Study on Deformation and Energy Release Characteristics of Overlying Strata under Different Mining Sequence in Close Coal Seam Group Based on Similar Material Simulation

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Abstract: For the characteristics of overburden deformation and energy release under different mining sequences of close-distance coal seam groups, physical material similar simulation experiments were carried out, and comprehensive monitoring methods such as dial gauge, total station, micro-seismic monitor, and pressure sensor were used to test the Guangou Coal Mine. The comparative analysis of the initial mining and the upward recovery of the B4-1 coal seam is carried out to study the migration law, mine pressure distribution, and energy release characteristics of the overlying strata during W1145 mining face mining and residual coal mining. The results show that the maximum subsidence of surface and rock formation caused by re-mining of B4-1 residual coal is 0.96 m and 2.57 m respectively, which is 0.42 m and 0.47 m lower than that of W1145 working face. The boundary angle, moving angle, and rock stratum formed by the upward recovery of the remaining coal seam are 79.3°, 81.1°, and 67.5° respectively, which are smaller than the 80.9°, 82.3°, and 75.8° formed by the first mining. The cumulative development height of the fracture zone caused by upward mining is 115.7 m, which is 8.0% smaller than the cumulative development height of the downstream fracture zone of 125.8 m. When the up-level mining is carried out, the fragmentation effect of the rock layer below the key layer is strong, which makes the loosely broken rock block have a better supporting effect. Therefore, the residual coal mining time is longer than that of the first mining. The initial pressure step of the residual coal recovery is 139.2 m, and the average step of the cycle is 34.2 m, which is significantly larger than the 128.0 m and 26.0 m of the first mining. The loose rock strata that are disturbed by the upward recovery are more likely to be broken. Therefore, there are more micro-seismic events during the re-mining of the remaining coal. The B4-1 residual coals have a total of 945 incidents of re-seismic micro-seismic events, which is 292 more than the W1145 working face. After the B2 coal seam mining disturbance, the energy of some rock layers above the B4-1 coal seam is released, so that the micro-seismic energy caused by re-mining of the remaining coal seam is small. Through microseismic monitoring, it can be concluded that the accumulated energy in the process of upward re-mining of remaining coal seam is less than that in the process of downward mining of W1145 working face. Upward recovery is more likely to cause damage in the disturbed loose rock formation. Therefore, the frequency of micro-seismic events during the upward recovery is higher, and the partial energy release of the rock after the disturbance is caused, so that the source energy generated in the unit length of the upward recovery is smaller than the initial one.

1. Introduction

With the reduction of coal resources, coal resources under various complicated conditions have gradually received attention. Among them, the typical short-distance coal seams are widely distributed within most of China's mining areas. For different mining sequences of close-distance coal seam groups, the use of up-draft mining has the advantages of short preparation time, quick coal output, and favorable drainage of working face. The use of down-draw mining has reduced initial construction volume and initial investment, and quick construction and coal production.

The selection of a mining sequence for close-range coal seam groups is often based on considerations of economy, technology, and safety. The characteristics of overburden changes affected by mining disturbance are different under different mining sequences. This study on overburden deformation and energy release characteristics under different mining sequences for close-range coal seam groups fills up the gap in the study of overburden changes and energy release differences under different mining sequences for relatively complex close-range coal seam groups. In order to solve the problem of coal resource exploitation under the complicated conditions that affect the safe production of coal in our country and restrict the harmonious development of the coal industry, it is particularly important to study the experiment of different mining sequence of close seam group.Through the research on different mining sequences of coal seam groups, not only can the effective utilization of resource exploitation under increasingly severe complicated geological conditions be guaranteed, but it also has the practical significance of selecting a reasonable mining sequence according to local conditions and promoting safe production.

For the characteristics of overburden deformation and energy release under different mining sequences of close-distance coal seam groups, Zhang et al. studied the feasibility of upward mining of 3 coal above the 4-coal mining area in the Zhongpingdong Coal Mine by using numerical simulation and other methods [1]. Lyu et al. proposed that during the downward mining of close-range coal seam, the working resistance and initial supporting force of the support should be increased to ensure the supporting strength of the working face [2]. Huang et al. put forward two layout schemes of upward mining roadway, i.e., internal dislocation and external dislocation, which effectively avoided the influence range of fracture zone and concentrated stress [3]. Jiao et al. carried out the mining test of the lower protective layer, monitored the movement curve of the strata, and mastered the space-time evolution law of cracks in the overlying strata [4]. Zhang et al. have analyzed the variation characteristics and zoning characteristics of surrounding rock stress distribution during upward mining, the main distribution areas of rock fissure enrichment areas, and their evolution laws [5]. Shao et al. have simulated and studied the evolution law of overlying strata fissures and the stability of interlayer strata in the upward mining of typical working faces in the Dongmao Coal Mine [6]. Zhang et al. determined the structural change characteristics of the upper coal seam after mining the lower coal seam in view of the upward mining of the close coal seam group in the Qinghemen Mine [7]. Li et al. studied the mining influence law of 13.14m B902 working face in No.9 coal seam on 7.02m B4101 working face in No.4 coal seam and the surrounding stress variation law in view of the combined mining of the Anjialing mine [8]. Gong et al. analyzed the overburden structure and surrounding rock stability control during the mining of close coal seam group in Dongqu Coal Mine by using UDEC numerical calculation method, which is a calculation and analysis program based on discrete element method theory [9]. Li et al. Deduced the equation of vertical approximate transfer law of concentrated stress and linear stress in rock mass [10]. Yu et al. used numerical simulation and other methods to deduce the development and expansion heights of broken roof groups during mining of different coal seams [11]. Wang et al. found that the amount of crushing and swelling of mining rock mass is

directly proportional to its depth and obtained the calculation equation of the subsidence coefficient of surface and rock mass during initial mining [12]. Ma et al. have carried out physical, similar material, experimental simulation research on coal pillar failure and overburden movement law in the Fengjiata Coal Mine [13]. Xu et al. simulated and studied the damage and movement laws of overlying strata during mining of 10# lower coal seam and 9# upper coal seam of close-range coal seam group with interval of 6.45m by UDEC numerical software [14]. Wang et al. systematically studied the laws of mining stress and overburden movement in deep stope [15].

Luan et al. has carried out research on the height of water flowing fractured zone in overlying strata after single mining and repeated mining of two layers of coal [16]. Jiang et al. analyzed the law of caving and movement of overlying strata during repeated mining, and concluded that there was "activation" of roof above gob due to increase of mining height caused by repeated mining [17]. Liu et al. proposed a method to predict the height of water flowing fractured zone by analyzing the distribution of damage zones in the model with simulation software FLAC3D [18]. Kang et al. analyzed the four stages of surface mining cracks and their formation mechanism based on field data, revealing the influence of mining cracks on surface movement and deformation in mountain areas [19]. Han et al. established the feasibility criterion of upward mining of close seam group, and determined the evaluation index of upward mining feasibility [20].

Yan et al. gave the equation for calculating the conventional offset of working face under the combined mining of short-distance thin coal seam groups [21]. The theory of "masonry beam" put forward by Qian et al., provides a basis for the study of bearing pressure [22]. Kong et al. based on the relationship between the micro-seismic event of surrounding rock in stope and the distribution of supporting pressure, put forward that the fundamental cause of surrounding rock failure is the movement of overlying strata and the adjustment of supporting pressure transfer [23]. Dou et al. according to the energy theory, the mechanism of rock burst caused by instability of spatial structure is discussed [24]. Yang et al. through the engineering geomechanical model test, the mining impact law and overburden dynamic failure mechanism of multi-coal mining are characterized [25]. Kong et al. used rock mechanics tests, similar simulation, and numerical simulation to study the roof fracture characteristics and overlying rock migration law of the upper coal seam under the repeated mining of the near coal seam group [26]. Ning et al. proposed a method to determine the height of fracture zone in the mining process of the close coal seam group based on two numerical values of separation distance and the final settlement value of close coal seam [27]. Yang et al. studied the development of mining stress during large-height upward mining and obtained the deformation and failure characteristics of overlying strata, the development patterns of mining stress and fissures, and the size of the relief area [28]. Huang et al. studied the dynamic periodic cracks in the process of multi-seam mining and showed that cracks have the phenomenon of activation and development. Through the coupling control of underground concentrated stress and surface cracks, they analyzed the three-field evolution in dense multi-seam mining [29,30]. Cheng et al. studied the evolution characteristics of roof movement and mining stress in the process of mining near-distance coal seams [31].

Based on the above analysis, many scholars have made fruitful research on overburden movement, fracture development, and stress change characteristics caused by mining of close-range coal seams. However, most of the research is aimed at deformation and damage caused by the single mining sequence of coal seams, and the comprehensive action mechanism of overburden deformation, roof weighting, and energy release is rarely mentioned for the analogy of different mining sequences of close-range coal seams.
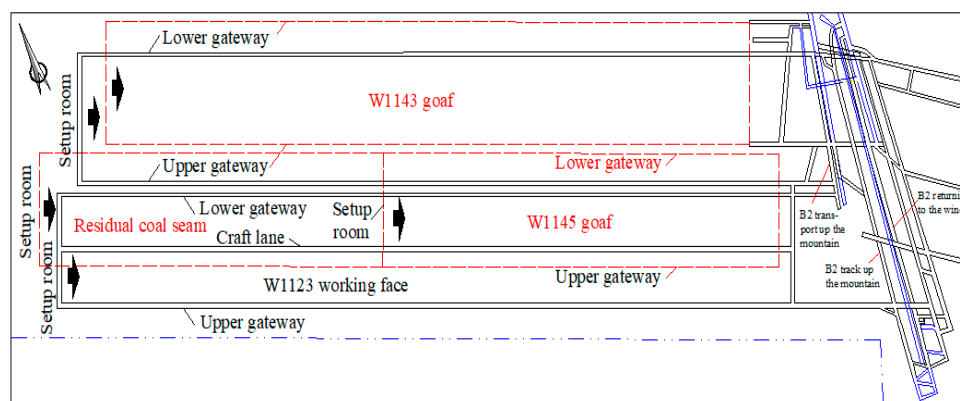
In this paper, physical material similarity simulation experiments are used, and comprehensive monitoring methods such as dial indicator, total station, micro-seismic monitor, pressure sensor, and other equipment are used. For different mining sequences of close coal seam groups in the Kuangou Coal Mine, the study on the differences under different mining sequences is carried out through the overlying rock movement rules, mine pressure behaviors, and energy release characteristics caused by downward initial mining and upward re-mining of the B4-1 coal seam group, which provides a

basis for the overlying rock movement rules and energy release characteristics during upward mining and downward mining of close coal seam groups, and provides a reference for the prediction and prevention of mine disasters under close coal seam group mining.

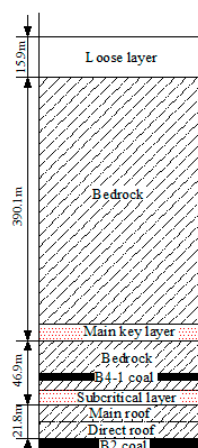## 2. Engineering Background and Similar Simulation Experiment Design

2.1. Engineering Background

The Kuangou Coal Mine of the Shenhua Company is located at the northern foot of Tianshan Mountain in Hutubi County, Xinjiang. The mine field is 9.7 km long from east to west, 3.15 km wide from north to south, and covers an area of about 20.1325 km^2. At present, the west wing mining area mainly mines B4-1 coal seam and B2 coal seam. B4-1 coal seam has an average thickness of 3.0 m and an average dip angle of 14. The W1145 working face with a strike of about 746 m and the remaining coal with a strike of about 384 m are located in B4-1 coal seam, and a comprehensive one-time mining method of full height is adopted. B2 coal seam has an average thickness of 9.5 m and an average inclination of 14, with hard roof and impact tendency. W1123 working face, with a recoverable strike length of 1468 m and a tendency of 192 m, is located in B2 coal seam, and fully mechanized top-coal caving is adopted, with a mining height of 3.2 m and a caving height of 6.3 m. At present, the Kuangou coal mine is mining W1123 working face, and the mining sequence is B4-1 coal seam W1145 working face, B2 coal seam W1123 working face, and B4-1 coal seam residual coal. The structural diagram of Kuangou coal mine is shown in Figure 1.

