



Article Study on the Law of Fracture Evolution under Repeated Mining of Close-Distance Coal Seams

Feng Cui ^{1,2,3,*}, Chong Jia ¹, Xingping Lai ^{1,2,3}, Yanbing Yang ¹ and Shuai Dong ¹

- ¹ Energy School, Xi'an University of Science and Technology, Xi'an 710054, China; 18203213041@stu.xust.edu.cn (C.J.); laixp@xust.edu.cn (X.L.); 19103077014@stu.xust.edu.cn (Y.Y.); 18203213033@stu.xust.edu.cn (S.D.)
- ² Key Laboratory of Western Mines and Hazard Prevention of China Ministry of Education, Xi'an 710054, China
- ³ Key Laboratory of Coal Resources Exploration and Comprehensive Utilization, Ministry of Natural Resources, Shaanxi Coal Geology Group Co., Ltd., Xi'an 710021, China
- * Correspondence: fengc@xust.edu.cn; Tel.: +86-1899-283-5236

Received: 6 October 2020; Accepted: 17 November 2020; Published: 19 November 2020



Abstract: The western region of China is rich in mineral resources. The vigorous development of mineral resources has exacerbated the environmental and safety problems in the region. One of the important links to solve this problem is to control the development laws and distribution characteristics of the overburdened cracks in the mining of this area. In this paper, the Xiashijie coal mine 3-2 coal seam and 4-2 coal seam are examples of repeated mining, and are examined as the background, through theoretical analysis to optimize the size of the coal pillars in the lower section, using the 3DEC numerical simulation experiment method and the rise of the cracks in the short-distance coal seam. Repeated mining monitoring and analysis of the development law are used to ascertain distribution characteristics of overburdened cracks caused by the repeated mining process of the working face. The results show that: (1) By establishing a mechanical model of the overlying strata structure under short-distance coal seam group mining, and carrying out the force analysis of the double section coal pillar under repeated mining, the reasonable size of a lower section coal pillar was determined to be 70 m. (2) As the development height of a fracture progresses with the working face, its expansion rate undergoes four obvious changes: fluctuations within a certain range, the expansion rate reaches the peak after the rock formation is concentrated and broken, the cyclical change gradually decreases, and the expansion rate is zero after complete mining. (3) The fracture zone height of 222 and 224 face under repeated mining in the 4-2 coal seam was 19.56–22.31 times and 22.38–24.54 times larger, respectively, and the post-mining fracture extension of the face with larger width and deeper burial under repeated mining was higher than that of the adjacent face. This study provides scientific guidance for the rational division of coal pillars and the solution of the problem of water conservation mining under repeated mining in the adjacent face of a short-distance coal seam.

Keywords: close-distance coal seam; repeated mining; numerical simulation; fracture evolution

1. Introduction

Mining operations are gradually deepening due to the reduction in more accessible coal resources. At the same time, more and more attention has been paid to the laws of fracture development in the process of mining under various complex conditions. There is an urgent need to study the evolution of fissures caused by repeated mining of adjacent working faces in near-level and near-distance coal seams.

The migration law of the overlying strata in the stope is one of the key issues in studying the development of the stope's cracks. The law of overlying rock movement under mining conditions has

always been a focus for researchers in coal and other mineral resource mining. For the deformation of overlying rock caused by underground mining, many domestic and foreign scholars have used simulation experiments to study the laws of overlying rock migration [1–5], which effectively guide the safety of mine operations in different geological environments. In addition, Ghabraie et al. used a physical model composed of sand and gypsum in accordance with the relevant similar rules to study settlement mechanisms [6]. Iwanec et al. used numerical methods to accurately predict the subsidence above single-layer and multi-layer long-wall panels, and combined the constitutive relationship to properly describe the mechanical behavior of the coal-measure formation [7]. In order to optimize the gas pre-drainage scheme of dangerous outbursts from coal seams, Cheng et al. studied the stress–fracture distribution and evolution characteristics of surrounding rock under the influence of double mining of the protective and protected layer [8]. Zhang et al. analyzed the mechanism of crack opening and propagation by using the relevant mechanical theories of elastoplastic mechanics and fracture mechanics under unloading conditions [9]. Liu et al. based on fractal theory, using the Brazilian splitting test and a field peep statistical test as research means, discussing the influence of rock mass fragmentation scale and uniformity on fractural characteristics [10].

Setting a reasonable width of the coal pillar section is the key to ensure safe mining of the coal seam face. Many scholars have made reasonable analyses on the optimization of the coal pillar size through theoretical formulas. Du et al. analyzed the mechanism of abnormal mining stress behavior under the boundary pillar of a shallow coal seam with a large mining height [11]. Feng et al. analyzed the problem of recovering the upper residual coal pillar through the residual coal mining layer in the central residual coal stope of the "upper pillar collapse" compound residual mining area under the influence of multi-mining [12,13]. Through analysis, the author discussed the mechanism of overburden failure in the mining process of short-distance coal seam groups, and studied the reasonable setting size of coal pillars [14–17]. In order to study the laws of fracture development and evolution in the process of coal seam mining, Shen et al. introduced longitudinal wave anisotropy detection technology to study water diversion fault zones [18]. In view of the complex environment of longwall mining, Rezaei et al. put forward an artificial neural network method to estimate the height of caving and crushing zones in a longwall goaf [19]. Cui et al. studied the development law of mining cracks in a gently inclined extra-thick coal seam by a physical simulation method [20]. Xu et al. used the methods of physical simulations and field measurements to study the deformation of strata overlying mining, and the spatio-temporal evolution of fractures [21]. Shang et al. studied the failure process of coal pillars and mining roadways in the lower coal seam under the action of irregular residual coal pillars in the upper part of the short-distance coal seam [22]. Suchowerska et al. combined the equation of vertical stress distribution near single longwall plate mining with finite element simulation to evaluate the vertical stress in the underlying strata [23]. Khanal et al. studied the effects of separation distance, mining offset, plate layout and plate orientation on surface subsidence and chain column stress [24]. Combining a variety of previous theoretical analysis methods for determining the size of coal pillars can provide a good analysis idea for determining the size of coal pillars for repeated mining of this coal seam group.

The development height of fissures is the basic parameter of water conservation mining, and has important guiding significance for the implementation of mine safety measures such as water prevention and control. Regarding the development and evolution of cracks during coal seam mining, Xu et al. studied the influence of the location of the key layers of the overburden on the height of the water diversion fracture zone [25]. Ye et al. obtained the evolution characteristics of overlying rock mining cracks by establishing a similar simulation laboratory experiment system [26]. Chen et al. used borehole imaging technology to calculate the height of the fracture zone under the condition of insufficient mining, by comparing the borehole images at different distances from the working face [27]. Majdi et al., equated the height of the pressure relief zone (HDZ) with the comprehensive height of the collapsed fracture zone above the panel roof caused by longwall mining, and described the development mechanism of the height of the zone [28]. Heather et al. studied the characteristics of

overlying rock and fissure changes during underground mining, and analyzed the impact of dynamic damage [29]. Hebblewhite et al. reviewed the main prediction models based on the observed behavior of the displacement and fracture of the strata above the longwall slabs in the New South Wales coal field in southern Sydney [30].

Many scholars have made fruitful studies on the development of cracks and the characteristics of stress changes caused by repeated mining in coal seam groups, but most of them are aimed at the problem of repeated mining in a single working face. However, the research on the adjacent faces of close coal seam groups and the spatio-temporal dynamic evolution mechanism of fractures are rarely mentioned.

This article aims at the problem of repeated mining of close coal seams in Xiashijie Coal Mine. A three-dimensional numerical simulation method was used to analyze the changing characteristics of the floor stress of adjacent working faces, and to study the temporal and spatial evolution of repeated mining cracks in adjacent horizontal working faces. This study provides a scientific basis for water conservation mining of short-distance coal seams.

