2 b^2}{b^4} \right) - A_{11} q_o ab. \tag{18}
\]

Due to \( \partial E_p/\partial A_{11} = 0 \)

\[
4Dn^2 A_{11} \left( 3a^4 + 3b^4 + 2a^2 b^2 \right) - q_o a^4 b^4 = 0. \tag{19}
\]

The deflection coefficient is

\[
A_{11} = \frac{q_o a^4 b^4}{4\pi D^4 \left( 3a^4 + 3b^4 + 2a^2 b^2 \right)}. \tag{20}
\]
Substituting Eq. (19) into Eq. (15), the vertical deflection of rock stratum can be got as
\[
\omega_1 = \frac{\gamma H a^2 b^2}{4\pi^2 D(3a^4 + 3b^4 + 2a^2 b^2)} \left[ 1 - \cos \frac{2m\pi x}{a} \right] \left[ 1 - \cos \frac{2n\pi y}{b} \right].
\] (21)

where \(\omega_1\) is the ultimate deflection of rock stratum during initial development of bed separation zone, \(m\) is the advancing distance of panel, \(a\) is the inclined length of panel, \(b\) is the inclined length of panel, \(m\).

In the periodic development separation model of overburden, the rock boundary adjacent to the gob is simply supported. Therefore, the rectangular sheet mechanical model with three fixed supports and one simply supported is selected for calculation [40].

\[
\omega|_{x=0} = 0 = \frac{\partial^2 \omega}{\partial x^2} |_{x=0},
\] (23)

\[
\omega|_{x=a} = 0 = \frac{\partial \omega}{\partial x} |_{x=a},
\] (24)

\[
\omega|_{y=b} = 0 = \frac{\partial \omega}{\partial y} |_{y=b}.
\] (25)

Expression of deformation potential energy of rectangular sheet
\[
U = \frac{E}{2(1 - \nu^2)} \iint_{0}^{a} \int_{0}^{b} \left[ \frac{\partial^2 \omega}{\partial x^2} \frac{\partial^2 \omega}{\partial y^2} \right] dx dy.
\] (26)

Since the deformation potential energy does not change with the change of \(Z\), replace \(D = Eh^3/12(1 - \nu^2)\) to get
\[
U = \frac{D}{2} \int_{0}^{a} \int_{0}^{b} (\nabla^2 \omega)^2 + (\nabla \omega)^2 dx dy.
\] (27)

The above formula is solved according to Green’s theorem
\[
U = \frac{D}{2} \int_{0}^{a} \int_{-b}^{b} (\nabla^2 \omega)^2 dx dy - (1 - \nu)D \int_{0}^{a} \int_{-b}^{b} \frac{\partial \omega}{\partial y} \frac{\partial^2 \omega}{\partial x^2} dx dy + \int_{-b}^{b} \int_{-b}^{b} \frac{\partial \omega}{\partial y} \frac{\partial^2 \omega}{\partial x^2} dy dx.
\] (28)

Since the second term integral in the above formula is calculated along the boundary of rectangular sheet, according to the boundary assumption, there is always \(\partial \omega/\partial y\), so it is simplified as
\[
U = \frac{D}{2} \int_{0}^{a} \int_{-b}^{b} (\nabla^2 \omega)^2 dx dy.
\] (29)

\[
I = \int_{0}^{a} \int_{-b}^{b} q_o \omega dx dy.
\] (30)

Substitute Eq. (31) into Eq. (30), then, \(E_p\) is
\[
E_p = U - I = \frac{D}{2} \int_{0}^{a} \int_{-b}^{b} (\nabla^2 \omega)^2 dx dy - \int_{0}^{a} \int_{-b}^{b} q_o \omega dx dy.
\] (31)

The vertical deflection function is assumed to be
\[
\omega = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} B_{mn} \left(1 - \cos \frac{2m\pi x}{a} \right) \left(1 - \cos \frac{2n\pi y}{b} \right).
\] (32)