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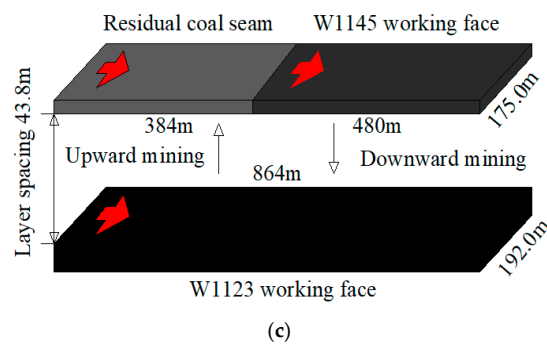

(**b**)

Figure 1. *Cont.*

(c)

Figure 1. Structural diagram of the Kuangou Coal Mine. (**a**) Mine layout, (**b**) comprehensive histogram of coal seam, and (**c**) schematic diagram of close-range coal seam groups.

2.2. Physical Material Model Design and Monitoring Arrangement

In view of the fact that the physical similarity simulation can better reflect the roof caving situation of the working face, this paper carries out the overburden similarity simulation experiment of B4-1 residual coal re-mining under the roof condition with impact tendency. Figure 2 shows the layout of material model monitoring. In the simulation experiment, a plane strain model frame with an overall dimension (length × width × height) of 5.0 × 0.3 × 1.89 m was used. The geometric similarity ratio ($\alpha_L = L_H /L_M$) of the simulation experiment was 1:200. According to the similarity theorem, the time similarity ratio ($\alpha_t = \sqrt{\alpha_L}$) was 1:14.14, the similarity ratio of bulk density, Poisson's ratio, and internal friction angle was 1:1, and the pressure similarity ratio ($\alpha_\rho = \alpha_l{}^3 \cdot \gamma_H /\gamma_M$) was 1:1.2 × 10^{-7}. The top of the model is paved with 0.05 m iron bricks to realize the equivalent load of the untested strata. Due to the monitoring requirements of the upward mining overburden structure movement rule and energy release characteristics, the physical similarity experimental model is equipped with a dial indicator, a total station displacement monitoring system, a micro-seismic monitoring system, and a support pressure monitoring system.
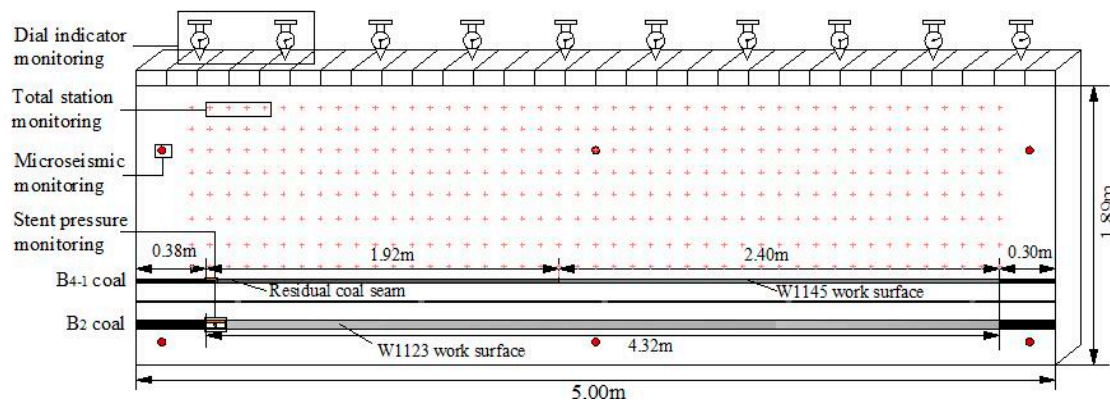

Figure 2. Material model monitoring layout.

In the physical simulation experiment, a total of 10 dial indicator monitors are arranged above the iron brick. The 1# and 10# dial indicators are 4.5 m apart and 0.25 m apart from the left and right boundaries of the model. The adjacent dial indicators are evenly distributed at intervals of 0.5 m.

The monitoring origin of the total station is arranged in the upper left corner of the model, and according to the intensity of overlying strata activities at different heights of coal seam mining, ten displacement survey lines A to J are arranged along the vertical direction of the model. Each survey line is equipped with 45 measuring points, with 1# and 45# measuring points 0.3 m away from the left and right boundaries of the model, and adjacent measuring points are evenly distributed at intervals of 0.1 m.

The micro-seismic monitoring system is equipped with 6 probes for energy monitoring. The 1#~6# measuring points are sequentially arranged from top to bottom and from left to right. The 1#, 2#, and 3# measuring points are 1.25 m from the lower boundary of the model, the 4#, 5#, and 6# measuring points are 0.05 m from the lower boundary of the model, and the 1# and 2#, 3# and 4#, and 5# and 6# measuring points are 0.1 m, 2.50 m, and 4.95 m from the left boundary of the model, respectively. In the process of coal seam mining, the Hanzhong fine resistance strain force sensor is used to monitor the overburden stress in real time.

2.3. Experimental Scheme

The physical material similarity model experiment in this paper divides B4-1 remaining coal seam into six regions, each region has an average length of 64 m. Considering the actual cutting depth of the drum is 0.8 m, the advancing speed is designed to be an integer multiple of 0.8 m, and the cumulative mining is 127 times. The experimental scheme is shown in Table 1. In order to carry out comparative analysis and research, the mining of W1145 working face is divided into 6 regions on average, according to the advancing degree of 8 m per day, and the range of each area is 80 m.

Table 1. Experimental program.

Coal Recovery	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6
Propulsion range (m)	0–64	64–126.4	126.4–190.4	190.4–254.4	254.4–316.8	316.8–384
Area length (m)	64	62.4	64	64	62.4	67.2
Advance (m/d)	1.6	2.4	3.2	4	4.8	5.6
Number of advances (n)	40	26	20	16	13	12

The distance between upper and lower coal layers is one of the main technical factors affecting upward mining. Therefore, a reasonable interval is the primary problem to study upward mining. So far, a lot of practical experience and research methods have been accumulated for upward mining. This time, the surrounding rock balance method, which is a discrimination method for upward sequential mining between near horizontal seams, gently inclined coal seams, and medium inclined coal seams, is used to analyze the feasibility of upward mining of B4-1 coal seam in the Kuangou Coal Mine. The criterion for upward mining of coal seam is that when there are hard strata in the overlying strata on the mining field, the upper coal seam should be located on the equilibrium strata closest to the lower coal seam, and the interval between strata necessary for upward sequential mining can be estimated according to eguation (1).

$$H > \frac{M}{K_1 - 1} + h \tag{1}$$

In the equation: M is the mining height of B2 coal seam, M = 9.5 m, K_1 is the rock expansion coefficient, K_1 = 1.20~1.30. This article selects K_1 = 1.30. h is the balance of the thickness of the rock mass itself, usually considered as h = 4.5 m. The parameters are brought into Equation (1) to obtain. The average layer spacing, H, between the B4-1 coal seam and the B2 coal seam is 43.8 m, which is greater than the necessary layer spacing of 36.2 m.

3. Deformation and Caving Characteristics of Overlying Strata under Different Mining Sequences of Coal Seam Groups

3.1. Difference of Overburden Migration

During the first downward mining process of W1145 working face in B4-1 coal seam (Figure 3), when the coal seam was advancing 56.0 m in region 1, a large area of suspended roof collapsed for the first time, and the separated seam developed gradually with the mining. In the process of advancing from region 2 to region 6, the top plate is affected by the gravity of the upper overburden and rock strata, and the overburden collapses from the center of the mined-out area, causing obvious damage, and continuously develops towards the advancing direction of the working face. Among them, when

region 2 is advanced by 128.0 m, the direct roof collapses for the first time, and the delamination develops to below the main key layer. The working face in region 3 continues to push forward and the lower separation space extends upward, while the roof failure areas of the working face are hinged with each other to form a stable structure, which hinders the upward movement of the collapsed roof, and causes the roof failure to present a continuous and regular collapse in the process of advancing from region 4 to region 6.
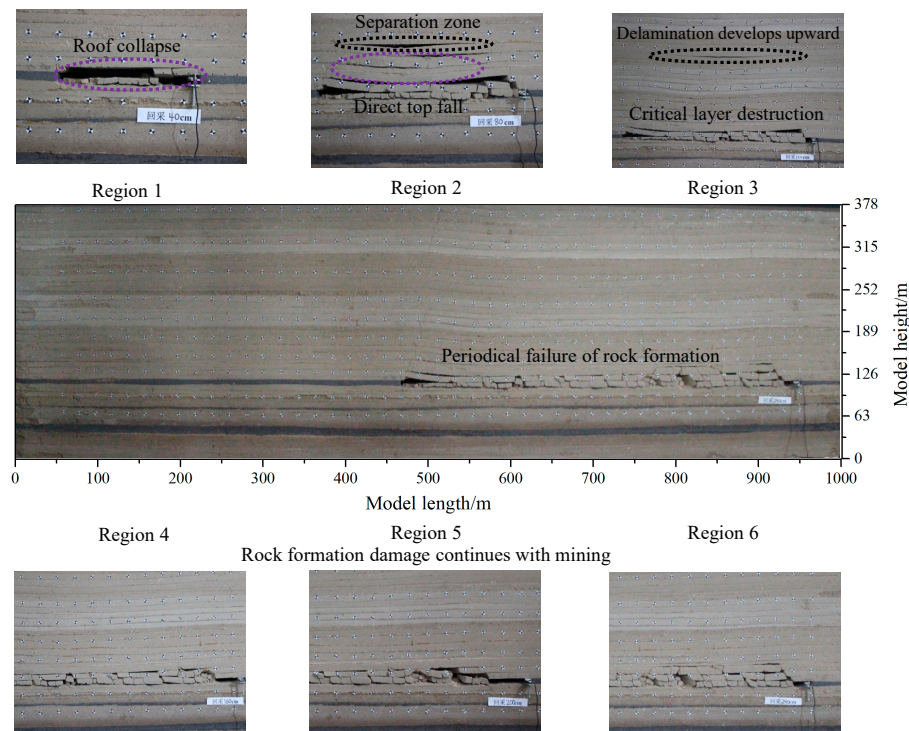

Figure 3. Characteristics of overlying strata in W1145 working face mining.

There are two main roof states in the mined-out area during the mining process of W1145 working face: the state of overhanging during the mining process of 0~56.0 m, and the 56.0~464.0 m stopping process is in a caving state, and its caving state is a regular periodic destruction process.

After the mining of W1123 working face was completed, during the upward mining of B4-1 remaining coal seam (Figure 4), there was no obvious change in the hard roof of region 1. When the coal seam was advancing by 64.0 m, the roof appeared as the local roof caving phenomenon. During the mining process in region 2, roof caving occurred continuously with the mining progress. By the end of mining in region 2, the direct roof was relatively stable, making the overlying strata appear obvious as the delamination phenomenon. During the mining process in region 3, the vertical fractures gradually expanded upward, and the direct roof collapsed for the first time when the working face was mining 155.2 m. By the end of mining in region 3, there was an obvious concentrated collapse zone, and an obvious separation zone was formed at about 55.0 m above the collapse zone from the B4-1 coal seam roof. In the mining process of region 4 and region 5, the step distance of roof failure obviously increases, the separation space far away from the working face is gradually compacted, and there are obvious cracks and separation in the gob roof near the working face, which continuously bend and sink with the advancing. In the process of mining in region 6, the number of newly generated fractures is relatively small. After the 126th advance, only 5.6 m long residual coal is instantaneously crushed under the huge pressure of the upper strata, and rock burst occurs, resulting in a 35.0 m long instantaneous caving zone of the roof.
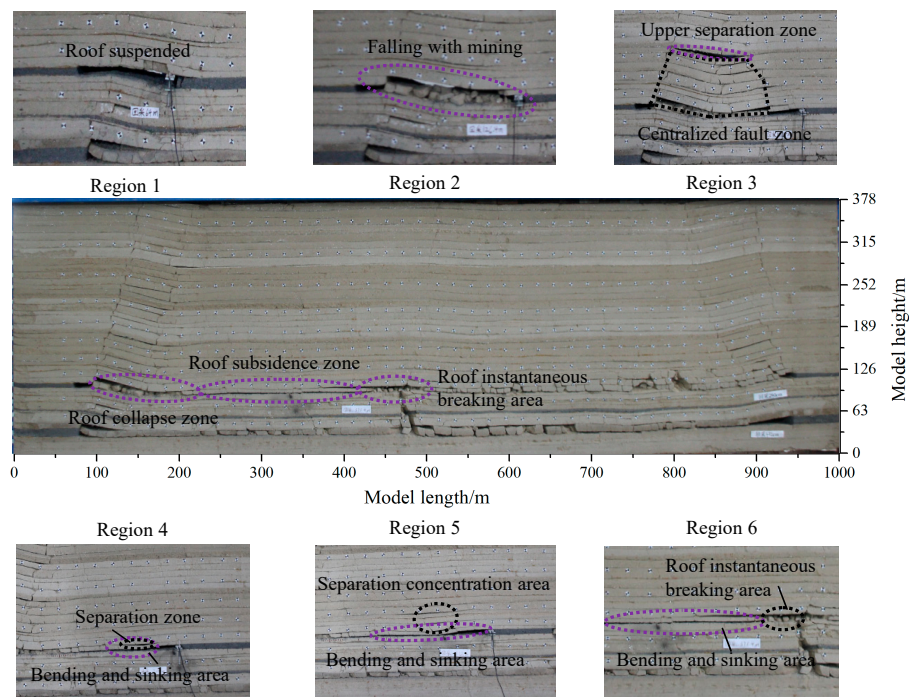
Figure 4. Residual coal re-mining overburden variation characteristics.