2. Engineering Background

Xiashijie Coal Mine belongs to Jiaoping Mining Area and is located northwest of Tongchuan City, in Shaanxi Province. The geographical location of the mining area is shown in Figure 1. The mining field is 4 km long, with an inclined width of about 3.3 km and an area of 13.2 km². The main coal seams in the mine are 3-2 coal seams and 4-2 coal seams, and the average dip angle of coal seams is 5° near horizontal coal seams, in which the average thickness of 3-2 coal seams is 4.5 m and that of 4-2 coal seams is 10.0 m, both of which have weak bursting liability.



Figure 1. Geographical location of mining area.

In Xiashijie Coal Mine, the widths of the 2301 and 2302 working faces of the 3-2 seam are 210 m and 240 m, respectively, and the widths of the 222 and 224 working faces of the 4-2 coal seam are 170 m and 200 m, respectively. The mining sequence of the coal seam group is a 2301 working face, 2302 working face, and 224 working face. The parameters of the working face are shown in Table 1, and the plane layout of the working face is shown in Figure 2.

Table 1. Working face parameters of close-distance coal seam in Xiashijie Coal Mine.

Main Coal Seam			Working Face				Thickness of	
Name	Average Depth (m)	Average Thickness (m)	Name	Inclined Length (m)	[–] Pillar Size (m)	Dip Angle	Intermediate Strata (m)	
3-2	608.24	4.5	2301 2302	210 240	30	- 0	01 54	
4-2	640.0	10.0	222 224	170 200	/	5°	21.76	

	K	224 open-off cut 2302 working face 2302 working f
T X V		222 open-off cut 2301 high extraction roadway 2301 high extraction roadway 2301 high extraction roadway 2301 high extraction roadway
Lujiashan mine field		220 220 headentry open-off cur 220 high extraction roadway 220 tailentry 220 grout rodeway

Figure 2. Layout plan of the working face in Xiashijie Coal Mine.

3. Design and Construction of Numerical Model

The 4-2 coal seam of Xiashijie Coal Mine has an average buried depth of 640 m. There is one key layer and two sub-key layers in the upper rock layer of the coal seam. Figure 3 shows a schematic diagram of the coal mine strata structure based on the geological data of the coal mine and the results of drilling holes.



Figure 3. Schematic diagram of stratum structure in Xiashijie Coal Mine.

The 3DEC discrete element numerical simulation software used in this experiment is the abbreviation of 3D discrete element method program, 3 Dimension Distinct Element Code. Rock blocks with different lithological properties (continuum) and geological structural planes (discontinuous characteristics) constitute the most basic elements of rock mass. Under the action of external forces, rock blocks can show mechanical behavior of continuous media, and rock blocks interact with each other through structural planes (discontinuous features) [31].

When the force on the structural plane exceeds its bearing limit, the rock blocks show real failure phenomena such as mutual shear dislocation or detachment, which leads to the fracture of the simulated rock strata. 3DEC is based on the "Lagrange algorithm" and is suitable for the simulation calculation of multi-block system motion and large deformation. According to the Mohr–Coulomb model, it is

used to simulate weak mechanical behavior caused by the accumulation of plastic shear displacement. It has a good effect for studying the fracture evolution law of overlying rock failure in this paper.

According to the stratum structure and engineering background, a three-dimensional numerical analysis model was constructed by using 3DEC discrete element numerical simulation software. The external dimension of the model (length \times width \times height) was 1200 \times 640 \times 350 m. The design and construction of the model are shown in Figure 4a,b, respectively. After constructing the model with 3DEC numerical simulation software, gravity was applied to the upper surface of the model. Displacement boundaries were applied to the front, back, left, right and bottom of the model. The upper surface of the model was a free surface so that the overlying strata and the ground surface could be continuously deformed during the mining progress of the 2301 face and 2302 face in 3-2 coal seam was 6 m. Through the calculation and analysis of numerical simulation, the overburden stress distribution and fracture evolution characteristics were studied, and the temporal and spatial evolution distribution characteristics of overburden fractures were revealed.



Figure 4. Design and construction of numerical model. (**a**) Numerical model design; (**b**) Numerical model construction.

During the construction of the model, stress measuring lines were arranged on the floor of the 3-2 coal seam and 4-2 coal seam of the three-dimensional model to monitor the stress change of the floor in the mining process on the working face.

Through mine field survey and on-site sampling of the TC3 borehole, the mechanical parameters of the coal were determined from the results of the mechanical test, and the average values of the mechanical parameters of the obtained coal were summarized and used as the parameters of the numerical simulation experiment. The main coal rock mechanics parameters simulated by this order value are shown in Table 2.

Rock Character	Bulk Density (kN∙m ⁻³)	Compressive Strength (MPa)	Tensile strength (MPa)	Elastic Modulus (GPa)	Poisson's Ratio	Internal Friction Angle (°)	Cohesion (MPa)
Conglomerate	2.35	30.76	1.86	2.65	0.19	33.46	2.25
Medium-grained sandstone	2.31	12.92	1.22	1.21	0.23	30.36	1.50
Coarse-grained sandstone	2.41	30.22	2.12	2.59	0.19	31.28	1.65
Sandy mudstone	2.54	4.78	0.23	0.35	0.27	26.28	0.48
Mudstone	2.62	8.82	0.65	0.83	0.25	27.21	0.81
3-2 coal goaf	2.45	39.84	2.00	7.52	0.16	31.74	16.22
3-2 coal	1.35	14.78	1.33	1.67	0.31	29.72	2.68
Intermediate strata	2.68	32.59	1.89	5.71	0.20	28.86	21.38
4-2 coal	2.40	19.83	1.86	1.82	0.21	30.89	3.61
4-2 coal floor	2.57	25.93	1.51	4.26	0.18	32.98	21.66

Table 2. Main coal and rock mechanical parameters.

4. Theoretical Analysis

Through the establishment of the mechanical model of an overburdened structure in close-distance coal seam group mining of single-layer coal mining and repeated mining, the determination coefficient k was introduced and the stress analysis of double-section coal pillar under repeated mining was carried out to determine the reasonable size of the section coal pillar. At the same time, the theoretical formula of the height of the two zones was used to determine the development height of the two zones under the empirical calculation.

4.1. Mechanical Structure Analysis of Adjacent Working Face under Repeated Mining

After repeated mining in the adjacent working face of the near horizontal and close-distance coal seam, the upper strata of the coal pillar in the goaf interval between the two adjacent coal seams shows an obvious double inverted trapezoid structure. The coal pillar in the lower coal seam section passes through the middle strata and bears the action of the upper overburden. If the coal pillar is not big enough, it causes disasters such as impact effect due to the instability of the overburden structure. Therefore, the force of the coal pillar in the adjacent face of the close-distance coal seam group was analyzed.

The mechanical model of overburden structure in close-distance coal seam group mining is shown in Figure 5, in which the dynamic models of single-layer coal mining and repeated mining are shown in Figure 5a,b, respectively. l_1 and l_2 are the width of the coal pillar in the upper section and the length of the upper inverted ladder body (m); h_1 , h_2 , h_3 and h_4 are the height of hard rock and its upper stable overburden, the height of inverted trapezoid in the upper section of coal pillar, the thickness of upper coal seam, and the thickness of middle strata, respectively (m). l_3 is the width of the upper stable overburden after repeated mining (m), and h'1 and h'2 are the height of the upper stable overburden after repeated mining and the height of the upper inverted ladder of the upper section of coal pillar, respectively. L_1 , L_2 and L_3 are the width of the coal pillar in the lower section, and the left and right residual width of the lower inverted ladder except for the coal pillar in the upper section, respectively (m).



Figure 5. Mechanical model of overburden structure in close-distance coal seam group mining.(a) Mechanical model of single-layer coal mining; (b) Repeated mining mechanical model.