Substitute Eq. (34) into (33)

\[
E_p = \frac{8D a^2}{b^2 \cos \frac{2\pi \nu}{b} \left(1 - \cos \frac{2\pi \nu}{a} \right)} \int_{0}^{a} \int_{0}^{b} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} B_{mn} \left(1 - \cos \frac{2m\pi x}{a} \right) \left(1 - \cos \frac{2n\pi y}{b} \right) \left(1 - \cos \frac{2n\pi y}{b} \right) dx dy.
\] (33)

Because it is fixed on three sides and simply supported on one side, all boundaries are given positioning and moving boundaries, \(m = n = 1\) is selected to meet the calculation requirements, and Eq. (32) is substituted into (31)

\[
E_p = \frac{8B_{11} a^2}{b^2 \left(1 - \frac{1}{a} - \frac{1}{2} + \frac{1}{3} + \frac{a}{8}\right)} - B_{11} q_o ab.
\] (34)

Due to \(\partial E_p/\partial B_{11} = 0\)

\[
\frac{8B_{11} a^2}{b^2 \left(1 - \frac{1}{a} - \frac{1}{2} + \frac{1}{3} + \frac{a}{8}\right)} - q_o ab^4 = 0.
\] (35)
Figure 7: The temporal and spatial evolution pattern of bed separation zone of mining different coal seams. ((a)–(c) are the temporal and spatial evolution pattern when mining coal 1, coal 2, and coal 3, respectively).
The deflection coefficient is

\[ B_{11} = \frac{3q_0 a^4}{\pi^2 D(24 - 12a + 8a^2 + 3a^2)}. \]  

Substituting Eq. (37) into Eq. (33), the vertical deflection of rock stratum can be obtained as

\[ \omega_2 = \frac{3a^4 \gamma H_x}{\pi^2 D(24 - 12a + 8a^2 + 3a^2)} \left[ 1 - \cos \left( \frac{2\pi x}{a} \right) \right] \left[ 1 - \cos \left( \frac{2\pi y}{b} \right) \right], \]  

where \( \omega_2 \) is the ultimate deflection of rock stratum during initial development of bed separation zone, \( m \); \( a \) is the 0.5 times the advancing distance of the panel, \( m \); \( b \) is the 0.5 times the inclined length of panel.

### 3.5. Identify of Bed Separation Zone Horizon

When the traditional caving method is used to deal with the goaf, due to the difference of lithology, the bed separation zone will be formed in the strata, and there will be different horizons in the bed separation zone, and the bed separation zone is most likely to be formed under the key stratum. Separation discrimination is divided into four steps [40]:

(a) **Classification of Overlying Lithology.** The adjacent two or more strata of rocks are classified into one class according to the comprehensive rock evaluation coefficient \( P \) (as shown in the following)

\[ P = \frac{\sum_i^m m_i Q_i}{\sum_i^m m_i}, \]  

where \( m_i \) is the \( i \)th normal thickness of the stratum, \( m \); \( Q_i \) is the \( i \)th lithology evaluation coefficient of stratification.

(b) **Determine the Horizon Where Separation May Occur.** When the deformation of the lower rock is greater than that of the upper rock, separation may be formed between the two parts of rock, represented by the following equation

\[ E_n H^2 \sum_{i=1}^{n} \rho_i H_i > \rho_{n+1} \sum_{i=1}^{n} E_i H_i^3. \]  

(c) **Calculate the Deflection of Different Combination Rock Masses.** According to the initial development of bed separation zone. Calculate according to Eq. (21).

(d) **Discriminant Analysis of Bed Separation Development Horizon.**

\[ \sum_1^n \omega_{\text{down}} > \sum_1^n \omega_{\text{up}}. \]  

Follow the above steps. In the first step, the lithology is classified according to formula (38). The second step is to calculate according to Eq. (39) and select the group conforming to Eq. (39). Third, calculate the maximum deflection of each group of upper and lower strata according to formula (21). Finally, the deflections of the upper and lower layers are compared, and the groups that meet all the above conditions are obtained. It can be seen that the stratum that may be separated are between rock layers no. 2 and no. 3, rock layers no. 6 and no. 7, rock layers no. 20 and no. 21, which are basically consistent with