There are three main roof states in the mined-out area during the residual coal mining process: the state of overhanging during the 0~62.4 m mining process, the 62.4~164.8 m and 378.4~384 m mining process in the caving state, the former with mining collapse, the latter is a large area of roof instantaneous collapse, and the 164.8~378.4 m mining process is in a state of bending and sinking.

Based on different mining sequences, the differences of overburden failure in B4-1 coal seam advancing process (Table 2) are analyzed. The mining of B2 coal seam helps to liberate B4-1 coal seam and weakens the impact tendency of overlying rock on the upper part of the remaining coal seam, so the large-area roof hanging step distance is longer when the remaining coal seam is re-mined. At the same time, affected by the mining disturbance of B2 coal seam, the overlying strata are loosened. The crushing and swelling effect of the strata below the key layer is stronger than that of the first mining, which has a better supporting effect. Therefore, the initial caving of direct roof under re-mining of residual coal lags behind the mining of W1145 working face. In addition, there are obvious differences in the change trend of the roof during the advancing process of the working face, in which the mining of W1145 working face presents "large area roof-caving with mining-periodic damage", while the re-mining of the remaining coal seam presents "large area roof hanging–caving with mining–bending subsidence–instantaneous rock burst".

Table 2. Variation of overlying strata under different mining sequences in B4-1 coal seam.

Difference	W1145 Working Face Mining	B4-1 Residual Coal Re-Mining
Large-area hanging step distance of roof/m	56.0	62.4
Direct roof-caving for the first time	Mining 128.0 m	Mining 155.2 m
Roof change trend	Large area roof hanging–caving with mining-periodic damage	Large area roof hanging–caving with mining–bending subsidence–instantaneous rock burst

3.2. Surface Deformation Characteristics under Different Mining Sequences

In the physical material similarity simulation experiment B4-1 coal seam mining process, the dial indicator monitor is used to analyze the surface subsidence characteristics, monitor the surface

strata displacement changes in different stages of advancement, and analyze the surface strata deformation law.

The surface subsidence characteristics in the B4-1 coal seam mining process are shown in Figure 5, which can be seen from the surface subsidence characteristics (Figure 5a) of W1145 working face mining. When the working face is advanced to 160 m, the surface is obviously deformed, and the maximum surface subsidence measured at the 6# measuring point is 0.51 m. With the advance of the first mining face of W1145, the point with the largest subsidence deformation of the surface strata gradually moves to the advancing direction of the working face until the mining of W1145 face is finished. The maximum subsidence point is basically located above the center of the mined-out area on the side of the mining line that is deviated from the stop line. The surface subsidence measured by the 5~9# measuring points are 0.63 m, 1.05 m, 1.38 m, 1.36 m, and 1.04 m, respectively. The sinking curve of the surface rock layer shows the "V-shaped" deformation of the mining to 160 m, and the "U-shaped" deformation distribution after the end of the mining of the W1145 working face.
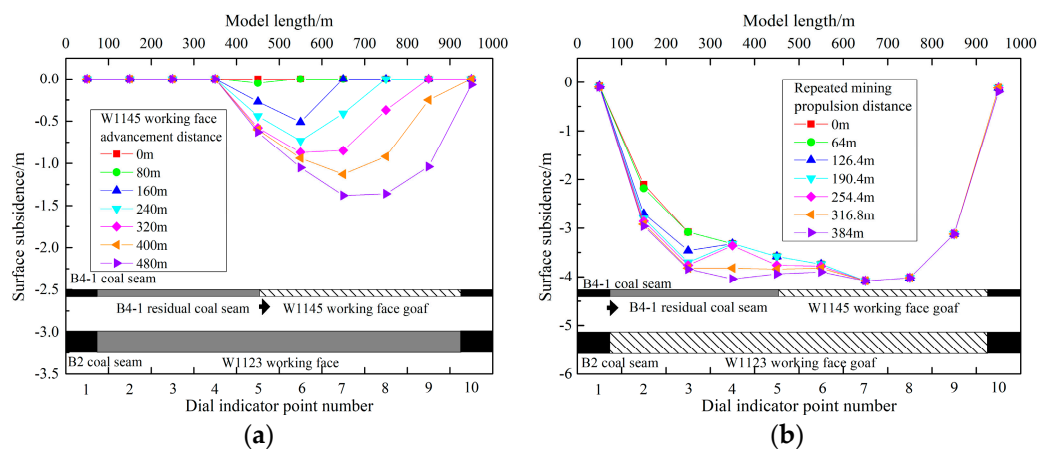

Figure 5. Surface subsidence characteristics. (**a**) Mining surface subsidence characteristics in W1145 working face, and (**b**) characteristics of surface subsidence in re-mining of residual coal.

According to the surface subsidence characteristics of re-mining of residual coal (Figure 5b), the surface subsidence before re-mining of residual coal is obviously lower than that above the mined-out area of W1145 face. The surface subsidence curve shows a "W-shaped" distribution characteristic with the peak points on the left and the middle approximately equal.

When the residual coal is pushed to 126.4 m, the surface strata change obviously. The vertical displacements measured at the 2# and 3# measuring points change from 2.03 m and 2.82 m to 2.55 m and 3.20 m respectively, and the subsidence amounts are 0.52 m and 0.38 m, respectively. The surface deformation of residual coal in the process of advancing from region 1 to region 4 is relatively small, and there is no obvious surface deformation except that the roof strata concentrated collapse caused by 164.8 m of residual coal advancing causes 2.3 m deformation at the 3# measuring point. When the residual coal is pushed to 316.8 m, the roof gradually sinks and accumulates for a long time, and the strata in the middle gradually sink and gradually affect the surface, making the surface at the 4# measuring point change obviously by 0.58 m. At the end of the re-mining of residual coal, the rock burst phenomenon caused the instantaneous settlement of a large area of rock strata to affect the surface, causing obvious subsidence of the surface in the range of 300~500 m, with the 4# and 5# measuring points being the most obvious, with subsidence amounts of 0.34 m and 0.52 m, respectively.

Comprehensive analysis of the subsidence characteristics of the surface shows that the maximum surface deformation after ascending mining is 4.04 m accumulated at the 4# measuring point, and the maximum surface deformation after descending mining is 4.07 m and 4.09 m accumulated at the 7# and 8# measuring points. The maximum surface subsidence caused by two different mining methods of descending mining and ascending mining are basically the same. The total surface displacement

caused by ascending mining is small, and the final surface subsidence curve shows a "W" distribution characteristic with a small central maximum point.

The surface subsidence curve gradually moves towards the working face with mining. The maximum subsidence of the surface strata caused by the first downward mining of W1145 face in B4-1 coal seam is 1.38 m, which is 0.42 m larger than the maximum subsidence of 0.96 m caused by the repeated upward mining of residual coal in B4-1 coal seam. Therefore, the surface subsidence caused by the downward mining in B4-1 coal seam is higher.

3.3. Deformation Characteristics of Overlying Strata under Different Mining Sequences

Through monitoring the subsidence of upper strata before and after the mining of physical model coal seam with the total station, the subsidence variation curves of different strata are obtained, as shown in Figure 6. The vertical displacement of measuring points at the W1145 working face after mining is the subsidence caused by mining, and the difference between the vertical displacement monitored at each measuring point of residual coal re-mining before and after mining is the subsidence caused by residual coal re-mining.
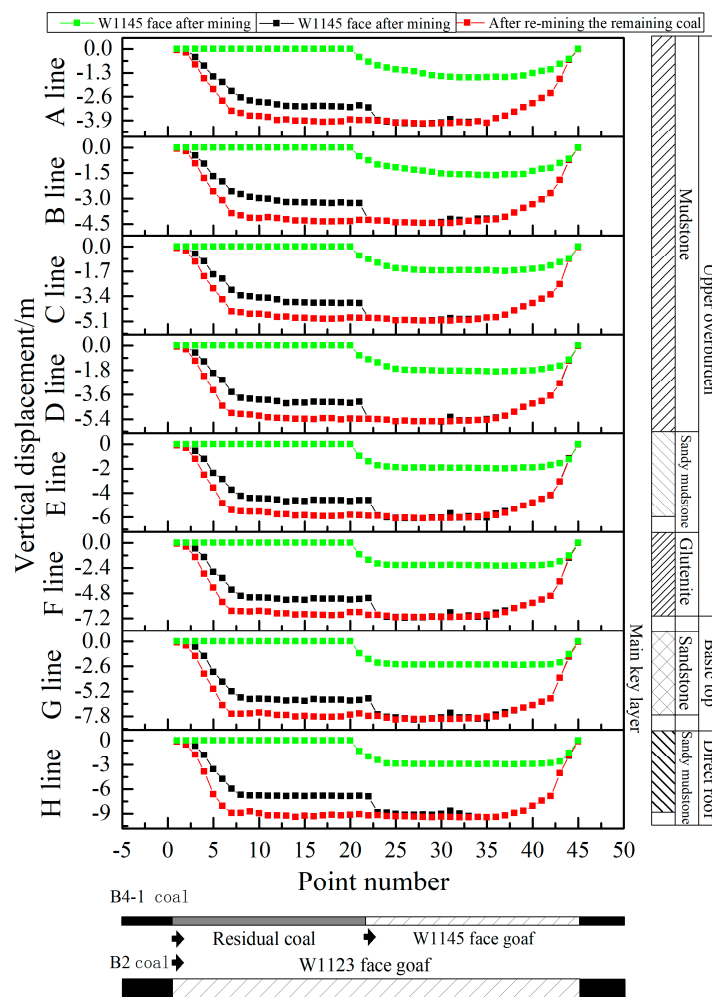
Figure 6. Vertical displacement of rock strata in coal seam mining.

The vertical displacement of the direct roof and the basic roof at the W1145 working face after mining has obvious symmetry and presents obvious U-shaped distribution. However, the asymmetry of the vertical displacement of the strata becomes more and more obvious with the increase of the layer height of the overlying strata, showing the feature that the left part of the depression moves slightly

lower than the right part. It is proven that there are more pores between the layers of the gob near the open cut surface after the W1145 working face is mined, and the caving between gob layers near the top of the stopping line is more sufficient.

The vertical displacement of overlying strata after mining in the W1123 face of B2 coal seam is obviously asymmetric. Because 384 m of residual coal has not been mined, the vertical displacement of overlying strata above B4-1 residual coal is obviously smaller than that above the mined-out area of the W1145 face, and the subsidence depression area of overlying strata after mining in B2 coal seam presents an obvious stepped distribution.

By the end of mining of B4-1 residual coal, the displacement of overlying strata in the depressed area of the residual coal gob is basically the same, showing obvious symmetry, while the left and right ends of the gob of B4-1 coal seam show slightly obvious asymmetry influenced by the mining sequence. The vertical displacement of rock stratum caused by downward mining is slightly larger than that of upward mining, in which the vertical displacement of sag area after direct roof mining is 9.38 m and 9.12 m respectively, with a difference of 0.26 m. At the critical position of the mined-out area between the re-mining of the residual coal and the W1145 face, due to the instantaneous crushing of the 5.6 coal pillar at the tail end of the residual coal, a large amount of rock caving is caused by rock burst, which makes the overlying rock at the critical position strongly affected by the crushing and swelling factors of the rock. The measured vertical displacement of the upper basic roof at the critical position is 7.52 m, which is lower than the average values of the vertical displacement of the depressed area after the direct roof is mined downward and upward by 8.03 m and 7.85 m.