In single-layer coal mining, the main force acting on the upper overburden when the coal pillar reaches a reasonable size in the upper section is recorded as F_1 , and Equation (1) is as follows:

$$F_1 = \gamma_1 l_2 h_1 + \gamma_1 (l_1 + l_2) h_2 / 2 \tag{1}$$

In the equation, γ_1 is the average bulk density of the overburden in the upper part of the coal seam, kN/m³. The average bulk density of the upper overburden in Xiashijie Coal Mine was 22.4 kN/m³.

Equation (2) is for calculating the vertical stress σ'_1 per unit area at the end of normal mining in the adjacent face of the upper coal seam, and is as follows:

$$\sigma_1' = \frac{F_1}{l_1} \tag{2}$$

The ratio of the vertical stress σ'_1 per unit area to the uniaxial compressive strength σ_1 of the coal sample at the end of normal mining in the adjacent face of the upper coal seam is recorded as the judgment index *k*, and the Equation (3) calculation is as follows:

$$k = \frac{\sigma_1'}{\sigma_1} \tag{3}$$

After repeated mining in the adjacent face of the lower coal seam, the ratio of the vertical stress σ'_2 of the section coal pillar to the uniaxial compressive strength σ_2 of the coal sample is not greater than the judgment index *k* of the single-layer mining of the upper coal seam, based on which the reasonable size of the coal pillar in the lower section is determined.

The double-section coal pillar was extracted from the dynamic structure model of repeated mining of close-distance coal seam group, and the force analysis of the double-section coal pillar is shown in Figure 6. According to this model, the force acting on the upper strata of the coal pillar in the lower section was analyzed, and the size of the coal pillar in the lower section was reasonably optimized.



Figure 6. Stress of double-section coal pillar.

After repeated mining, the main acting force of the upper overburden of the coal pillar in the upper section is F'_1 , and Equation (4) is as follows:

$$F_1' = \gamma_1 l_3 h_1' + \gamma_1 (l_1 + l_3) h_2' / 2 \tag{4}$$

Because the remaining size of the coal pillar in the section is small and the breaking angle of the strata is basically stable, the upper roof length $L_2 + L_3$ of the inverted trapezoid in the middle strata and the width of the upper stable strata l_3 after the failure of the strata are regarded as synchronized with the width of the coal pillar L_1 at the bottom, that is:

$$L_2 + L_3 = L_1 + a (5)$$

$$l_3 = L_1 + b \tag{6}$$

In the Equations (5) and (6), *a* and *b* are constants (m).

The action of falling strata on the left and right ends of the lower inverted ladder body is recorded as q_1 and q_2 , and the action of the overlying rock collapse lagging behind the lower inverted ladder body is regarded as an idealized linear increase and evenly distributed on L_2 and L_3 , then q_1 and q_2 are shown in Equation (7):

$$q_{1} = \gamma_{1}L_{2}h_{2}'/2 q_{2} = \gamma_{1}L_{3}h_{2}'/2$$
(7)

The force acting on the lower inverted ladder body:

$$F_{2} = F'_{1} + q_{1} + q_{2} + \gamma_{2}l_{1}h_{3}$$

= $\gamma_{1}l_{3}h'_{1} + \gamma_{1}(l_{1} + l_{3})h'_{2}/2 + \gamma_{1}(L_{2} + L_{3})h'_{2}/2 + \gamma_{2}l_{1}h_{3}$ (8)

In Equation (8), γ_2 is the bulk density of the upper coal seam (kN/m³). The bulk density of Xiashijie 3-2 coal seam and 4-2 coal seam was 1.35 kN/m³ and 1.45 kN/m³, respectively.

The force acting on the upper overburden of the coal seam in the lower section is:

$$F_{3} = F_{2} + \gamma_{3}(L_{1} + L_{2} + L_{3} + l_{1})h_{4}/2$$

= $\gamma_{1}l_{3}h'_{1} + \gamma_{1}(l_{1} + l_{3})h'_{2}/2 + \gamma_{2}(L_{2} + L_{3})h'_{2}/2$
+ $\gamma_{2}l_{1}h_{3} + \gamma_{3}(L_{1} + L_{2} + L_{3} + l_{1})h_{4}/2$ (9)

In Equation (9), γ_3 is the bulk density of the middle strata of the close-distance coal seam (kN/m³). The average bulk density of the middle strata in Xiashijie Coal Mine was 25.3 kN/m³.

When the rest of the coal pillar in the lower section reaches its limit, Equation (10) is the vertical stress of the upper strata per unit area of the coal pillar:

$$\sigma_2' = k\sigma_2 = \frac{F_3}{L_1} \tag{10}$$

According to the above theoretical analysis, the reasonable size L_1 width of section coal pillar can be calculated by simultaneous Equations (3), (5), (6), (9) and (10). Equation (11) is as follows:

$$L_{1} = \frac{F_{3}}{k\sigma_{2}} = \frac{1}{\sigma_{2}'} \begin{bmatrix} \gamma_{1}(L_{1}+b)h_{1}'+\gamma_{2}(L_{1}+a)h_{2}'/2 \\ +\gamma_{1}(l_{1}+L_{1}+b)h_{2}'/2+\gamma_{2}l_{1}h_{3} \\ +\gamma_{3}(2L_{1}+a+l_{1})h_{4}/2 \end{bmatrix}$$
(11)

Simplified:

$$L_{1} = \frac{\left\{\gamma_{1}\left[bh_{1}' + (l_{1} + b)h_{2}'/2\right] + \gamma_{2}(ah_{2}'/2 + l_{1}h_{3}) + \gamma_{3}(a + l_{1})h_{4}/2\right\}}{\sigma_{2}' - \left[\gamma_{1}h_{1}' + (\gamma_{1} + \gamma_{2})h_{2}'/2 + \gamma_{3}h_{4}\right]}$$
(12)

4.2. Calculation of Reasonable Coal Pillar Size between Adjacent Working Faces

Because the actual mining of 2301 and 2302 working faces of the 3-2 coal seam has been completed, the size of the coal pillar in the process of adjacent re-mining of the 4-2 coal seam was reasonably optimized based on the post-mining parameters of the 3-2 coal seam combined with the results of theoretical analysis.

The 3-2 remaining coal pillar width l_1 after actual mining in the 2301 and 2302 working faces of the Xiashijie Coal Mine was 30.0 m, and the widths of the 2301 and 2302 working faces were 210 m and 240 m, respectively. The height of the 3-2 coal seam at the upper part h_3 was 4.5 m, and the rock height h_4 between the two coal seams was 21.76 m. According to the size and the mechanical parameters of this kind of coal and rock, the length of upper inverted trapezoid body L_2 was 43.3 m, and the height of upper overlying rock H_1 and the inverted trapezoid body H_2 of the coal pillar in the upper section were 580.24 m and 23.5 m, respectively.

After the single-layer coal mining, the various parameters were brought into Equation (1), as shown in Equation (13). Through calculation, it can be seen that the upper overlying strata F_1 of the upper section coal pillar reached a reasonable size of about 582.1×10^3 kN.

$$F_1 = \gamma_1 l_2 h_1 + \gamma_1 (l_1 + l_2) h_2 / 2$$

= 22.4 × 43.3 × 580.24 + 22.4 × (30.0 + 43.3) 23.5 / 2 (13)
≈ 582.1 × 10³ kN

Taking F_1 and l_1 as 582.1 × 10³ kN and 30.0 m, respectively, and inputting these values into Equation (2), the vertical stress per unit area σ'_1 is 19.40 MPa. Bringing the uniaxial compressive strength of 14.78 MPa of F'_1 and upper section coal samples into Equation (3), results in Equation (14):

$$k = \frac{\sigma_1'}{\sigma_1} = \frac{20.83}{14.78} = 1.31 \tag{14}$$

Bringing the judgment index k and the uniaxial compressive strength of 19.83 MPa of the lower section coal sample into Equation (10), we can know that when the rest of the lower section coal pillar reaches the limit, the vertical stress of the upper strata of the coal pillar per unit area is shown in Equation (15).

$$\sigma_2' = k\sigma_2 = 1.31 \times 19.83 = 25.98 \tag{15}$$

The widths of the 222 working face and 224 working face in the 4-2 coal seam were 170 m and 200 m, respectively. Through the numerical simulation calculation of several groups of coal pillar sections with different sizes, it was concluded that the average height of the upper stable overburden h'_1 and the average height h'_2 of the upper inverted ladder body of the upper section coal pillar after repeated mining were 569.8 m and 33.94 m, respectively. At the same time, according to the numerical simulation calculation of several groups of different coal pillar sizes, the L_1 , L_2 , L_3 and l_3 , incorporated it into Equations (5) and (6), results in the average values of a and b constants for multiple sets of coal pillar sizes in different sections being 29.9 m and 52.1 m, respectively.