### Table 2: Physical and mechanical parameters of coal and rock mass.

<table>
<thead>
<tr>
<th>No.</th>
<th>Lithology</th>
<th>Bulk density (kN/m³)</th>
<th>E (GPa)</th>
<th>ν</th>
<th>C (MPa)</th>
<th>Φ  (°)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Medium sandstone</td>
<td>25.42</td>
<td>13.25</td>
<td>0.17</td>
<td>10.63</td>
<td>34.00</td>
<td>4.00</td>
</tr>
<tr>
<td>5</td>
<td>Fine sandstone</td>
<td>24.79</td>
<td>16.45</td>
<td>0.18</td>
<td>12.55</td>
<td>31.00</td>
<td>4.65</td>
</tr>
<tr>
<td>4</td>
<td>Siltstone</td>
<td>24.89</td>
<td>9.09</td>
<td>0.30</td>
<td>9.11</td>
<td>41.00</td>
<td>6.40</td>
</tr>
<tr>
<td>3</td>
<td>Sandy mudstone</td>
<td>25.10</td>
<td>5.42</td>
<td>0.24</td>
<td>6.83</td>
<td>33.00</td>
<td>2.25</td>
</tr>
<tr>
<td>2</td>
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<td>25.50</td>
<td>3.05</td>
<td>0.16</td>
<td>4.98</td>
<td>32.00</td>
<td>1.57</td>
</tr>
<tr>
<td>1</td>
<td>Limestone</td>
<td>24.00</td>
<td>5.53</td>
<td>0.21</td>
<td>3.63</td>
<td>38.00</td>
<td>2.06</td>
</tr>
</tbody>
</table>

### Table 3: Physical and mechanical parameters of joints between rock blocks.

<table>
<thead>
<tr>
<th>No.</th>
<th>Lithology</th>
<th>Normal stiffness (GPa)</th>
<th>Tangential stiffness (GPa)</th>
<th>C (MPa)</th>
<th>Φ  (°)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Medium sandstone</td>
<td>15.25</td>
<td>5.32</td>
<td>10.63</td>
<td>24.00</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td>Fine sandstone</td>
<td>18.45</td>
<td>6.18</td>
<td>12.55</td>
<td>28.00</td>
<td>1.65</td>
</tr>
<tr>
<td>4</td>
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<td>12.09</td>
<td>3.24</td>
<td>9.11</td>
<td>35.00</td>
<td>1.40</td>
</tr>
<tr>
<td>3</td>
<td>Sandy mudstone</td>
<td>7.42</td>
<td>3.24</td>
<td>6.83</td>
<td>25.00</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Mudstone</td>
<td>5.05</td>
<td>2.16</td>
<td>4.98</td>
<td>20.00</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>Limestone</td>
<td>6.53</td>
<td>2.21</td>
<td>3.63</td>
<td>30.00</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 8: Displacement curve ((a)–(c) are the subsidence curves when mining coal 1, coal 2, and coal 3, respectively).
the calculation of key strata. At the same time, according to the calculation of collapse zone, it can be seen that no. 2 and no. 3 strata are located in caving zone, so the bed separation zone cannot be formed. Thus, there are two layers of bed separation horizon.

4. Numerical Simulation of Temporal and Spatial Evolution Pattern of Bed Separation Zone in Multiple Coal Seam Mining

4.1. Model Establishment. UDEC was used to simulate the development pattern and height of bed separation zone during repeated mining. According to the roof and floor conditions of the panel, the model size is $400 \text{ m} \times 200 \text{ m}$, 50 m coal pillars are reserved on the left and right, and mining distance 300 m. The constitutive relation adopts Mohr Coulomb model. The boundary constraints of the model are as follows: the displacement and velocity vectors of the left and right boundaries are set to zero; the lower boundary is fully constrained; the upper boundary of the model is a free boundary. The buried depth of the coal seam is 300 m, and the height of the model is 200 m. Therefore, a uniformly distributed load of 2.5 MPa is applied to the upper boundary [41–43]. The physical and mechanical parameters were measured in the laboratory. The mining sequence simulates the actual mining sequence of the mine, and the downward mining is carried out, mining coal 1, coal 2, and coal 3 successively, thus understand the temporal and spatial evolution pattern of bed separation zone during repeated mining. The repeated mining mode and survey line layout are shown in Figure 6.