After repeated mining of residual coal, the relatively stable interlayer rock strata are further compressed under the influence of mining of the upper B4-1 coal seam, and the caving zone of interlayer rock strata is further compressed under the influence of repeated mining of residual coal, so that the crushing expansion effect is reduced and further compacted, so that the number 6 measuring point falls behind the main roof for the first time, the subsidence amount reaches 3.29 m, which is 3.0 m higher than that of B4-1 coal seam. Therefore, protective measures should be strengthened when mining to the number 6 measuring point, i.e., the model length is 180 m, to ensure safe mining. The repeated mining of residual coal also has a certain influence on the strata above the W1145 face. Due to the long-term disturbance of the repeated mining of residual coal, the loose caving rock blocks continue to compact, forming a new stable structure after the crushing and swelling effect is reduced. The vertical displacement of some overlying rock positions continues to increase, with the displacement of measuring point 31# on total station detection line H, where the direct roof is located, being the largest, reaching 0.51 m.

After re-mining the remaining coal seam, the subsidence of the middle part of the model is less than that of both ends, and the subsidence of the upper strata above the main key strata due to downward mining of the right overburden of the model is slightly greater than that due to upward mining of the left overburden. Before and after the re-mining of the remaining coal, the subsidence curve gradually transits from "step-like" to "groove-like" distribution. Affected by B4-1 residual coal mining, the periodic collapse of the main roof makes the subsidence curve of the direct roof and the basic roof show obvious fluctuation type. The three-hinged arch-like balance structure formed by mutual articulation and extrusion between rock blocks leads to the discontinuity of the subsidence curve. Therefore, the vertical displacement of the direct roof and the basic roof measured by G and H lines varies greatly. However, after the mining of B2 coal seam, the overlying strata of the residual coal sink obviously, but it is relatively gentle and has no obvious fluctuation, thus it can be seen that the residual coal of B4-1 coal seam is located in the bending subsidence zone after the mining of B2 coal seam.

In the process of coal seam mining, the vertical displacement measured by the same measuring line at different measuring points of the same rock stratum is different. The further away from the coal seam, the smaller the vertical displacement difference at different measuring points of the same layer in the overlying rock stratum, the greater the vertical displacement difference at different side points of

the same layer closer to the coal seam between the direct roof and the basic roof. In the overlying strata above the coal seam measured by different measuring lines at the same measuring point, the lower the horizon, the lower the vertical displacement of the strata.

Under the strong supporting action of the main key layer, the porosity of the direct roof located below the main key layer is relatively high, so that the average vertical displacement of the depressed area of the main key layer located at the basic roof is 7.94 m, and the average vertical displacement of the direct roof is 9.25 m, which is 1.31 m, the maximum displacement at the same line spacing.

In the vertical displacement change of the same rock stratum caused by the upward mining and the downward mining of B4-1 coal seam and B2 coal seam, the rock stratum displacement caused by the upward mining is relatively small, and the closer to the coal seam, the more obvious the trend is, the smaller the displacement difference caused by the different upward and downward mining of the rock stratum with higher horizon, and the average difference in the direct top-middle depression area is 0.26 m. B4-1 coal seam suffered from direct roof caving due to downward mining of the W1145 working face, making the average displacement of the direct roof sag area measured by line H 2.94 m. The average displacement of the direct roof sag area of line H caused by the upward re-mining of the remaining coal seam is 2.57 m, and the downward first mining of B4-1 coal seam is 0.47 m higher than the vertical displacement of the direct roof caused by the upward re-mining.

3.4. Development Scope of Surface Subsidence Basins under Different Mining Sequences

There are obvious differences between upward mining and downward mining in the degree of surface movement and deformation and the influence scope of mining subsidence. By characterizing the boundary point, critical boundary point, boundary angle, movement angle, and break angle of the main section of the moving basin, forming an included angle with the gob boundary at the time of full mining, specific analysis is made.

In this paper, after the end of down-mining and up-mining, the boundary angle is taken as the connecting line between the 10 mm subsidence point of surface strata and the gob boundary. Taking the line connecting the outermost point with surface inclination of 3 mm/m, curvature of 0.2×10^{-3}/m, and horizontal deformation of 2 mm/m and the gob boundary as the moving angle, the connecting line between the surface rock break point and the gob boundary is taken as the rock break angle.

According to the detection data of overburden movement and surface movement in the physical material simulation experiment, and based on the parameters when fully mining, various angle parameters of the surface subsidence basin are calculated according to the following equation:

$$\alpha = \arctan \frac{D}{L} \tag{2}$$

Among them: α is the boundary angle, moving angle, breaking angle, and other angle parameters. D is the vertical height of overburden from the gob boundary point to the upper surface of model, m, and L is the horizontal distance from the gob boundary point to the angle parameter selection boundary point, m.

Since the surface subsidence in various angle parameters is much smaller than the cumulative vertical height of overburden, it is assumed that the cumulative vertical height of overburden is always 302 m. According to the monitoring results, the horizontal distances for the boundary angle parameters of upward re-mining and downward mining are 56.8 m and 48.5 m respectively, and the horizontal distances for the movement angle parameters are 47.2 m and 40.7 m respectively, which are, in turn, brought into Equation (2). Figure 7 is a schematic diagram of the surface subsidence basin drawn by connecting the obtained angle and the cut-off angle with the caving angle of the strata when mining is stopped.
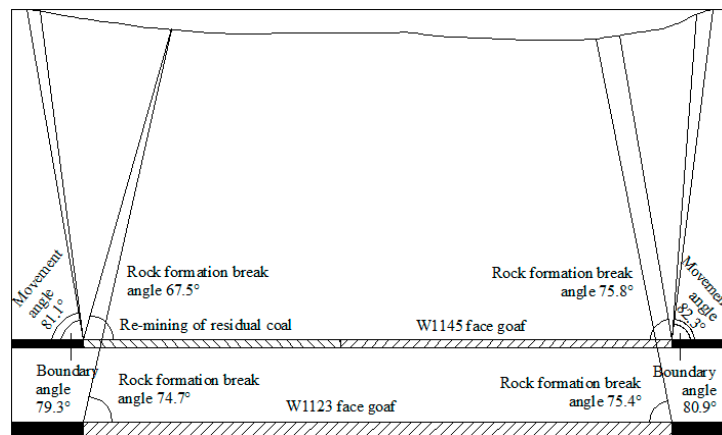
Figure 7. Schematic diagram of surface subsidence basin.

The boundary angles formed by mining B4-1 coal seam upwards and downwards are 79.3 and 80.9, respectively. The moving angles are 81.1 and 82.3, respectively. After mining, the difference between the break angle of the rock strata at the cut-off and cut-off lines of B2 coal seam is small, being 74.7 and 75.4, respectively. The damage area under the envelope of the break line of the rock strata is basically distributed in an isosceles ladder shape. As the mining order of the downward mining W1145 face is prior to that of B2 coal seam, the break angle of the rock strata is almost unaffected by B2 coal seam, so the break line of the rock strata at the cut-off formed after the mining of the W1145 face is approximately parallel to B2 coal seam, and the break angle of the rock strata at the cut-off is 75.8.

As the mining sequence of the upward residual coal re-mining lags behind B2 coal seam, the rock burst angle of the residual coal re-mining is significantly affected by B2 coal seam. On the basis of the W1123 face cut-off line formed after B2 coal mining, the residual coal mining closes the original rock burst part and generates new fractures again. The re-generated broken lines are mainly concentrated on both sides of the connecting line between the residual coal cut-off line and the upper end point of the W1123 face cut-off line, making the rock burst angle of the residual coal re-mining cut-off line smaller, about 67.5. The boundary angle, movement angle, and rock stratum breaking angle formed by the repeated mining of residual coal on the stopping line for upward mining are smaller than those for downward mining, and the difference values are 1.6, 1.2, and 8.3, respectively.

3.5. Development Characteristics of Water Flowing Fractured Zones under Different Mining Sequences

There are obvious differences in the distribution of fracture zones between downward mining and upward mining. According to the experimental scheme, after the W1145 face, W1123 face, and residual coal are mined in sequence, according to the evolution trend of the final shape of fracture zone development and the cumulative height of the vertical fracture zone of overlying rock in the process of advancing, and according to the maximum development height of the fracture zone under different advancing distances and the upward development height of fracture per unit length after advancing measured by the fracture expansion height under each advancing degree, i.e., the fracture expansion rate, the fracture zone development law of upward re-mining and downward mining is shown in Figure 8. The upward propagation speed of fracture:

$$v = h/s \tag{3}$$

where v is the upward propagation speed of the fracture, m/s, h is the upward expansion height of the fracture after advancing, m, and S is the propulsion degree of this propulsion, m/time.
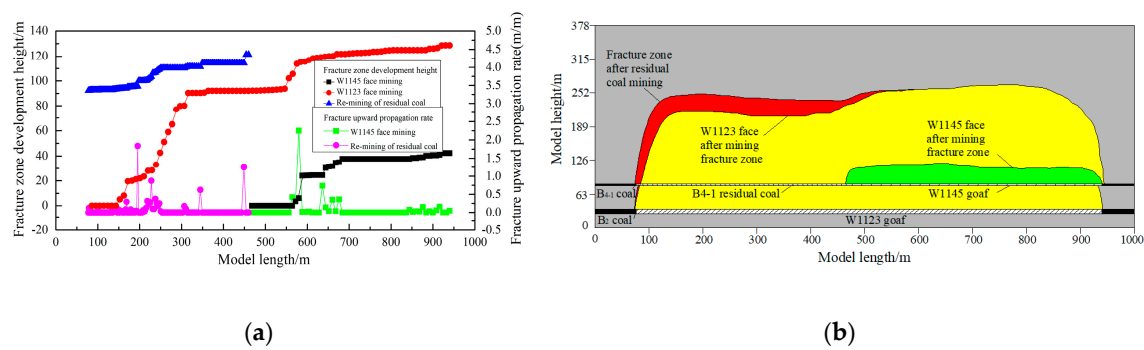
Figure 8. Law of fracture zone development. (**a**) Evolution trend of maximum height in the fracture zone, and (**b**) distribution law of fractured zones in different working faces after mining.

For B4-1 coal seam in the process of downward mining of the W1145 first mining face, the fracture concentrated upward development is mainly the first caving of the direct roof advancing 139.2 m at the working face, the expansion rate is about 2.3 m/m. When the working face is advancing 224 m, the fracture zone development is basically stable, and the average height of the fracture zone at the end of mining is 41.5 m. The average thickness of B2 coal seam is 9.5 m, which is much higher than the average height of B4-1 coal seam of 3.0 m. Therefore, the fissure develops upward for a long time when the W1123 working face advances, and the fissure zone above the remaining coal develops basically stably when the working face advances 240 m, with the average height of the fissure zone of 92.1 m. When the working face is advancing 499.2 m, the fracture zone above the gob of the W1145 working face is basically stable, with an average height of 125.8 m.

During the re-mining of B4-1 coal seam, when the direct roof-caving with residual coal advancing 128.0 m and the rock burst with residual coal advancing 378.4 m occurred, the fissures concentrated and developed upward, with the expansion rates of about 1.3 m/m and 1.8 m/m, respectively. After the residual coal advancing 277.4 m, the accumulated development average height of the upper fissure zone of B2 coal seam below the residual coal was 115.7 m. The average height of fractured zone caused by residual coal mining is 23.6 m upward, which is less than the average height of fractured zone 17.9 m after W1145 face mining.

The re-mining of residual coal has a great influence on the changes of rock strata above the open cut of the W1145 working face. The fracture zone above the critical area between the W1145 working face and the residual coal seam has obvious expansion, while the fracture above the gob of the W1145 working face far away from the critical area has no obvious difference. Comprehensive analysis shows that the average height of the fracture zone caused by the first downward mining of the W1145 working face in B4-1 coal seam is 41.5 m, which is 17.9 m higher than the height of the fracture zone caused by the second upward mining of the remaining coal. The cumulative developed average height of fracture zone after downward mining is 125.8 m, which is 10.1 m higher than the cumulative developed height of the fracture zone caused by upward mining of 115.7 m.