Bringing the known parameters into Equation (12) obtains the L_1 result as shown in Equation (16).

$$L_1 = \frac{713,543.5}{12,262.91} \approx 58.19 \tag{16}$$

Based on the above analysis, the size of the coal pillar which reached the safety limit during repeated mining in the 4-2 coal seam was 59.79 m. Due to the complexity of mine geological conditions and the unknown aspects of repeated mining, the mine is prone to induce rock burst disasters and accidents, a wealth coefficient of 1.2 is reserved, and the reasonable coal pillar size is about 70 m. In this numerical simulation experiment, the size of coal pillar between adjacent working faces in 4-2 coal seam was determined to be 70 m.

4.3. Theoretical Formula Calculation of Development Height of Two Zones

Refer to *Mining Damage Science* [32]. When the inclination angle of the coal seam is 0° to ~54° in the slicing mining of thick coal seams, the two-zone empirical calculation formula under the hard overlying rock: the caving zone height Equation (17) and the calculation Equations (18) and (19) for calculating the height of the fracture zone are as follows.

$$Hc = \frac{100\sum M}{2.1\sum M + 16} \pm 2.5$$
 (17)

$$Hf = \frac{100\sum M}{1.2\sum M + 2.0} \pm 8.9$$
 (18)

$$Hf = 30\sqrt{\sum M} + 10\tag{19}$$

In which: $\sum M$ is the cumulative mining thickness of the coal seam, and its cumulative thickness does not exceed 15 m; The symbol "±" is the allowable error range. H_c is the height of caving zone and H_f is the height of fracture zone.

The mining height of the 3-2 coal seam in Xiashijie Coal Mine was 4.5 m and the cumulative mining height of the 3-2 coal seam and 4-2 coal seam was 14.5 m. The heights of the two zones obtained by bringing them into the empirical calculation results are shown in Table 3. It can be seen from Table 3 that the height of the caved zone of the 3-2 coal seam after mining was s 15.2 to 20.2 m, the height of fractured zone was 60.8 ± 8.9 m, and the maximum height of the fracture zone calculated by Equation (2) was 73.6 m. The height of caving zone after repeated mining in the 4-2 coal seam was 28.7–33.7 m, the cumulative height of the fracture zone was 74.7 ± 8.9 m, and the maximum height of fracture zone calculated by Equation (2) was 124.2 m.

	Development Height of Two Zones					
Working Face	Height of Caved Zone (m)	Height of Fractured Zone (m)				
0	8	Equation (1)	Equation (2)			
After mining of 3-2 coal seam	15.2~20.2	51.9~69.7	73.6			
After mining of 4-2 coal seam	28.7~33.7	65.8~83.6	124.2			

Table 3. Height of two zones under development.

5. Evolution Law of Fractures in Inclined Overburden

In this section, statistics are developed on the floor stress and crack development height during the mining process of the 3D model working face. There is comparative study of the overlying rock migration, floor stress distribution, and crack evolution laws during repeated mining of adjacent working faces.

5.1. Development of Cracks in Inclined Overburden of Repeated Mining in the Working Face

According to the changes in the floor rock stress, measured by the stress measurement line in the mining process of the working face, the distribution curve of the advanced supporting pressure after mining of each working face was drawn. Based on this, the distribution characteristics of rock pressure under repeated mining of coal seams were analyzed.

Figure 7 shows the evolution characteristics of post-mining inclined overburden in close adjacent face, in which, the distribution of post-mining overburden in face 2301 is shown in Figure 7a. The roof of face 2301 fully collapsed and the upper strata of the goaf was destroyed. The height of caved zone was in the range of 18.6–22.4 m, and the height of the fractured zone was in the range of 141.7–152.3 m. The distribution of the overburden in 2302 face is shown in Figure 7b. The roof of the 2302 face fully collapsed, and the damage of the upper strata in the goaf was more obvious. The height of the caved zone was in the range of 19.0–23.2 m, and the maximum height of the fractured zone was 173.7 m. At this time, the height of the fractured zone in the goaf of the 2301 working face continued to develop upward to 155.4 m.



Figure 7. Evolution characteristics of post-mining inclined overburden in close adjacent working face. (a) is 2301 working face after mining, (b) is 2302 working face after mining, (c) is 222 working face after mining, (d) is 224 working face after mining.

The distribution of the overburden in the 222 working face after mining is shown in Figure 7c. The roof of the working face fully collapsed after mining, and the height of the caved zone was in the range of 58.2–69.8 m. The damage of the upper strata in the goaf was obvious, the fractured extended upward, and the height of the fractured zone reached 208.8 m. The distribution of the overburden in the 222 face is shown in Figure 7d. The roof of the working face fully collapsed in the 224 face, and the height of the caved zone was within the range of 60.8–74.6 m. The damage of the upper strata in the goaf was obvious, and the height of the fractured zone in the goaf was 236.8 m. At this time, the height

of the fractured zone in the goaf of 222 working face continued to develop upward to 212.2 m. Figure 8 shows the spatial distribution characteristics of the repeated mining tendency fracture field of the 4-2 coal seam at the model length of 600 m, in which the distribution of the post-mining crack field is shown in Figure 8a. The roof crack field extended upward, and the concentrated distribution area of crack field showed "ladder" distribution. The strata deformation area was mainly concentrated in the range of model length 380–540 m and height 30–220 m, and the maximum height of the fractured zone was about 195.6 m. The distribution characteristics of the fractured field in the overlying strata at the end of mining in the 224 working face are shown in Figure 8b. The crack field in the roof of the 224 face expanded upward, and the concentrated distribution area of the crack field was "ladder". The deformation area of the strata was mainly concentrated in the range of the model length 110–280 m and the height of 20–270 m, and the maximum height of the fractured zone was about 245.5 m. At this time, the height of the fractured zone in the goaf of the 222 working face continued to develop upward to 206.7 m.



Figure 8. Spatial distribution characteristics of fracture field of repeated mining tendency in the 4-2 coal seam. (a) Distribution of fracture field after 222 face mining; (b) Distribution of fracture field after 224 face mining.

5.2. Stress Distribution Law of Inclined Floor

After the mining of each working face was finished, the model was divided at the length of 600 m, and the stress distribution characteristics of the inclined overlying strata caused by repeated mining in the close-distance coal seam group were analyzed, and through the stress distribution characteristics of the inclined floor of the working face after mining, the stress distribution law of repeated mining inclined floor in the working face was studied comprehensively.

Figure 9 shows the distribution characteristics of the post-mining tendency stress field of the close adjacent face. The distribution of the post-mining stress field of face 2301 is shown in Figure 9a. The stress of the overburden in the goaf of face 2301 decreased considerably, and the vertical stress of the rest of the overlying strata outside the goaf was not significantly different from when the initial balance was stable. The coal wall showed obvious stress concentration effects, and the vertical stress of coal seam 3-2 was generally up to 40 MPa. The maximum vertical stress of local overburden reached 70 MPa. The post-mining stress field distribution of the 2302 face is shown in Figure 9b, and the stabilized 3-2 coal seam floor stress is mainly in the range of 12.5–22.6 MPa, with an average stress of 17.2 MPa. The floor stress at the initial equilibrium shows a slightly higher stress in the deep part of the left side of the coal seam.