4.2. Analysis of Temporal and Spatial Evolution Pattern of Bed Separation Zone. The following Figure 7 shows the temporal and spatial evolution pattern of bed separation zone of mining different coal seam. The physical and mechanical parameters of rock mass are shown in Table 2, and the mechanical parameters of rock joints are shown in Table 3.

As shown in Figure 7, according to the mining succession sequence of the mine, downward mining is implemented, and coal 1 is mined first. In the process of mining coal 1, when mining to 90 m, the bed separation zone is initially developed, the initial shape is a fine crack, and the development location is below key stratum 4. Mining to 130 m. With the increase of mining distance, the bed separation zone continues to expand and gradually becomes an arc fracture. The bed separation began to close at 150 m, closed completely at 170 m, and the initial development ended. The 230 m bed separation zone developed periodically for the first time. Due to the relationship between model size and boundary coal pillar, the bed separation zone did not expand. Then, coal 2 was mined, and the bed separation development horizon is the same as that of coal 1, and the pattern is basically synchronous. The bed separation develops for the first time at 90 m and gradually expands at 110 m, and the shape becomes a triangle. When mining reaches 130 m, the bed separation zone mainly extends horizontally, presenting an inverted trapezoidal shape, and begins to close at 150 m. After the completion of coal min-

ing, the key stratum 4 bends and sinks, the bed separation zone is closed, and there is residual space attached to the stopping line. Finally, coal 3 was mined. During the mining process, the development height of the fracture zone was approximately 36 m, and the key stratum 2 was not broken. When mining to 100 m, the bed separation zone developed for the first time. Because there was a key stratum between coal 3 and coal 2 and the distance was far, the bed separation zone was developed below the key stratum 2, approximately 32 m away from the coal seam, which could not affect the key stratum 2.

4.3. Analysis of Bed Separation Zone Clearance. To quantify the development of bed separation zone, the displacement curves of adjacent strata with bed separation zone are extracted on the basis of fracture map. The difference between the two displacement curves intuitively reflects the size of bed separation zone, and the curve color is the same under the same advancing distance. During the mining of coal 1 and coal 2, it can be seen that the bed separation zone mainly occurs below the high-level key stratum. When mining coal 3, the bed separation zone mainly occurs below the low-level key stratum. Figure 8 shows the roof displacement curve of the separation development position when mining different coal seams, in which, (a), (b), and (c) are the displacement curves when mining coal 1, coal 2, and coal 3, respectively. Figure 9 shows the difference between the two displacement curves, namely, the amount of bed separation clearance.

According to Figure 9 and the above bed separation zone development pattern, when mining coal 1 and coal 2, the bed separation zone is mainly reflected in the difference between survey line 3 and survey line 4, and when mining coal 3, it is mainly reflected in the difference between survey line 1 and survey line 2. It can be seen from Figure 9 that when coal 1 is recovered to 90 m, the bed separation zone begins to develop, and the maximum bed separation zone clearance is 0.7 m. When coal 1 is recovered to 110 m, the bed separation zone expands rapidly, and the maximum bed separation zone clearance also increases rapidly, with a maximum of 2.2 m. It develops slowly at 130 m and 150 m, and then the bed separation zone gradually closes. When coal 1 is recovered to approximately 160 m, the bed separation zone is closed, and the bed separation zone clearance is close to 0 m. At this time, a total of 160 m is recovered; when the mining reaches 80 m, the separation development is the largest. Therefore, it can be seen that a bed separation development cycle is 160 m to 180 m, and the largest in the middle of the advance. It can be seen that the bed separation development pattern increases rapidly at first, then increases slowly and tends to be stable, and then decreases gradually. When the subsequent mining reaches 230 m, the bed separation zone appears periodic development, and the distance from the initial development is 50 m, which is 40 m less than the advance distance of the initial development; then, when mining coal 2, the initial development trend is synchronous with that of coal 1. The difference is that the amount of separation clearance is slightly less than that of coal 1. Contrary to the pattern that the amount of separation clearance
increases with the increase of mining height, it is analyzed that the reason may be caused by the bending and subsidence of the high key stratum after the influence of coal 3 mining; when mining coal 3, because it is far away from coal 2 and the high-level key stratum is broken, the bed separation zone only exists below the low-level key stratum, and the separation clearance is relatively small. The reason is that the thickness of the immediate roof above coal 3 is large, the collapse backward fills the goaf, the overlying strata are easy to form a hinged structure, and the caving is insufficient. In terms of morphology, it develops longitudinally first, stops when the longitudinal development reaches a certain degree, and then mainly turns into horizontal development. When mining continues, the bed separation zone is closed. As