4. The Law of Mine Pressure and Energy Release under Different Mining Sequence of Coal Seam Groups

The mining of the W1145 working face in B4-1 coal seam is mainly affected by the relatively stable overlying rock on the upper part of the coal seam, while the overlying rock on the upper part of B4-1 residual coal seam has been disturbed by the mining of B2 coal seam. In addition, the re-mining of residual coal will also be affected by the fractured strata between the lower layers. In order to explore the comprehensive influence of residual coal on the upper disturbed strata and the lower fractured strata, and to compare and analyze the difference of the influence of coal seam only on the upper stable strata, now, through the pressure sensor and SOS microseismic monitor (Joint monitoring of "dlm-so signal acquisition station" and "AS-1 sejsgram recorder".) arranged in the physical similar material simulation experiment, the support pressure and seismic source events measured after coal

seam advancing are monitored, and the energy evolution trend and the periodic pressure progressive law during B4-1 coal seam advancing are analyzed.

4.1. Periodic Pressure and Stent Pressure Distribution under Different Mining Sequences

4.1.1. Periodic Pressure Judgment and Its Distribution Law

The weighting resistance of the working face under a single push is adopted to analyze the weighting step distance. The sum of the average resistance of the support and its mean square deviation is taken as the main index to judge the periodic pressure of the roof. P_i is defined as the first propulsion support pressure, t_i is the propulsion sequence according to the scheme, and the data calculation equation is:

$$P_t = \frac{(P_0 + P_1)t_1/2 + (P_1 + P_2)t_2/2 + L + (P_{n-1} + P_n)t_n/2}{t_1 + t_2 + L + t_n} \tag{4}$$

$$P_t = \frac{1}{n}\sum_{i=1}^{n} P_{ti} \tag{5}$$

$$\sigma_P = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_{ti} - P_t)^2} \tag{6}$$

In the equation, P_t is the weighted resistance after n propulsion, MPa, $\overline{P}_t$ is the average weighted resistance, MPa, n is the cumulative number of propulsion, P_{ti} is the weighted resistance of the *i*-th advance, and σ_P is the weighted resistance mean squared.

According to the calculation results, the weighted resistance is counted, as shown in Table 3. By B4-1 coal seam, downward first mining and upward re-mining support weighted resistance can be seen. Before the shifting, the weighted resistance and the mean square error are generally higher than those after the shifting. The change of the support pressure before the shifting is obvious, and the weighting resistance of the first mining is higher than that of the upward mining.

Table 3. Weighted resistance statistics.

Category	Downward First Mining		Upward Recovery	
	After the Support	Before the Support	After the Support	Before the Support
Average weighted resistance $\overline{P}_t$/MPa	24.4	24.6	23.3	23.7
Weighted mean square deviation of resistance σ_P/MPa	3.1	3.5	1.0	2.3
Support pressure P'_t/MPa	27.5	28.1	24.3	26.0

The criterion of roof weighting is:

$$P'_t = P_t + \sigma_P \tag{7}$$

Traditionally, the dynamic load coefficient K is often used as an index to measure the weighting strength of the basic top cycle. The dynamic load coefficient can be expressed as $K = P_i/P'_t$, that is, the ratio of the support pressure after a single push to the weighting discrimination pressure. According to the comparison between the value obtained from the roof weighting discrimination basis, P'_t, and the support pressure under each advancing distance, when the support pressure is greater than the discrimination basis in the advancing process, the dynamic load coefficient K > 1 is the periodic pressure. When the pressures of adjacent supports meet the discriminant, the peak pressure shall be taken as the periodic pressure.

Through continuous monitoring of the support pressure in the process of B4-1 coal seam advancing and analysis of the change trend of the roof pressure in the working face, it is concluded that the

periodic pressure characteristics in the first mining and the repeated mining of residual coal in the W1145 working face are as shown in Tables 4 and 5, respectively.

Table 4. W1145 working face mining cycle weighting characteristic table.

Number of Periodic Pressures	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Propulsion length/m	128.0	160.0	192.0	224.0	248.0	288.0	304.0	336.0	360.0	392.0	416.0	432.0	456.0	472.0
Periodic pressure step distance/m	128.0	32.0	32.0	32.0	24.0	40.0	16.0	32.0	24.0	32.0	24.0	16.0	24.0	16.0
Pressure/MPa	30.6	28.7	32.8	30.5	32.2	31.5	28.8	30.3	28.2	27.6	30.2	30.1	28.3	28.2

Table 5. Residual coal re-mining periodic pressure characteristic table.

Number of Periodic Pressures	1	2	3	4	5	6	7	8
Propulsion length/m	139.2	155.2	174.4	198.4	264.0	288.0	328.0	378.4
Periodic pressure step distance/m	139.2	16.0	19.2	24.0	65.6	24.0	40.0	50.4
Pressure/MPa	26.7	29.0	29.8	32.0	32.2	30.4	34.6	58.5

Through monitoring the support pressure data before moving the support in different measuring areas in the mining process of the W1145 working face and applying the periodic pressure discrimination basis, it is concluded that the periodic pressure characteristics in the mining process of the W1145 first mining face in B4-1 coal seam are as shown in Table 4. There are 14 obvious weighting phenomena in the downward first mining of the W1145 face, and the step distance during the initial caving is the largest, reaching 129.0 m, and then the caving step distance is reduced, and presents fluctuating changes. The periodic pressure interval in the mining process basically fluctuates in the range of 16.0~40.0 m, with an average interval of 26.0 m.

There are eight obvious weighting steps in B4-1 residual coal re-mining, with the largest weighting step at the time of initial caving. The weighting steps at the fifth and eighth times are 65.6 m and 50.4 m respectively, showing the characteristics of longer weighting steps. The periodic pressure step basically shows the repeated fluctuation trend of "decrease-increase". During re-mining, the periodic pressure step is basically in the range of 16.0~65.6 m, and the average weighting step is about 34.2 m.

4.1.2. Difference of Stent Pressure Distribution

Figure 9 shows the change trend of support pressure in the B4-1 coal seam mining process, in which the periodic pressure distribution in the downward first mining advancing process of W1145 is relatively uniform, and the peak pressure value appears at 32.8 MPa when the working face advances to 192.0 m, which is located at about one third of the working face advancing, which is obviously different from the peak value of support pressure in the residual coal re-mining at the end of mining. The roof pressure change trend before and after the frame shift is the same at the W1145 working face. The support pressure shows a change trend of high in the middle and low at both ends. The pressure change fluctuation is obvious during the whole mining process.

Before and after moving the support, the average pressure of residual coal re-mining in region 1 and region 2 is 22.9 MPa and 22.7 MPa, respectively. The pressure values of the roof are not much different, and the distribution is uniform and the change is small. When the residual coal is pushed to 139.2 m, the initial weighting occurs, and the support pressures before and after moving the support are 26.7 MPa and 23.8 MPa, respectively. There are three obvious weightings in the pushing process of region 3. After the support pressure reached 34.6 MPa, the roof was in a stage of gradual subsidence with a large area suspended. The support pressure area after the support was moved in this region and was stable, which proved that the overlying strata mainly acted on the collapsed rocks in the gob during the subsidence stage of the roof. The support pressure decreased rapidly with the advancing of the working face. When the residual coal advanced 378.4 m, the damaged rocks in the gob were insufficient to support the overlying strata pressure under the action of the longer roof. Furthermore,

the overlying strata action is mainly transferred to the upper coal pillar in front of the working face, so that the pressure value of the residual coal before advancing 378.4 m to move the frame reaches the maximum value of 58.5 MPa in the process of re-mining, and the coal pillar after moving the frame is not sufficient to support the overlying strata action, and rock burst occurs. The support pressure before and after the frame shift is relatively stable in the first two regions of the residual coal re-mining, and the support pressure before the frame shift changes obviously in the second half of the advancing stage.
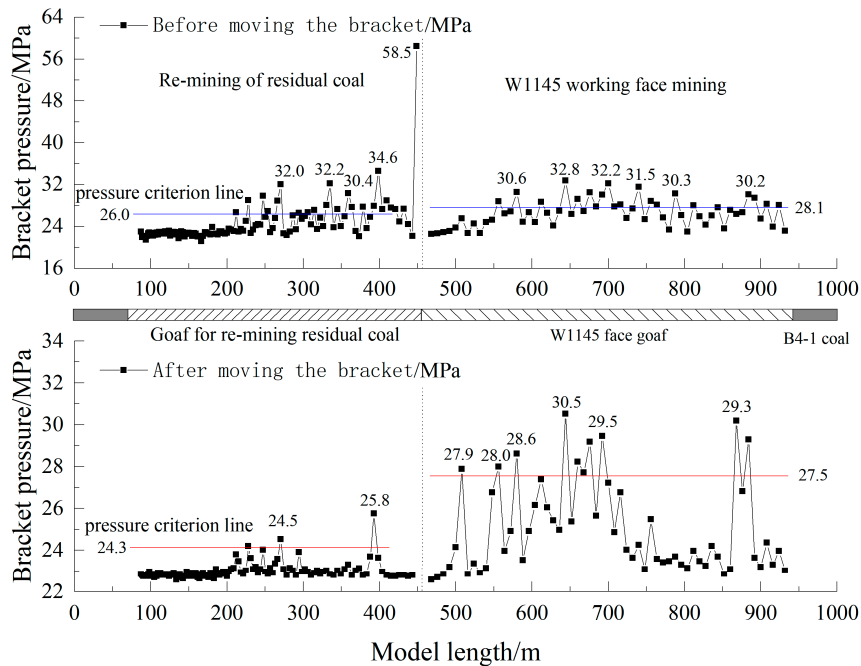

Figure 9. Change trend of support pressure in the working face.

A comprehensive analysis of the differences between the first downward mining and the upward mining of residual coal at the W1145 working face shows that during the first downward mining, the support pressure before and after moving the support is generally higher than that during the upward mining. In the process of advancing in regions 1 and 2, the re-mining of residual coal shows that the roof is suspended in a large area and falls with mining, which has little influence on the upper main roof. Therefore, the initial weighting step distance of residual coal re-mining is 139.2 m, which is significantly larger than the initial weighting step distance of 128.0 m caused by mining in the W1145 working face.

Because the overlying strata of B4-1 coal seam are obviously affected by the mining disturbance of the lower coal layer and some of the strata are loose before the re-mining of the remaining coal, the caving porosity generated by the re-mining of the remaining coal is higher, and under the better supporting effect of more loose broken rock blocks, the number of broken rings generated by the main roof during the re-mining of the remaining coal is less. B4-1 coal seam produced 14 weightings in the process of downward mining 480 m of the W1145 working face. During the upward re-mining of more than 384 m of coal, a total of 8 obvious periods of pressure are generated. The average weighting times per hundred meters are 2.9 times and 2.1 times, respectively. Roof weighting occurs faster when mining the W1145 face downward. In B4-1 coal seam, the periodic pressure intervals for downward mining and upward mining are 26.0 m and 34.2 m respectively, and the average periodic pressure interval for upward re-mining is 8.2 m longer than that for downward first mining.

4.2. Evolution Characteristics of Energy Release

Real-time monitoring is carried out on the energy size, occurrence frequency, and focal position of micro-seismic events generated during B4-1 coal seam mining. The focal energy measured by the micro-seismic system is divided into 5 levels according to different sizes, which are 0–50 J, 50–100 J, 100~150 J, 150~200 J, and above 200 J, respectively. The energy evolution and progressive law during B4-1 coal seam propulsion are analyzed.

4.2.1. Spatial Distribution Characteristics of Energy Release

The frequency and energy of micro-seismic events measured by the micro-seismic system can effectively verify the overburden movement in the gob of the upper coal seam under the condition of upward mining. Based on the location of micro-seismic events, the migration law of overburden structure under repeated mining is inverted to evaluate the accuracy of overburden change law and provide a theoretical basis for overburden change law. Based on the micro-seismic positioning results monitored during the mining process and the evolution of event frequency and energy, the energy variation characteristics and differences between the upward re-mining and the downward first mining are comprehensively analyzed.

The distribution of micro-seismic events measured by microseisms in the mining of the W1145 working face (Figure 10a) shows that under the influence of the mining disturbance of the W1145 working face, its seismic source is basically located above the mined-out area of the W1145 working face, and there is basically no seismic source distribution above the residual coal in B4-1 coal seam. Its seismic source distribution is relatively uniform, with a small range and no obvious concentrated distribution of seismic sources. The seismic source of the upper overburden is relatively scattered. The seismic source energy from the roof of coal seam to the upper strata shows a decreasing trend step by step, and the seismic source energy in the overburden near the middle of the mined-out area is significantly higher than that of both sides.