Figure 9. Distribution characteristics of post-mining inclined stress field in close adjacent working face. (a) is the stress field distribution of 2301 face, (b) is the stress field distribution of 2302 face, (c) is the stress field distribution of 222 face, (d) is the stress field distribution of 224 face.

The post-mining stress field distribution of the 222 working face is shown in Figure 9c. The stress of the overlying strata in the goaf decreased considerably and the stress concentration was weak. The stress concentration phenomenon of coal pillar between 2301 face and 2302 face in the 3-2 coal seam is obvious, and the maximum stress of the coal pillar reached 107 MPa. The post-mining stress field distribution of 224 working face is shown in Figure 9d. The stress of the overlying strata above the goaf decreased considerably, and the vertical stress of the other overlying strata outside the goaf had no obvious difference compared with that when the initial equilibrium reached stability, and the phenomenon of stress concentration was weak. The stress concentration phenomenon of the coal pillar between the 2301 face and 2302 face in the 3-2 coal seam was obvious, and the maximum stress of the coal pillar reached 104 MPa. The stress concentration phenomenon of coal pillar in the middle of 222 working face and 224 working face of 4-2 coal seam was weak, and the maximum stress of coal pillar reached 80 MPa.

Due to the wide range of the overburden in the stress field distribution characteristics of Figure 9, the color bars of the coal floor stress are less different. Therefore, the stress curve of the coal floor after mining on the working face is shown in Figure 10. Figure 10a shows the stress change of floor in 3-2 coal seam mining. After the initial equilibrium, the floor stress of the 3-2 coal seam was within the range of 12.50~22.60 MPa, with an average stress of 15.72 MPa, and the floor stress at the initial balance showed the characteristics of slightly higher stress in the deep area on the left side of the coal seam. After the end of mining on the 2301 working face, the stress distribution curve in the range of 350.0–580.0 m was U-shaped, and there was obvious stress concentration on the coal floor on both sides of the goaf. The peak stress of the floor on the left side of the goaf was 40.65 MPa, 2.59 times higher than that of the initial balance, which was less than that on the right side of the goaf, where the stress was 52.33 MPa.



Figure 10. The stress curve of the coal floor after mining on the working face. (**a**) Stress change of floor in 3-2 coal seam mining; (**b**) Stress change of floor in 4-2 coal seam mining.

After the end of mining on the 2302 working face, the stress distribution curve in the range of 75.0–580.0 m was W-shaped, and there was obvious stress concentration on the coal floor on both sides of the goaf. The peak stress of the floor on the left side of the goaf was lower than that on the right side of the goaf. The peak stress was 67.42 MPa on the right side of the goaf, which was 4.29 times higher than the average stress of the floor under the coal pillar on the right side of the 2302 face goaf. After mining on the 2302 working face, the stress on the floor around the middle coal pillar was 26.77 MPa more than that in 2301 working face.

The stress change on the floor in 4-2 coal seam mining is shown in Figure 10b, in which the stress concentration effect of the 4-2 coal seam floor was considerably weaker than that of the 3-2 coal seam floor in the plane model tendency after the 3-2 coal seam mining was stable. The 4-2 coal seam floor located below the coal pillar in the 3-2 coal seam section produced a peak stress of 35.44 MPa, and the peak stress below the 3-2 remaining coal seam on the left and right sides of the model was small. They were 30.59 MPa and 25.81 MPa, respectively. The buried depth of the left floor of the 4-2 coal seam was slightly larger than that of the right floor, so the peak stress of the floor of the left coal seam was slightly higher than that of the right.

When the adjacent faces of the 3-2 coal seam were mined successively, the peak stress on the coal pillar floor in the upper section increased from 40.60 MPa to 67.42 MPa. When the adjacent faces of the 4-2 coal seam were mined sequentially, the peak stress on the coal pillar floor in the lower section increased from 61.76 MPa to 66.27 MPa. Because the pillar center of the 3-2 coal seam was on the same axis as that of the 4-2 coal seam, the peak stress of 66.27 MPa on the pillar floor after repeated mining in the close-distance coal seam was less than that of the single coal seam after mining.

6. Temporal and Spatial Evolution Law of Overburden Fissures in Mining Strike of Working Face

According to the daily push progress of the 2301 and 2302 working mine faces, which were 6 m and 4 m, respectively, the simulation was pushed forward again after each mining reached balance, so as to achieve the effect of overlying rock deformation and fracture development after actual one-day mining, and study the space-time evolution law of cracks after one-day mining. Through the statistics of the overburden change and floor stress in the mining process of the working face, the characteristics of overburden movement and floor stress distribution in the repeated mining process of the adjacent face were compared and analyzed.

6.1. Distribution Characteristics of Ground Stress under Repeated Mining in the Working Face

According to the stress change on the floor strata measured by the stress measuring line in the mining process of the three-dimensional model face, the leading abutment stress distribution curve of the main position under the pushing progress was made, on the basis of which the stress distribution characteristics of the adjacent face of the close-distance coal seam under repeated mining were analyzed.

The change trend on floor stress in the process of repeated mining of close-distance coal seam is shown in Figure 11. The leading abutment stress (Figure 11a) on the mining floor in 2301 working face was 19.85 MPa when advancing to 10 m, and in the process of mining from 0 to 210 m, the leading abutment stress increased gradually with the mining of the working face. In the process from one square to the end of mining, the leading bearing stress increased in a relatively stable fluctuating way, and reached 53.49 MPa at the end of mining, i.e., when the 2301 working face was mined to 1040 m, the leading bearing stress ranged from the peak value to the steady stress value, with a total of nine measuring points, and the length of the area was about 45 m.



Figure 11. Stress variation strike of repeated mining floor in close-distance coal seam. (a) is 2301 working face after mining, (b) is 2302 working face after mining, (c) is 222 working face after mining, (d) is 224 working face after mining.

The leading abutment stress (Figure 11b) on the mining floor of the 2302 working face was 19.73 MPa when it advanced to 10 m. During the process of mining 0~240 m of the working face, the leading abutment stress increased gradually. In the process from one square to the end of mining, the leading bearing stress increased in a relatively stable fluctuating way, and reached 55.66 MPa at the end of mining, i.e., when the 2302 working face was mined to 1040 m, the leading bearing stress ranged from the peak value to the steady stress value.

The leading abutment stress (Figure 11c) on the mining floor of the 222 working face was 18.90 MPa when advancing to 10 m, and in the process of mining 0~170 m of the working face, the leading abutment stress increased gradually. In the process from one square to the end of mining, the leading bearing stress showed a relatively stable fluctuating increasing trend. By the end of mining, i.e., when the 222 working face was mined to 1040 m, the leading bearing stress reached 63.99 MPa, which was significantly higher than the 53.49 MPa stress on the 2301 working face after mining. There were 10 measuring points in the leading stress area from peak value to steady stress value, and the area length was about 50 m.

The stress change trend of 4-2 coal seam floor in the process of mining at 224 face is shown in Figure 11d. The stress of the 224 working face was 19.84 MPa when it was mined to 10 m. In the process of mining the working face from 0 to 200 m, the bearing stress increased. In the process from one square to the end of mining, the leading bearing stress increased in a relatively stable wave-like manner. When the 224 working face was mined to 1040 m, the leading bearing stress reached 65.65 MPa,

which was significantly higher than the 55.66 MPa of the 2302 working face after mining, and the length of the leading stress area was about 50 m.