Figure 9: Variation pattern of bed separation clearance ((a)–(c) are the bed separation interval when mining coal 1, coal 2, and coal 3, respectively).
can be seen from Figure 10, the maximum value of bed separation clearance occurs twice during mining.

4.4. Spatial Variation Characteristics of Different Strata Structures. On the basis of the above research, four models such as repeated mining single or multikey stratum and nonrepeated mining single or multikey stratum overburden structure model are constructed. As shown in Figure 11, the spatial variation characteristics of different overburden structures are analyzed.

As shown in Table 4, overburden structures can be divided into four categories. When there is no gob above the panel, there is no repeated mining. Under the condition of no repeated mining, when there is a single key stratum, the separated stratum mostly exists below the key stratum; when there are multiple key strata, the separated stratum first develops below the low key stratum. With the mining of the panel, the bed separation zone develops upward to the lower part of the high-level key stratum. In the case of repeated mining, when there is a single key stratum, it is discussed in two cases. The first case is that the key stratum exists above all coal seams, as shown in Figure 8(c). At this time, a large separation zone will be formed under the key stratum when the upper coal is mined. When mining the lower coal, when the coal seam spacing is less than 4 times of the mining height of the lower coal, the crack will penetrate the upper coal floor [44]. If the key stratum is not completely broken, secondary separation may occur, which is the same as the mining of coal 1 and coal 2 in the numerical simulation. Therefore, in the first case, separate stratum grouting can effectively control surface subsidence. The second case is that the key stratum exists between the coal seams. In this case, it is difficult to form a large separation area because there is no key stratum in the upper coal mining. When the lower coal is mined, a bed separation zone will be formed below the key stratum. In case of multiple
(a) Single key stratum without repeated mining

(b) Multiple key strata without repeated mining

(c) Single key stratum with repeated mining

Figure 11: Continued.
key strata, it is discussed in two cases. In the first case, the key strata are all located above all coal seams. When mining the upper coal, it is similar to Figure 9(b). When mining the upper coal, the bed separation zone first occurs under the low key stratum. With the increase of the mining distance of the upper coal or the beginning of mining the lower coal,
the low key stratum is broken, and the separated stratum is developed below the high key stratum. The second case is the clearance distribution of key strata and coal seams, as shown in Figure 8(d). In this case, there will be three bed separation zones, and one is the bed separation zone below the high-level key stratum during upper coal mining. The second is the separation below the low key stratum during lower coal mining. Third, the high-level key stratum is not broken after the upper coal mining, the low-level key stratum is broken during the lower coal mining, and the separation occurs below the high-level key stratum.

5. Borehole Peeping in Bed Separation Zone

(1) Layout and observation of measuring points in borehole

Regardless of the separation zone filling, it is essential to find out the development pattern of overburden “two zones” in the mining process. The on-site observation methods include borehole flushing fluid consumption method, borehole segmented water injection method, and deep hole multipoint displacement meter method [45]. To accurately observe the development of bed separation zone, it was finally decided to use borehole peeping method. According to the theoretical analysis and numerical simulation results, the height of the collapse zone is 8 to 12 m, and the height of the fracture zone is 30 m. Taking this as a reference, a reasonable drilling height can be set. Three groups of boreholes are arranged under the support of panel B, with the drilling depths of 10 m, 20 m, and 30 m, respectively, and the direction is perpendicular to the roof. At this time, the panel advances approximately 100 m. The layout of drilling measuring points is shown in Figure 12.

(2) Analysis of observation results

The results of drilling peep are shown in Figure 13. Among, a, b, c borehole depth is 10 m; d, e, f borehole depth is 20 m; g, h, i borehole depth is 30 m.