In the process of residual coal mining, the seismic sources measured by the micro-seismic system are mainly distributed in two concentrated areas, namely, the model length is 340–450 m and 520–680 m. Through micro-seismic monitoring of the distribution of micro-seismic events in the whole process of residual coal re-mining (Figure 10b), it can be seen that the concentrated areas of upward re-mining focus are mainly distributed above the main key layer on B4-1 coal seam, and are mainly concentrated in the basic roof with a height of 70–190 m and some rock strata above it. The two concentrated areas are respectively located in the rock strata on both sides of the critical positions of residual coal and mined-out areas of the W1145 working face. The further away from the focal concentration area, the energy and the number of focal points in the upper overburden and surrounding strata of the model gradually decrease and disperse. The total energy in the process of residual coal propulsion is 46,893.4 J, and the total energy in the focus area is 41,277.9 J, accounting for 88% of the total energy.

According to the spatial distribution characteristics of micro-seismic positioning, B4-1 coal seam has obvious similarities in energy distribution between downward and upward mining processes. The seismic source events are mainly distributed in the overlying strata above the main key strata. The seismic source distribution in the bottom strata of B4-1 coal seam is less, and the energy level of the top strata of coal seam decreases step by step. The difference is that there are obvious differences in the transverse distribution of the seismic sources, in which the energy generation in the first downward mining process of the W1145 working face shows a uniform change trend with the advancing of the working face, while the energy concentration distribution of the seismic source generation in the repeated mining process of residual coal is obvious due to different advancing.
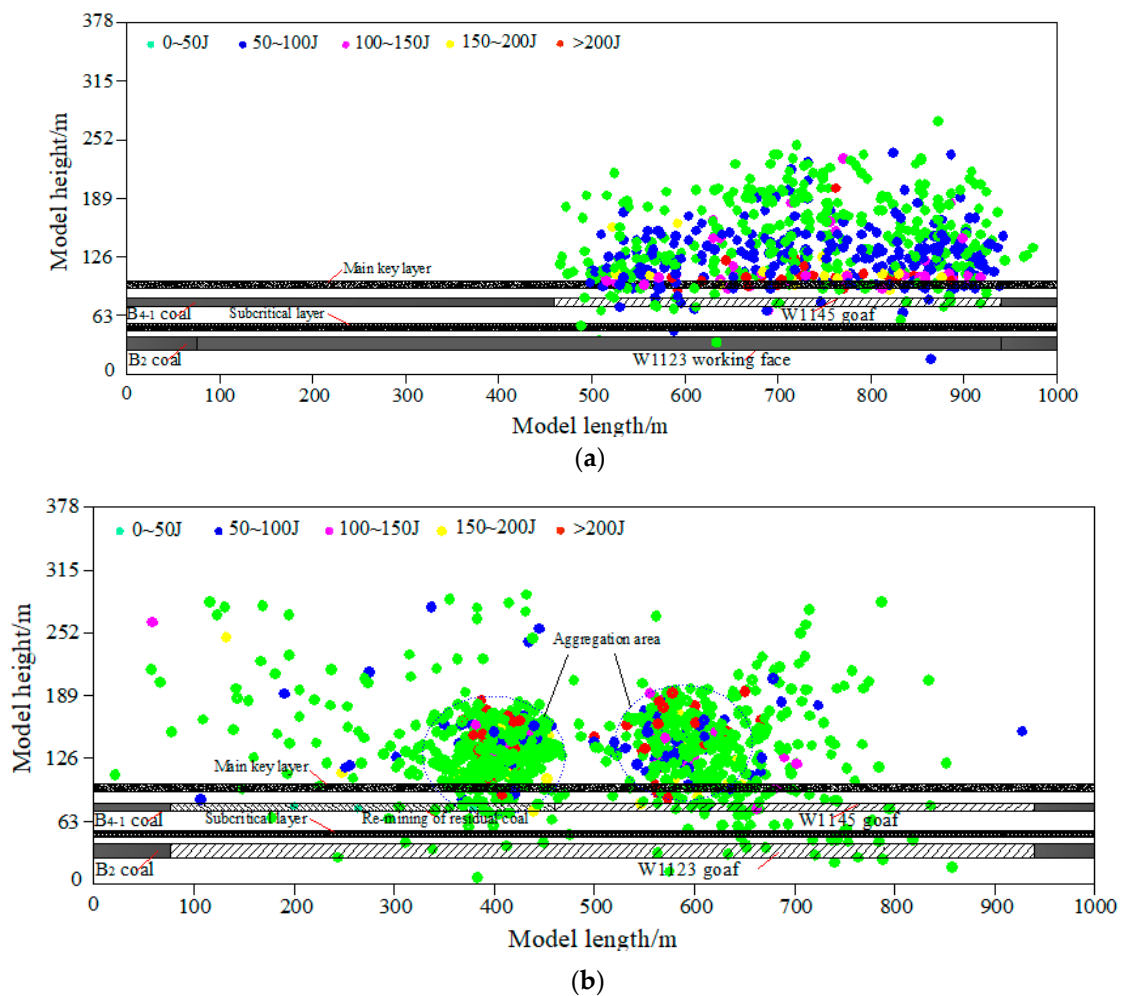
(a)

(b)

Figure 10. Spatial distribution characteristics of seismic sources in B4-1 coal seam mining. (**a**) Distribution of mining micro-seismic events at the W1145 working face, and (**b**) distribution of micro-seismic events in residual coal mining.

The obvious difference in the distribution of transverse seismic sources during the mining of B4-1 coal seam shows the difference in overburden changes during the upward first mining and downward re-mining. According to the relatively uniform distribution of seismic sources during the downward first mining process, the relatively regular periodic failure phenomenon of roof and overlying strata in the W1145 working face mining is explained. According to the obvious concentrated distribution of two seismic sources in the upward process, the damage of overlying strata in the upper part of the remaining coal seam region 6 is more severe, and the mined-out area of the W1145 working face is close to the position of the open cut. Due to the repeated mining of the remaining coal, the original stable articulated structure changes and the articulated strata are activated, resulting in a large amount of energy release.

The differences of energy events and energy magnitude between the six regions of the W1145 working face and the six regions in the process of coal re-mining are analyzed in detail. Due to the different length of the region, the average energy during a single propulsion is increased for differential comparison. Statistics of seismic source data for B4-1 coal seam mining based on micro-seismic monitoring data are shown in Table 6, and the variation difference of overlying strata during downward and upward mining is inverted accordingly.

Table 6. B4-1 Coal seam mining micro-seismic statistics.

Serial Number	Residual Coal Propulsion Range	Micro-Seismic Event/n	Accumulated Energy/J	Single Event Average Energy/J	W1145 Face Advancing Range	Micro-Seismic Event/n	Accumulated Energy/J	Single Event Average Energy/J
Region 1	0~64	60	2081.6	34.7	0~80 m	49	1839.3	57.9
Region 2	64~126.4	291	12,889.4	44.3	80~160	80	6667.2	83.3
Region 3	126.4~190.4	278	12,981.8	46.7	160~240	135	19,161.6	141.9
Region 4	190.4~254.4	124	4742.5	38.2	240~360	147	27,454.2	186.8
Region 5	254.4~316.8	65	1785.4	27.5	360~400	123	15,218.5	123.7
Region 6	316.8~384	127	12,412.7	97.7	400~480	129	15,635.2	121.2

Re-mining of residual coal resulted in 945 events with cumulative energy of 46,893.4 J, and the average energy of a single event was about 49.6 J. W1145 mining produced 653 events, with cumulative energy of 85,976.0 J and average energy of a single event of about 131.7 J. From the statistical data in Table 6, it can be seen that there are few micro-seismic events and low accumulated energy in region 1. Reverse downward first mining and upward re-mining result in a large area of suspended roof during the advancing process of area 1, without obvious overburden deformation. There are many micro-seismic events in the process of advancing more than coal in region 2 and region 3, which reversely shows the change characteristics of overlying strata with frequent roof collapse upon mining. However, in the mining process of W1145 coal seam, there are few micro-seismic events and the energy generated by a single event is relatively high, which disproves the fact that the complete rock strata rupture is higher than the energy released by rock strata rupture after disturbance.

The micro-seismic events and energy in the process of advancing the remaining coal in regions 4 and 5 are all lower than that of the mining of the W1145 face, and the energy generated by a single event is especially obvious, which shows that the number of changes of overburden caused by the remaining coal mining in the area is less and the degree of overburden damage is weaker.

Due to the energy release of rockburst in the process of advancing the remaining coal in region 6, the energy generated by a single event is the maximum value in the process of re-mining the remaining coal, while the energy value of a single event in area 6 of the W1145 working face is still smaller, which shows that the energy release in the process of downward first mining is generally higher than that in upward re-mining.

The micro-seismic events in the mining process of the W1145 working face are characterized by a small number of events and high accumulated energy. Affected by the mining disturbance of B2 coal seam, the fractured rock strata between coal seams are loose, and the upper rock strata of residual coal produce bending changes, which make the number of events in the process of residual coal re-mining large and the accumulated energy low, mostly energy events below 50 J. In order to analyze the damage mechanism under the mutual superposition of focal events, the energy superposition distribution nephogram during B4-1 coal seam mining is drawn as shown in Figure 11.
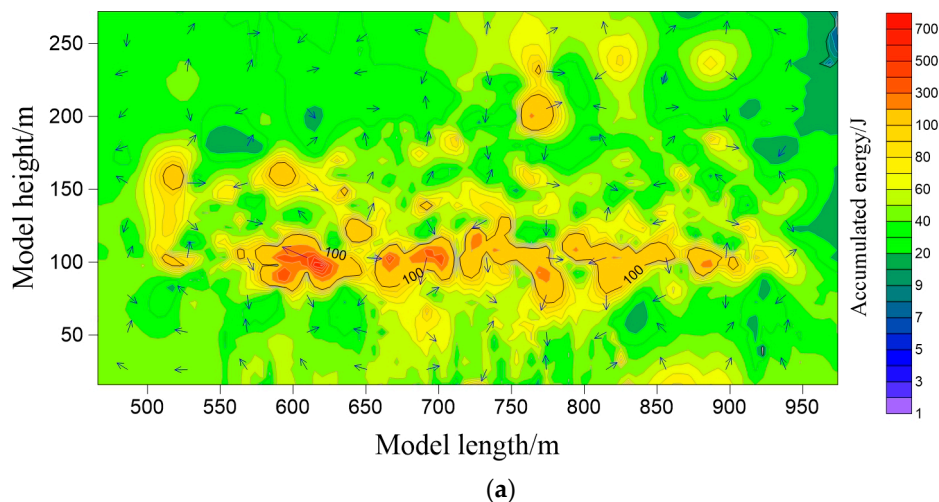

(**a**)
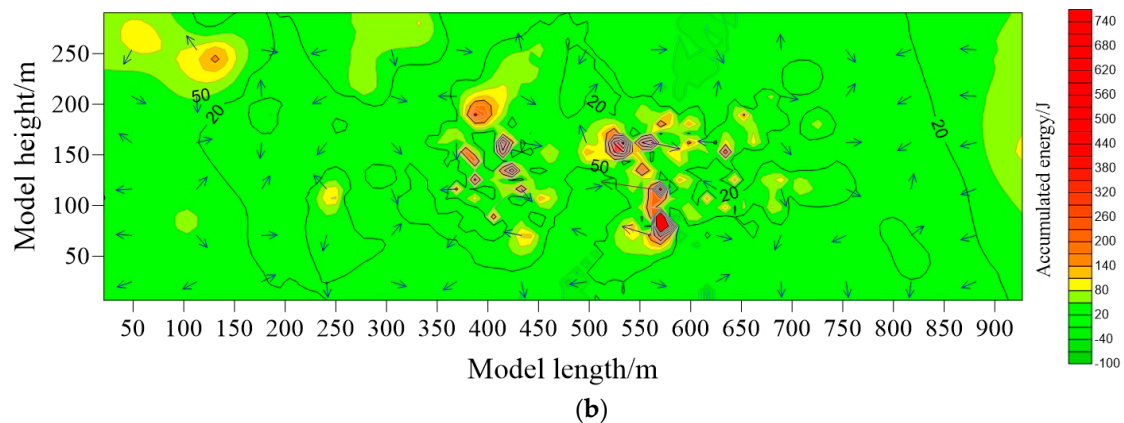
Figure 11. *Cont.*

(**b**)

Figure 11. Superimposed distribution characteristics of source energy in B4-1 coal seam mining. (**a**) Superimposed distribution characteristics of mining energy in the W1145 working face, and (**b**) superimposed distribution characteristics of residual coal recovery energy.