The floor stress on adjacent working faces under repeated mining was counted, and the ratio of the peak value of advanced abutment stress to the average stress of coal floor before mining was recorded as a concentration coefficient, in which the average stress of floor before mining in the 2301 working face and 2302 working face of the 3-2 coal seam was 15.24 MPa and 15.64 MPa, respectively. The average stress on the floor before mining in the 222 working face and 224 working face of the 4-2 coal seam was 16.27 MPa and 16.66 MPa respectively. The statistics of leading bearing stress under repeated mining in adjacent working faces are shown in Table 4.

	3-2 Coal Seam				4-2 Coal Seam			
Mining Distance	2301 Working Face		2302 Working Face		222 Working Face		224 Working Face	
(m)	Stress (MPa)	Factor	Stress (MPa)	Factor	Stress (MPa)	Factor	Stress (MPa)	Factor
10	19.85	1.30	19.73	1.26	18.90	1.16	19.84	1.19
20	23.92	1.56	24.32	1.55	23.51	1.44	24.92	1.50
30	23.41	1.54	23.58	1.51	24.38	1.50	24.44	1.47
40	21.40	1.40	22.96	1.47	23.40	1.44	23.80	1.43
50	24.77	1.63	25.24	1.61	31.74	1.95	27.40	1.64
60	27.33	1.79	27.80	1.78	42.28	2.60	42.80	2.57
100	32.91	2.16	35.75	2.29	46.38	2.85	47.84	2.87
One time square	42.24	2.77	44.13	2.82	56.24	3.46	54.45	3.27
Two times square	49.14	3.22	50.65	3.24	59.34	3.65	60.14	3.61
Three times square	50.40	3.31	52.12	3.33	60.28	3.70	62.43	3.75
Four times square	51.88	3.40	53.23	3.40	62.52	3.84	60.41	3.63
End of mining	53.49	3.51	55.66	3.56	61.53	3.78	62.28	3.74

Table 4. Statistical table of leading abutment stress under repeated mining in adjacent face.

In the mining process of the 3-2 coal seam, the concentration coefficient of advanced bearing stress of the 2301 working face increased from 1.30 to 3.51, and that of the 2302 working face increased from 1.26 to 3.56. In the mining process of the 4-2 coal seam, the concentration coefficient of advanced bearing stress of the 222 working face increased from 1.16 to 3.93, and that of the 224 working face increased from 1.19 to 3.94. In the mining process of adjacent working faces in the same coal seam, the concentration coefficient of advanced abutment stress was relatively synchronous with the advancing of working faces, and the difference was small. In the 3-2 coal seam, the concentration coefficient of advanced bearing stress on the 2302 working face with a slightly larger buried depth and longer working face width was slightly higher than that of the 2301 working face. In the 4-2 coal seam with a deep buried depth, the concentration coefficient of advanced abutment stress in the mining process of the 222 working face and 224 working face was relatively synchronous, and there was no obvious difference in coefficient size.

Under the repeated mining of different coal seam working faces, the leading bearing stress at the same advancing distance was considerably higher at the 2301 working face than that in the mining process of the 222 working face of the 4-2 coal seam in the lower layer. In the mining process of the 224 working face of the 4-2 coal seam in the lower layer, the leading abutment stress at the same advancing distance was considerably higher than that of the 2302 working face. In addition, because the overburden space after the upper coal mining was more complex, the increase of leading abutment stress in the mining process of the 4-2 coal seam working face in the same area and different depths was considerably higher than that of the 3-2 coal seam working face.

6.2. Space-Time Evolution Characteristics of Overburden Fissures in Repeated Mining Strike of Working Face

According to the development height of fractures and the upward development rate of fractures after a single advance in the mining process of the working face, the law of fracture evolution in the

process of mining adjacent faces in close-distance coal seams is shown in Figure 12, based on which the space-time evolution law of fractures under repeated mining in close-distance coal seams was comprehensively analyzed.



Figure 12. The law of fracture evolution in the process of mining adjacent faces in close-distance coal seams. (**a**) is the evolution trend of fractures in the mining process of 2301 working face, (**b**) is the evolution trend of fractures in the mining process of 2302 working face, (**c**) is the evolution trend of fractures in the mining process of 222 working face, (**d**) is the evolution trend of fractures in the mining process of 224 working face.

The evolution trend of fractures in the mining process of the 2301 working face and 2302 working face in the 3-2 coal seam is shown in Figure 12a,b, respectively. The height of fractures formed in the 2301 working face for 30 m was 1.8 m. During the process of mining 0~130 m, the fracture expansion rate fluctuated in the range of 0~1.86 m, and the fracture development gradually increased with the advancing of the working face. When the 2301 working face was mined to 135 m, the fracture propagation rate reached the maximum value of 8.02 in the mining process of working face, and the maximum development height of fracture zone was 113.3 m. During the gradual advancing process from 140 m to 615 m in the 2301 working face, the fracture propagation rate was less than 1.50, and there were nine relatively obvious fracture development processes which generally decreased step by step. During the advancing process of the 2301 working face after mining 620 m, the upward expansion rate of the fracture was 0, and the maximum height of the fracture zone was 154.5 m.

When the 2302 working face is mined 35 m, the crack height is 3.3 m. During the mining process of 0~125 m, the crack expansion rate fluctuates in the range of 0~2.16. The fissure height after mining 125 m is 70.1 m. When the 2302 working face is mined to 130 m, the crack growth rate reaches the maximum value of 9.32, and the maximum height of the crack zone is 116.7 m. During the gradual advancement of the 2302 working face from 135 m to 660 m, the crack growth rate was less than 1.53, and there were 11 relatively obvious crack development processes, which gradually decreased overall. After 665 m is mined at the 2302 working face, the crack upward expansion rate is 0, and the maximum height of the crack zone is 173.7 m.

The evolution trends of fractures in the mining process of working faces 222 and 224 in the 4-2 coal seam are shown in Figure 12c,d, respectively. The initial fracture height of the working face 222 was 4.2 m. During the process of mining 0~60 m, the fracture expansion rate fluctuated in the range of 0~0.84, and the fracture development gradually increased with the advancing of the working face. When the working face was mined for 60 m, the fracture height was 18 m. When 222 working face

was mined to 65 m, the middle strata of the 3-2 coal seam and 4-2 coal seam collapsed intensively, which made the fractured zone develop rapidly to the upper part of the 2301 goaf after repeated mining, the fracture expansion rate reached the maximum value of 25.98 in the process of mining the working face, and the fracture zone height suddenly increased to 148.8 m. During the gradual advancing process from 65 m to 540 m in the 222 working face, the fracture propagation rate was less than 1.86, and there were 13 relatively obvious fracture development processes which generally decreased step by step. During the advancing process of the 222 working face after mining 540 m, the upward expansion rate of fracture was 0, and the maximum height of fracture zone was 223.1 m.

The initial fracture height of the 224 working face was 6.1 m after mining for 35 m. During the process of mining 0~60 m, the fracture expansion rate fluctuated in the range of 0~1.22, and the fracture development gradually increased with the advancing of the working face. The fracture height of the working face was 19.4 m when mining for 60 m. When the 224 working face was mined to 65 m, the middle strata of the 3-2 coal seam and 4-2 coal seam collapsed intensively, which made the fracture zone develop rapidly to the upper part of the 2302 goaf after repeated mining, the fracture expansion rate reached the maximum value of 30.95 in the process of mining the working face, and the fracture zone height suddenly increased to 174.2 m During the gradual advancing process from 65 m to 600 m in the 224 working face, the fracture propagation rate was less than 2.12, and there were 13 relatively obvious fracture development processes which generally decreased step by step. During the advancing process of the 224 working face after mining 600 m, the upward expansion rate of fracture was 0, and the maximum height of the fracture zone was 245.4 m.