From the peeping results at the end of the borehole, it can be seen that when the borehole depth is 10 m, the rocks
in borehole 1, 2, and 3 are relatively broken, a large number of through cracks appear, and both transverse cracks and longitudinal cracks exist; when the depth is 20 m, the peeping results show that the rock in borehole 3 is relatively complete, and there are transverse fractures in borehole 1 and borehole 2 obviously, that is, stratification, indicating stratification at this position, which is similar to the numerical simulation results. When the depth is 30 m, it can be seen from the peeping results of three boreholes that the rock in the borehole is complete and there is no crack. Combined with the rock stratum histogram and theoretical analysis, this part is key stratum 2, indicating that key stratum 2 is not broken when mining to 100 m, which is consistent with the results of theoretical analysis and numerical simulation.

6. Discussion and Conclusions

In terms of separation clearance, based on previous studied, the bed separation evolution characteristics during repeated mining are studied. From a macro point of view, the bed separation development pattern, like most studies, has experienced a development expansion closure change process [23]. From the results of numerical simulation, it is found that when mining coal 1 and coal 2, the bed separation clearance of coal 2 is less than that of coal 1, which is contrary to the previous theory that the larger the mining height is, the larger the bed separation development size is [38], because the separation development position is the same when mining two coal seams. Although the upper rock stratum (high-level key stratum) of the bed separation zone is not broken after mining coal 1. However, bending subsidence occurs, resulting in small separation space. The disadvantage is that only the bed separation evolution characteristics of traditional caving method are studied, and the dynamic evolution characteristics of bed separation after grouting are not studied. Relevant studies show that during single-stratum coal mining, after bed separation grouting, the rock fracture above the bed separation zone is significantly reduced, the rock subsidence is reduced [26–28], and the bed separation development is not studied. The next research work can study the evolution characteristics of the bed separation zone from two aspects. The first aspect is to grouting the bed separation zone after the initial development of the bed separation zone and observe its periodic development. The second aspect is to study the bed separation evolution characteristics of lower coal mining, such as whether the bed separation will develop or not.

Through theoretical analysis and numerical simulation, the main conclusions are as follows:

(1) The bed separation zone development position of panel C is predicted by using this method, it is found that the development position of bed separation zone is mainly below the key strata of the second and fourth strata

(2) From the development position of bed separation zone, the development position of bed separation zone is below the high-level key stratum in the process of mining coal 1 and coal 2 and below the low-level key stratum in the process of mining coal 3. The development position of bed separation zone is basically consistent with the theoretical discrimination; from the morphological point of view, it develops longitudinally first, stops when the longitudinal development reaches a certain degree, and then mainly turns into horizontal development. When mining continues, the bed separation zone is closed. In terms of the amount of separation clearance, the maximum amount of bed separation clearance is 2.2 m in the case of coal 1, and it decreases to about 1.8 m in the case of coal 2. The reason is that the stiffness of key strata decreases under the influence of mining and bending subsidence occurs

(3) Four overburden structure models of single/multiple key strata with repeated mining and single/multiple key strata without repeated mining are constructed, and the spatial variation characteristics of bed separation zones under different overburden structures are analyzed. When a single key stratum exists between coal seams due to repeated mining, it is difficult to form a large separation zone because there is no key stratum in the rock stratum during upper coal mining, and a separation zone will be formed below the key stratum during lower coal mining. When the key stratum exists above all coal seams, a large separation zone will be formed under the key stratum when the upper coal is mined. When mining the lower coal, when the coal seam spacing is less than 4 times of the mining height of the lower coal, the crack will penetrate the upper coal floor. If the key stratum is not completely broken, secondary separation may occur. When multiple key strata are all located above all coal seams, there will be large separation under the high-level key stratum. When multiple key strata and coal seams are distributed at clearances, the separation below the high-level key stratum during upper coal mining and the separation below the low-level key stratum during lower coal mining are formed

(4) The overburden activity above the panel is monitored through borehole peeping. According to the borehole peeping results, when mining the third stratum of coal, the height of collapse zone is 10 m, and the height of fracture zone is 35 m, which is consistent with the theoretical calculation and numerical simulation results

Data Availability

The data used to support the findings of this study are available from the #1 author upon request.

Conflicts of Interest

The authors declare no conflict of interest.
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References