According to the superposition distribution of mining energy in the W1145 working face (Figure 11a), in the process of downward first mining, the energy is mainly concentrated in four regions within the range of 18 m up and down with the model height of 100 m as the axis, and its energy density shows a gradual decreasing trend from the left side to the right side of the model, gradually decreasing from 700 J/m^2 in the left concentrated region to 100 J/m^2. According to the superposition distribution of residual coal re-mining energy of B4-1 coal mining focal energy superposition distribution characteristics (Figure 11b), in the process of residual coal propulsion, energy is concentrated in the range of 355–625 m in length and 75–220 m in height of the model, in which there are four obvious energy concentration areas, and the area centered at (525 m, 95 m) has the highest accumulated energy, with the accumulated energy density reaching 740 J/m^2.

4.2.2. Energy-Frequency Distribution Characteristics of Micro-Seismic Monitoring

According to the magnitude of the energy measured by the seismic source and the frequency of generating the seismic source during each step of propulsion, the micro-seismic energy-frequency characteristics of B4-1 coal mining are made (Figure 12), and the difference of the seismic source energy and frequency under a single propulsion is compared between downward first mining and upward second mining.

In W1145 working face mining (Figure 12a), the number of micro-seismic events fluctuated less during the first to 15th forward propulsion, and the single event remained within 10 times, indicating that the gob roof presented a relatively stable state during the 15th forward propulsion before the first downward mining. During the 16th to 37th middle propulsion, the number of focal points fluctuated obviously. The number of micro-seismic events in a single propulsion was in the range of 8 to 24 times. During the 24th, 31st, and 36th propulsion, the energy was 7435.3 J, 5928.4 J, and 11,294.7 J, respectively. The higher energy in a single micro-seismic event indicates that the complete rock strata were broken more frequently. During the 37th to 60th rear propulsion, the energy magnitude and frequency are obviously weakened compared with those in the middle part. The obvious energy peaks in the 49th and 52nd propulsion are 5520 J and 6060 J respectively, and the event frequency is 16 and 15 respectively, which shows that the overburden activity is obvious in the propulsion range, but the damage degree is weak and the overburden in the middle part is broken.

In the second mining of residual coal (Figure 12b), during the 1st to 45th front propulsion, there were few micro-seismic events and low energy, and the number of single propulsion events remained basically within 3, indicating that the roof was relatively complete within the propulsion range and no obvious rock formation damage occurred. During the 46th to 79th middle propulsion, the number of micro-seismic events fluctuated frequently, gradually increasing from 4 micro-seismic events in a

single propulsion to 51 micro-seismic events in the 71st propulsion. The frequency of micro-seismic events increased and fluctuated obviously, indicating that the rock strata in the propulsion range were frequently damaged. During the 58th to 70th propulsion, the energy released by the overlying strata was generally higher, indicating that the rock strata in this area were more severely damaged. During the 80th to 127th rear propulsion, the number of micro-seismic events fluctuated repeatedly, and there were obvious peaks of micro-seismic events during the 81st, 88th, 103rd, 116th, 118th, 122nd, and 126th propulsion, which indicated the cyclic change of overlying rocks in the propulsion range. At the 126th propulsion, the source energy was 5192.2 J and reached the maximum value of single propulsion energy, which indicated that when the residual coal propulsion was coming to an end, due to the limited bearing capacity of the coal pillar, a large-scale destruction of the overlying strata after the coal pillar was crushed by extrusion occurred.
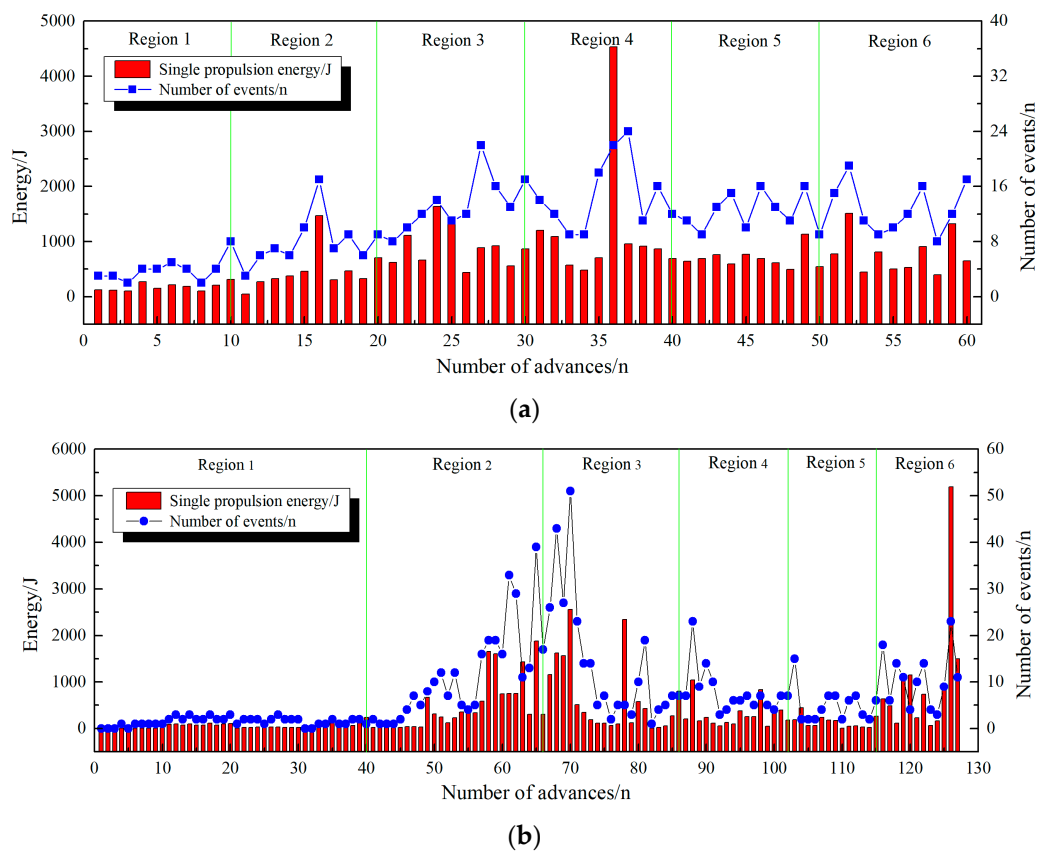

(a)

(b)

Figure 12. Characteristics of micro-seismic energy-frequency in B4-1 coal seam mining. (**a**) Characteristics of mining micro-seismic events in the W1145 working face, and (**b**) characteristics of micro-seismic events in re-mining of residual coal.

The analysis shows that the micro-seismic monitoring results can better reflect the change law of overlying strata. From the difference of micro-seismic energy and frequency during a single push, it can be seen that the overlying strata of residual coal re-mining are already loose, and it is easier to destroy and form a stable equilibrium structure with less energy than the initial mining of the W1145 face. Therefore, the frequency of residual coal re-mining is generally more, and the energy is less than that of the initial mining.

4.2.3. Characteristics of Energy Density and Frequency Distribution

The amount of energy generated after advancing per unit length is defined as energy density, and the number of events generated after advancing per unit length is defined as event frequency. The calculation equations of energy density and event frequency are shown in Equations (8) and (9),

respectively. The evolution laws of energy density and event frequency in B4-1 coal seam mining process are plotted with the degree of advancement as the node and are compared and analyzed.

$$\rho_E = \frac{E_t}{d} \tag{8}$$

Among them: ρ_E is the energy density, J/m, E_t is the amount of energy generated by a single propulsion, J, and d is according to the single propulsion distance of the experimental scheme, m.

$$f_E = \frac{f_c}{d} \tag{9}$$

where, f_E is the frequency of events where energy occurs, n/m, and f_c is the number of events generated by a single push, n.

According to the evolution law of energy density and event frequency of upward re-mining and downward mining (Figure 13), it can be seen that during the downward first mining of the W1145 working face within the range of 460~940 m of model length, the event frequency is generally low, basically distributed in the range of 0.8~2.7 n/m. The energy density of the W1145 working face has five obvious peaks in the process of advancing, reaching 928.8 J/m, 741.3 J/m, 1412.5 J/m, 690.0 J/m, and 757.5 J/m, respectively.
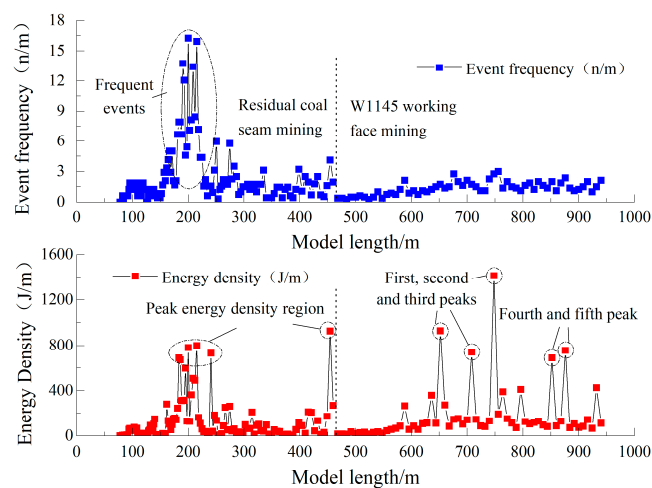

Figure 13. Evolution law of energy density and event frequency in upward and downward mining.

During the re-mining of residual coal in the range of 76~460 m of model length, the event frequency is generally high. The event frequency of residual coal advancing 180.8~222.4 m is the frequent occurrence area, among which, the event frequency of working face advancing to 200 m and 215.2 m is as high as 16.3 n/m and 15.9 n/m, and the event frequency in the other frequent occurrence areas is basically 4.5~13.4 n/m. Significant energy density peak areas appeared in the 183.2~215.2 m propulsion range highly related to the frequent occurrence area. The frequency of the event is only 4.1 n/m and the energy density is as high as 927.2 J/m within the 5.6 m advancing range of 378.4 m, which is the highest energy density in the process of re-mining the residual coal.

The results of energy density and event frequency evolution law of upward re-mining and downward mining show that the energy of W1145 working face of B4-1 coal seam is characterized by "low frequency-low density" within the advancing range of 460–588 m model length. In the propulsion range of 596~940 m, the energy shows obvious "low frequency-high density" characteristics, and the event frequency in the first mining process is only low frequency.

In B4-1 coal seam, the seismic source events and energy show the characteristics of "low frequency-low density" in the advancing range of model length 76~178.4 m and 244~448.8 m. In the range of model length 180.8~240.8 m, the energy shows obvious "high frequency-high density"

characteristics. In the propulsion range of 454.4~460 m of model length, the energy shows the characteristic of "low frequency-high density".

In addition to the differences in energy characteristics in different regions, there are also obvious differences in similar characteristics between the first downward mining and the second upward mining of residual coal. In the characteristic region of "low frequency-high density" of energy, the first time of down mining is 5 obvious energy peaks generated at a longer step distance, while the second time of up mining is mainly the frequent occurrence of high density of energy generated in the concentrated region.

4.3. Synergetic Analysis of Roof Weighting and Energy Release

In order to study the difference of energy and mine pressure between the first downward mining and the second upward mining in B4-1 coal seam, and to analyze the interaction law between energy and pressure, the characteristics of energy and pressure accumulation and release during the first downward mining and the second upward mining are comprehensively studied through the relationship between the energy magnitude during the advancing process of micro-seismic monitoring and the periodic pressure of supports.

According to the relationship between energy and mine pressure in the mining process of the W1145 working face (Figure 14a), it can be seen that the energy value of single propulsion is relatively low, mainly concentrated within 400 J during the propulsion process of 0~112 m energy accumulation area. The working face advancing to 192 m, 248 m, 288 m, 392 m, and 416 m produces five obvious energy peaks, of which the third peak energy reaches 11,300 J, which is the maximum energy during advancing. The five peak energies correspond to different periodic pressure positions, while for the 14 periodic pressures, except for the five propulsion, only five pressures are the micro-energy peak points, and the other four propulsion generate less energy. This shows that the release of high energy generally causes the overlying rock to form a new stable structure after obvious changes, so the release of higher energy is located at the periodic weighting. However, periodic weighting is not necessarily the place where higher energy is released. Sometimes, the release of low energy will also make the change of overlying strata reach a new stable structure, release the pressure and form weighting before the pressure is released. The peak energy in the mining process of the W1145 working face presents obvious periodic changes, and the periodic generation step of energy release is obviously larger than the periodic pressure step.