In the mining process of a working face, the evolution trend of fractures in the mining process of the working face can be divided into three parts: "Progressive random growth-cyclical growth-stable phase." by using the mining distance when the rate of fracture propagation is gradually stable at 0.

The working face is in the first stage of mining, and the fracture height is small. During the working face advancing with the roof caving, the fracture development is randomly increasing gradually. Within the scope of the second stage, the height of fracture development shows a dynamic development process of periodic increasing step by step with the advance of the working face, and the increase gradually decreases. In the third stage, the fracture gradually moves forward with the advancing of the working face, but the maximum height of the fracture remains constant.

In the 3-2 coal seam mining and 4-2 coal seam re-mining, the fracture development height gradually increased with the advancement of the working face in the mining process within the scope of three times square; after mining for three times, the height of fracture development tended to be stable.

According to the development height of fracture zones in the process of mining the working face, the spatial distribution characteristics of fracture zones under repeated mining in close adjacent working face are shown in Figure 13.



Figure 13. Spatial distribution characteristics of fracture zone under repeated mining in close adjacent face. (a) Repeated mining of the 2301 working face and 222 working face; (b) Repeated mining of the 2301 working face and 222 working face.

It can be seen from the characteristics of the spatial distribution of downward fracture zones in the repeated mining of the 2301 and 222 working faces (Figure 13a), combined with those of the repeated

mining of the 2302 and 224 working faces (Figure 13b), that during the mining process of the 2301 and 2302 working faces in the 3-2 coal seam, the spatial distribution state of fracture zones was "inverted bowl-stepped-rectangular". In the process of mining the 222 working face and 224 working face in the 4-2 coal seam, after mining for 50 m, the middle rock stratum collapsed, and the fracture field in the goaf rapidly developed to the upper part of goaf in the 3-2 coal seam working face.

According to the three-dimensional model, the distribution law of the height of the two zones under repeated mining in the close-distance coal seam working face is shown in Table 5, and it can be ascertained from the comprehensive development height of the two zones:

	Working Face	Cave	ed Zone	Fractured Zone		
Coal Seam	Advance State	Cumulative Height (m)	Mining Height Multiple	Cumulative Height (m)	Mining Height Multiple	
3-2	After 2301 face mining	18.4~23.0	4.09~5.11	141.7~154.5	31.49~34.33	
	After 2302 face mining	19.0~23.8	4.22~5.29	157.3~173.7	34.96~38.60	
4-2	After 222 face mining	57.8~71.2	5.78~7.12	195.6~223.1	19.56~22.31	
	After 224 face mining	60.4~75.2	6.04~7.52	223.8~245.4	22.38~24.54	

Table 5. Height distribution law of two zones in repeated mining of close-distance coal seam.

The caved height of the 2301 face after mining was 18.4~23.0 m, which was about 4.09~5.11 times larger than the mining height. The height of the caved zone after mining at the 2302 face was 19.0~23.8 m, which was about 4.22~5.29 times larger than the mining height. The cumulative height of the caved zone after mining on the 222 face was 57.8~71.2 m, which was about 5.78~7.12 times larger than the mining height. The cumulative height of the caved zone after mining on the 224 face was 60.4~75.2 m, which was about 6.04~7.52 times larger than the mining height.

The fractured height of the 2301 face after mining was 141.7~154.5 m, which was about 31.49~34.33 times larger than the mining height. The fractured height of the 2302 face after mining was 157.3~173.7 m, which was about 34.96~38.60 times larger than the mining height. The post-mining fissure zone development height of the 3-2 coal seam 2301 working face and 2302 working face under numerical simulation maintained a high degree of consistency with the actual mine. The cumulative height of the fractured zone after mining on the 222 face was 195.6~223.1 m, which was about 19.56~22.31 times larger than the mining height. The cumulative height of the fractured zone after mining height. The cumulative height of the fractured zone after mining height. The cumulative height of the fractured zone after mining height. The cumulative height of the fractured zone after mining height. The cumulative height of the fractured zone after mining height. The cumulative height of the fractured zone after mining height. The cumulative height of the fractured zone after mining height. The cumulative height of the fractured zone after mining height. The cumulative height of the fractured zone after mining on the 224 faces was 223.8~245.4 m, which was about 22.38~24.54 times larger than the mining height. The development height of the two zones of repeated mining in the close-distance coal seam group with a deep buried depth is considerably higher than the theoretical height.

In the mining process of close-distance coal seam group, the fractures in the 2302 working face of the 3-2 coal seam and the 224 working face of the 4-2 coal seam with a large width and deep buried depth developed higher after mining. The mining height multiplication factor of the caved zone of repeated mining in close-distance coal seam was large, which made the upper overburden change space small, so the mining height multiple of the fractured zone of repeated mining in close-distance coal seam group was small.

7. Conclusions

- (1) This article followed the repeated mining of the 3-2 coal seam and the 4-2 coal seam in Xiashijie Coal Mine. Through the establishment of a mechanical model of the overlying rock structure for the mining of coal seams at close distances. The determination coefficient k was introduced and the force analysis of the double-section coal pillar under repeated mining was carried out. The reasonable size of the coal pillar was determined to be 70 m.
- (2) As the development height of the fracture progressed with the working face, its expansion rate underwent four obvious changes: fluctuations within a certain range; the expansion rate reached the peak after the rock formation was concentrated and broken; the cyclical change gradually

decreased; the expansion rate was zero after complete mining. When the maximum crack growth rate and the rate gradually stabilize to 0, the mining of working face can divide the evolution trend of cracks in the mining process of working face into three parts: "Progressive random growth-cyclical growth-stable phase".

(3) The height of the fractured zone in the 2301 working face of the 3-2 coal seam after mining was 141.7~154.5 m, which was about 31.49~34.33 times larger than the mining height. The height of the fractured zone in the 2302 working face after mining was 157.3~173.7 m, which was about 34.96~38.60 times larger than the mining height. The cumulative height of fractured zones in the 222 working face of the 4-2 coal seam after mining was 195.6~223.1 m. The cumulative height of fractured zones in the 224 working face after mining was 223.8~245.4 m. In the 4-2 coal seam, the heights of the 222 and 224 fractured zones under repeated mining are 19.56–22.31 and 22.38–24.54 times the mining height, respectively, and the post-mining fracture extension of the face with a larger width and deeper burial under repeated mining was higher than that of the adjacent face.

Author Contributions: F.C. conceived, designed, and analyzed the test results; C.J. performed the experiments and wrote the manuscript. X.L. supervised the research work. Y.Y. participated in part of the drawing, and S.D. carried out the translation work. All authors have read and agreed to the published version of the manuscript.

Funding: This work was sponsored by the National Natural Science Foundation of China (No.51874231), which is part of the Shaanxi Innovation Capability Support Program (Program No. 2020KJXX-006), the Shaanxi Natural Science Fundamental Research Program Enterprise United Fund (2019JLZ-04) and the New Star of Science and Technology in Shaanxi Province. "Special Support Program" of Shaanxi Province in 2017 and Shaanxi Innovation Team Program (No. 2018TD-038) are gratefully acknowledged. The authors wish to acknowledge the financial support of the Outstanding Youth Science Fund of Xi'an University of Science and Technology (2019YQ2-16).

Conflicts of Interest: The authors declare no conflict of interest.

References

- 1. Sun, L.; Yang, K.; Yan, S.Y.; Xu, M.G. Experimental Analysis of Overlying Strata Movement Characteristic under Close Distance Coal Seam Group Downward Mining. *Chin. J. Undergr. Space Eng.* **2014**, *10*, 1158–1163.
- 2. Li, S.G.; Ding, Y.; An, Z.F.; Li, H.T.; Wei, X.W. Experimental research on the shape and dynamic evolution of repeated mining-induced fractures in short-distance coal seams. *J. Min. Saf. Eng.* **2016**, *33*, 904–909.
- 3. Cui, F.; Jia, C.; Lai, X.P.; Chen, J.Q. Study on the evolution characteristics and stability of overburden structure in upward mining of short distance coal seams with strong burst tendency. *Chin. J. Rock Mech. Eng.* **2020**, *39*, 507–521.
- 4. Mondal, D.; Roy, P.N.S.; Kumar, M. Monitoring the strata behavior in the Destressed Zone of a shallow Indian longwall panel with hard sandstone cover using Mine-Microseismicity and Borehole Televiewer data. *Eng. Geol.* **2020**, *271*, 105593. [CrossRef]
- 5. Rezaei, M.; Hossaini, M.F.; Majdi, A. A time-independent energy model to determine the height of destressed zone above the mined panel in longwall coal mining. *Tunnell. Undergr. Space Technol.* **2015**, *47*, 81–92. [CrossRef]
- Ghabraie, B.; Ren, G.; Zhang, X.Y.; Smith, J. Physical modelling of subsidence from sequential extraction of partially overlapping longwall panels and study of substrata movement characteristics. *Int. J. Coal Geol.* 2015, 140, 71–83. [CrossRef]
- 7. Iwanec, A.M.S.; Carter, J.P.; Hambleton, J.P. Geomechanics of subsidence above single and multi-seam coal mining. *J. Rock Mech. Geotech. Eng.* **2016**, *8*, 304–313. [CrossRef]
- 8. Cheng, Z.H.; Qi, Q.X.; Li, H.Y.; Zhang, L.; Liu, X.G. Evolution of the superimposeed mining induced stress-fissure field under extracting of close distance coal seam group. *J. China Coal Soc.* **2016**, *41*, 367–375.
- 9. Zhang, Y.; Zhang, C.L.; Zhao, F. Dynamic evolution rules of mining-induced fractures in different floor area of short-distance coal seams. *J. China Coal Soc.* **2015**, *40*, 786–792.
- 10. Liu, H.T.; Zhao, Z.Q.; Zhang, S.K.; Liu, B.G.; Bai, Y. Relationship between failure characteristics and fracture spacing of surrounding rock of short-distance coal seams group. *J. China Coal Soc.* **2015**, *40*, 766–773.
- 11. Du, F.; Yuan, R.F.; Zheng, J.L.; Song, G.J. Mechanism of abnormal strata pressure of mining under coal pillar in close distance shallow coal seams. *J. China Coal Soc.* **2017**, *42*, 24–29.

- Feng, G.R.; Guo, F.; Bai, J.W.; Zhang, Y.J.; Qi, T.Y.; Guo, J.; Zhang, M.; Kang, L.X. Safety mining evaluation of middle abandoned coal seam in "upper pillar-lower longwall" composite mining areas. *J. China Coal Soc.* 2017, 42, 2245–2253.
- 13. Feng, G.R.; Wang, P.F. Simulation of recovery of upper remnant coal pillar while mining the ultra-close lower panel using longwall top coal caving. *Int. J. Min. Sci. Technol.* **2020**, *30*, 55–61. [CrossRef]
- 14. Cui, F.; Dong, S.; Lai, X.P.; Chen, J.Q.; Cao, J.T.; Shan, P.F. Study on rule of overburden failure and rock burst hazard under repeated mining in fully mechanized top-coal caving face with hard roof. *Energies* **2019**, *12*, 4780. [CrossRef]
- 15. Cui, F.; Zhang, T.H.; Lai, X.P.; Cao, J.T.; Shan, P.F. Study on the evolution law of overburden breaking angle under repeated mining and the application of roof pressure relief. *Energies* **2019**, *12*, 4513. [CrossRef]
- Cui, F.; Jia, C.; Lai, X.P. Study on Deformation and Energy Release Characteristics of Overlying Strata under Different Mining Sequence in Close Coal Seam Group Based on Similar Material Simulation. *Energies* 2019, 12, 4485. [CrossRef]
- 17. Cui, F.; Yang, Y.B.; Lai, X.P.; Jia, C.; Shan, P.F. Experimental Study on the Effect of Advancing Speed and Stoping Time on the Energy Release of Overburden in an Upward Mining Coal Working Face with a Hard Roof. *Sustainability* **2020**, *12*, 37. [CrossRef]
- 18. Shen, T.; Yuan, F.; Song, S.J.; Xue, H.J.; Wen, X.G. Application of P-wave anisotropy detection in detecting the conducting fracture zone. *J. China Coal Soc.* **2017**, *42*, 197–202.
- 19. Rezaei, M. Development of an intelligent model to estimate the height of caving-fracturing zone over the longwall gobs. *Neural Comput. Appl.* **2019**, *30*, 2145–2158. [CrossRef]
- Cui, F.; Jia, C.; Lai, X.P.; Cao, J.T.; Shan, P.F. Research on development law of overlying rock two zones under repeated mining in extra-thick coal seam with gently inclined and brusting liability roof. *J. Min. Saf. Eng.* 2020, *37*, 514–524.
- 21. Xu, X.L.; Zhang, N.; Tian, S.C. Mining-induced movement properties and fissure time-space evolution law in overlying strata. *Int. J. Min. Sci. Technol.* **2012**, *22*, 817–820. [CrossRef]
- 22. Shang, H.; Ning, J.; Hu, S.; Yang, S.; Qiu, P. Field and numerical investigations of gateroad system failure under an irregular residual coal pillar in close-distance coal seams. *Energy Sci. Eng.* **2019**, *7*, 2720–2740. [CrossRef]
- 23. Suchowerska, A.M.; Merifield, R.S.; Carter, J.P. Vertical stress changes in multi-seam mining under supercritical longwall panels. *Int. J. Rock Mech. Min. Sci.* 2013, *61*, 306–320. [CrossRef]
- 24. Khanal, M.; Adhikary, D.; Jayasundara, C.; Balusu, R. Numerical study of mine site specific multiseam mining and its impact on surface subsidence and chain pillar stress. *Geotech. Geol. Eng.* **2015**, *34*, 217–235. [CrossRef]
- 25. Xu, J.L.; Wang, X.Z.; Liu, W.T.; Wang, Z.G. Effects of primary key stratum location on height of water flowing fracture zone. *Chin. J. Rock Mech. Eng.* **2009**, *28*, 380–385.
- 26. Ye, Q.; Wang, G.; Jia, Z.Z.; Zheng, C.S.; Wang, W.J. Similarity simulation of mining-crack-evolution characteristics of overburden strata in deep coal mining with large dip. *J. Pet. Sci. Eng.* **2018**, *165*, 477–487. [CrossRef]
- 27. Chen, Y.; Zhu, S.Y. Determination of caved and water-conducting fractured zones of "two soft and one hard" unstable coal seam. *Acta Geod. Geophys.* **2020**, *55*, 451–475. [CrossRef]
- 28. Majdi, A.; Hassani, F.P.; Nasiri, M.Y. Prediction of the height of destressed zone above the mined panel roof in longwall coal mining. *Int. J. Coal Geol.* **2012**, *98*, 62–72. [CrossRef]
- 29. Heather, E.L.; Douglas, T.; Mark, K.L.; Habte, A. Effects of overburden characteristics on dynamic failure in underground coal mining. *Int. J. Min. Sci. Technol.* **2017**, *27*, 121–129.
- 30. Hebblewhite, B. Fracturing, caving propagation and influence of mining on groundwater above longwall panels–a review of predictive models. *Int. J. Min. Sci. Technol.* **2020**, *30*, 49–54. [CrossRef]
- 31. Itasca Consulting Group, Inc. Online Contents for 3 Dimensional Distinct Element Code (3DEC Version 5.0); Itasca Consulting Group, Inc.: Minneapolis, MN, USA, 2013.
- 32. Yu, X.Y.; Zhang, E.Q. Mining Damage Science, 2rd ed.; Coal Industry Press: Beijing, China, 2010.

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).