According to the relationship between energy and mine pressure in the process of residual coal mining (Figure 14b), it can be seen that in the process of 0~85.6 m propulsion, the energy of single propulsion is mainly concentrated within 100 J, which is regarded as the energy accumulation area. During the 87.2~142.4 m propulsion process, the measured energy fluctuated frequently, forming an energy frequent region. The obvious energy peaks in the region showed an increasing trend. The energy released at the fourth peak reached an area peak of 2556.6 J, and the initial pressure formed before the energy was released was 26.7 MPa.

When the residual coal is advanced to 164.8 m, the energy measured by the microseism suddenly increases to 2342.9 J, which corresponds to the large-scale overburden failure caused by the repeated mining of the residual coal at 164.8 m. Before the energy burst, i.e., when the residual coal was propelled 155.2 m, the measured energy was only 120 J when a pressure of 30.7 MPa was generated. There is no obvious energy release in the last two pushing progress, which proves that the energy burst in the process of coal re-mining is not accidental, but the sudden release after the energy is accumulated again due to the increase of roof area after the periodic weighting continues to push forward.

During the mining process of the remaining coal in regions 4 and 5, the hard roof is suspended in a large area under the action of rock strata. After many times of mining, the remaining coal slowly sinks to the coal seam floor, thus the number of micro-seismic events in this range is small and the energy is low. When the residual coal reaches 378.4m, the micro-seismic measured energy reaches 5192.2 J, which corresponds to the rockburst phenomenon caused by the sudden crushing of the 5.6 m

coal pillar. The seventh periodic pressure generated under the advancing degree reaches 58.5 MPa and is the periodic weighting peak.
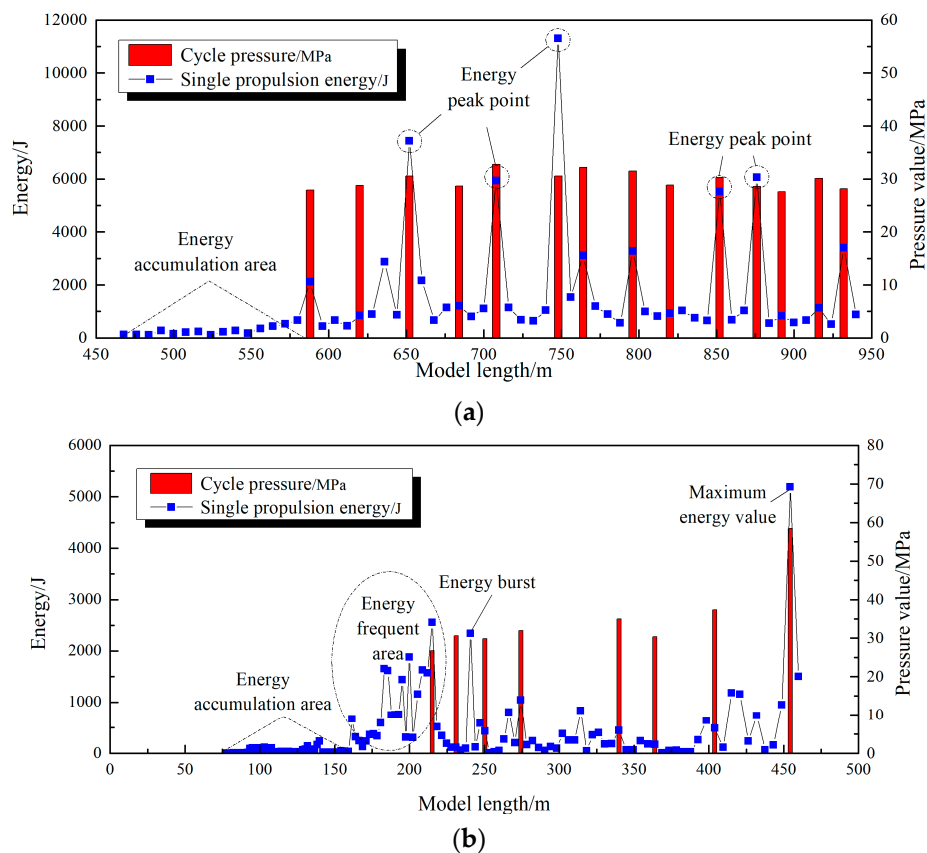

Figure 14. Relationship between mining energy and mine pressure in B4-1 coal seam. (**a**) Relationship between mining energy and mine pressure in the W1145 working face, and (**b**) relationship between mining energy of residual coal and mine pressure.

To sum up, the periodic pressure formed in the mining process of B4-1 coal seam has the ability to do work, thus all have energy. The greater the pressure, the stronger the ability to do work. The release of higher energy in the first downward mining is located at the periodic pressure, while the release of higher energy in the upward re-mining of residual coal sometimes lags behind the incoming pressure. During the first downward mining at the W1145 working face, the rock strata are relatively complete. The release of high energy generally causes the overburden to change obviously and form a new stable structure, which releases the overburden pressure. Therefore, the release of high energy during the first downward mining is located at the periodic weighting. In the upward re-mining of the residual coal after the disturbance of the lower coal mining, due to the high degree of rock fragmentation, after releasing less energy during weighting, the support of some broken rocks makes the overlying rock insufficient to produce obvious damage, and the suspension of the lower roof continues to increase to produce large-scale damage of the overlying rock. After the higher energy is released, a new stable structure is formed to reduce the accumulated pressure.

5. Discussion

Based on the above analysis, the main differences between the upward re-mining and the downward mining will be counted. According to the overburden deformation, surface and rock subsidence, roof pressure, energy release characteristics, etc., are summarized as shown in Table 7.

Table 7. Statistics on main characteristics of upward and downward mining in B4-1 coal seam.

Category	Re-Mining of Residual Coal	W1145 Face Mining
Propelling distance/m	384	480
Maximum surface subsidence/m	0.96	1.38
Maximum subsidence of rock stratum/m	2.57	2.94
Boundary angle/(°)	79.3	80.9
Angle of movement/(°)	81.1	82.3
Fracture angle of rock stratum/(°)	67.5	75.8
B4-1 coal mining fracture upward expansion height/m	23.6	41.5
Average height of fractured zone after double-layer coal mining/m	115.7	125.8
Average weighted resistance before stent movement/MPa	23.7	24.6
First press step distance/m	139.2	129.0
Periodic weighting average step distance/m	34.2	26.0
Periodic weighting distance range/m	16.0~65.6	16.0~40.0
Frequency of energy events/n	945	653
Cumulative energy/J	46,893.4	85,976.0
Mean energy density/(J/m)	122.1	179.1
Average frequency of events/(n/m)	2.5	1.4

　　　Comprehensive comparative analysis shows that in the overburden deformation and caving characteristics, the overburden subsidence, surface subsidence basin angle parameters, and fissure upward expansion height after B4-1 residual coal re-mining are generally smaller than those after the first mining due to the extrusion caused by overburden failure after mining at the W1145 working face. The maximum subsidence caused by repeated mining of B4-1 residual coal seam is 0.96 m, which is 0.42 m lower than that of the W1145 working face. The maximum subsidence of strata is 2.57 m, which is 0.47 m lower than that of the W1145 working face. The boundary angle, movement angle and rock layer break of B4-1 residual coal seam are 79.3, 81.1 and 67.5 respectively, which are smaller than those of 80.9, 82.3 and 75.8, respectively. The fracture zone caused by mining of B4-1 residual coal seam has an upward height of 23.6 m, which is 43.1% lower than the height of 41.5 m caused by mining of the W1145 working face. The cumulative height of the fracture zone caused by upward mining is 115.7 m, which is 8.0% lower than the cumulative height of the fracture zone caused by downward mining of 125.8 m.

　　　Under different mining sequences, the support pressure during the first downward mining is generally higher than that during the second upward mining. The W1145 average weighted resistance before moving the first mining frame downward is 24.6 MPa, which is 0.9 MPa higher than 23.7 MPa for upward re-mining. Because the lower strata of the key strata are obviously more disturbed by the mining of B2 coal seam than the upper strata, the crushing and swelling effect of the rocks below the key strata is stronger than that of the first downward mining in the process of the second upward mining of residual coal, and the supporting effect of loose and broken rocks is better, thus the first pressure step distance of the second upward mining of residual coal is 139.2 m, obviously larger than that of the first downward mining of 128.0 mm. The average step distance of periodic weighting for the recovery of residual coal is 34.2 m, greater than 26.0 m for the first recovery. The key strata in the mining process of the W1145 working face are broken regularly, so the pressure step distance of B4-1 coal seam during the downward initial mining period is located in the fluctuation range of 16.0~40.0 m for a total of 24.0 m, which is smaller than the fluctuation range of 49.6 m for the pressure step distance of 16.0~65.6 m for the upward repeated mining period of residual coal.

　　　Loose rock strata disturbed by upward re-mining are more likely to be broken, so there are more micro-seismic events in the process of residual coal re-mining. 945 micro-seismic events occurred in B4-1 residual coal seam upward re-mining, 292 more than the first mining under the W1145 working face. At the same time, the occurrence frequency of micro-seismic events in the process of upward re-mining of residual coal is 2.5 J/m, greater than 1.4 J/m in the process of downward first mining of the W1145 working face. However, the energy released from some strata above B4-1 coal seam after the mining disturbance of B2 coal seam makes the micro-seismic energy caused by repeated mining of the remaining coal seam smaller. The accumulated energy in the process of upward re-mining is 46,893.4 J,

less than 85,976.0 J in the mining process of the W1145 working face. At the same time, the average energy density of residual coal mining is 122.1 J/m, less than 179.1 J/m in the mining process of the W1145 working face.

6. Conclusions

(1) The mining of B2 coal seam is helpful to liberate B4-1 coal seam, which weakens the impact tendency of overlying rock on the upper part of the remaining coal seam, thus the large-area roof hanging step distance is longer when the remaining coal seam is re-mined. At the same time, the mining disturbance of B2 coal seam makes the overlying strata loose. When the residual coal is re-mined upward, the crushing and swelling effect of the strata below the key layer is stronger than that of the first mining downward, which has better supporting effect. Therefore, the first caving of the direct roof of the re-mining residual coal lags behind the mining of the W1145 working face.

(2) The maximum surface subsidence caused by repeated mining of the B4-1 remaining coal seam is 0.96 m, which is 0.42 m lower than the first mining of the W1145 working face. The maximum subsidence of strata is 2.57 m, which is 0.47 m lower than that of the first mining in the W1145 working face.

(3) The boundary angle and moving angle of B4-1 coal seam are 79.3 and 81.1 respectively, which are less than 80.9 and 82.3, respectively. The broken line of the rock formation at the stopping point formed after mining at the W1145 face is approximately parallel to B2 coal seam, and the broken angle of the rock formation is about 75.8. On the basis of the broken line of the W1123 face cut after B2 coal mining, the regenerated broken line is mainly concentrated on the two sides of the connecting line between the upper end of the broken line of the remaining coal cut and the W1123 face cut, making the rock stratum broken angle after the remaining coal re-mining smaller, about 67.5.

(4) In B4-1 coal seam, the average height of fracture zone caused by the first downward mining of the W1145 working face is 41.5 m, which is 17.9 m higher than the height of the fracture zone caused by the second upward mining of remaining coal. The cumulative developed average height of the fracture zone after downward mining is 125.8 m, which is 10.1 m higher than the cumulative developed height of fracture zone caused by upward mining of 115.7 m.

(5) The support pressure during the first downward mining is generally higher than that during the second upward mining. The mining disturbance of the lower strata of the key stratum is obviously stronger than that of the upper strata due to B2 coal seam, which makes the crushing and swelling effect of the strata below the key stratum stronger than that of the first downward mining when the remaining coal is re-mined, thus the supporting effect of loose and broken rock blocks is better, and the initial weighting step and the average periodic weighting step of the remaining coal re-mining are 139.2 m and 34.2 m respectively, which are obviously larger than the 128.0 m and 26.0 m of the first downward mining.

(6) The residual coal overburden has been loosened. It is easier to destroy and form a stable equilibrium structure under the smaller energy than the initial W1145 surface. Therefore, the re-mining of residual coal is generally more frequent and less energy than the initial mining.

(7) The micro-seismic events generated in the advancing process of the W1145 working face in B4-1 coal seam have only low frequency, and the upward re-mining energy has the characteristics of "low frequency-low density", "high frequency-high density", and "low frequency-high density".

(8) The periodic pressure formed in the mining process of B4-1 coal seam has the ability to do work, so all have energy. The greater the pressure, the stronger the ability to do work. The release of higher energy in the first downward mining is located at the periodic weighting, while the release of higher energy in the second upward mining of residual coal sometimes lags behind the weighting.

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