International Journal of Energy
ISSN: 2957-9473 | Vol. 3, No. 2, 2023

Characteristics and Laws of Overburden Failure Caused by Repeated Mining of Multi Coal Seams

Guangchun Liu

School of resources and civil engineering, Liaoning Institute of Science and Technology, Benxi, 117004 China

Abstract: With the depletion of coal resources, people began to mine deeper coal resources. In response to the special geological conditions of multiple coal seams, scientific and safe mining of deep coal seams has great practical significance and value. This article analyzes and studies the characteristics and laws of overburden failure caused by multi coal seam mining through physical simulation experiments in Majiazhuang coal mine with multiple coal seam occurrence conditions. The research results indicate that the failure of the overlying rock exhibits a "two zone" characteristic, that is, only the collapse zone and. The mining of multiple coal seams in overburden fracture zones will penetrate to the surface, disrupting groundwater circulation. Different mining thicknesses lead to different heights of overlying rock failure, and the greater the thickness of coal seam mining, the greater the height of overburden failure. The height of overburden damage caused by the mining process of the 15th coal seam runs through each coal seam and goaf to guide the surface.

Keywords: Overburden; Repeated Mining; Multi Coal Seam; Physical Simulation; Digital Image Correlation.

1. Introduction

Energy is the material foundation for human survival and development, and as an important strategic resource, energy has been valued by various countries in all over the world.[1]. Due to the worldwide Energy crisis, all countries are vigorously encouraging the development of new energy. Although many new energy sources are constantly emerging, the fact that coal resources are the main energy source cannot be completely changed in a short period of time [2-3]. In China, The consumption of coal resources accounts for over 70% of total energy consumption. With the continuous mining of coal, the mining output amount of coal resources in the east has become increasingly scarce. Most coal cities have or are facing the situation of Resource depletion, while the shallow coal in the west has almost been mined out. Therefore, people began to mine deep coal seams [4-7]. Most coal mines in the northwest region belong to multi seam mining areas. In recent years, with the continuous extraction of the upper coal seam and the increasing mining depth, the problem of repeated mining is also increasing[8-11].After coal resources are extracted from underground, the original rock stress is destroyed, the rock strata move and deform, leading to surface subsidence, damage to the surface environment, and serious damage to the surface ecology[12,13].Multi seam mining and repeated mining behavior can lead to more severe overlying rock damage and surface damage.[2,8].However, there is currently a relatively lack of research on the movement patterns of rock layers and surface under repeated mining conditions in multiple coal seams, and a relatively complete theoretical system has not yet been formed. Due to the damage caused by multiple mining operations, the overlying rock situation has become more complex and variable, and the problem of repeated mining cannot be solved using the rock and surface movement patterns under the initial mining conditions [14-16]. Therefore, studying the movement and deformation laws of overburden under repeated mining conditions and solving various engineering practical problems brought about by multi seam mining has important practical significance, providing theoretical reference and practical guidance for mining of MCS

The height of overlying rock failure during coal seam mining mainly includes two aspects: one is the height of overlying rock collapse, and the other is the height of crack zone development. The sum of these two heights is commonly referred to as the overburden failure height. This article uses physical simulation experiments combined with surface monitoring results to analyze the failure status and mechanical distribution characteristics of overlying strata in multi coal seam mining. Provide theoretical basis and technical support for multi seam mining and surface treatment in multi seam mining areas.

2. Methodology

The strength and thickness of the rock layers between coal seams and between coal seams and the surface are important factors affecting the failure of overlying strata. According to the "3 Zones" theory, as shown in Figure1, overlying rock failure can be divided into curved zones, fractured zones, and collapsed zones. In shallow coal seams, the "3 Zones" are usually incomplete, with only fractured and collapsed zones. Under the condition of multiple coal seam mining, the upper coal seam mining will cause damage to the overlying rock and surface. The mining of the lower coal seam will cause collapse and cracks in the overlying rock, and even lead to repeated mining damage in the goaf and overlying rock of the upper coal seam, resulting in secondary settlement and deformation. Therefore, we usually analyze the height of overlying rock failure by calculating the height of fracture zones and collapse zones. According to the principle of rock failure and empirical calculation formulas, the height of the collapse zone and the height of the fracture zone can be calculated separately. So, the failure height of the overlying rock is the algebraic sum of the height of the collapse zone and the fracture zone.

The calculation method is shown in Formula 1:

$$H = H_1 + H_2 \tag{1}$$

Among them, H_1 is the height of the collapse zone, m.H_2 is the height of the fracture zone, m.

2.1. Calculation of Overburden Collapse Height

Research has shown that the height of overlying rock failure is related to many geological and mining conditions, and it is currently impossible to establish a specific expression that includes all relevant influencing factors. In China, empirical formulas obtained through mathematical statistical methods based on a large amount of on-site observation data have been widely recognized and applied.

Calculation method for the maximum height of the falling zone:

$$H_1 = \frac{100\sum m}{4.7\sum m + 19} \pm 2.2 \tag{2}$$

Among them, m is the mining thickness of the coal seam, m.

2.2. Calculation of Fracture Development Height

The height of crack development in the overlying rock is completely different from the height of the collapse zone. The fracture in the overlying rock is much more complex than the collapse zone. The formation of cracks leads to discontinuity in the rock layer, forming a block structure. The spacing between blocks is usually calculated after simplifying the rock beam into a fixed support beam.

Calculate according to the following formula:

$$L_i = h\sqrt{\frac{2\sigma_{\max}}{q}} \tag{3}$$

Among them, σ_{max} is maximal tensile strength, MPa. q is the load action of the upper rock layer, MPa. h is the thickness of the rock beam, m.

Rock beam fracture is usually the middle fracture, therefore, the spacing between horizontal cracks is:

$$D_1 = \frac{1}{2}L_i = h\sqrt{\frac{\sigma_{\max}}{2q}} \tag{4}$$

As the working face continues to advance, the rock layer gradually forms a "cantilever beam" structure after the initial collapse. When the "cantilever" beam reaches its load-bearing limit and collapses, a new "cantilever" beam will be formed, and then collapse occurs, resulting in periodic collapse phenomenon.

Step distance of periodic collapse:

$$L_s = 2h\sqrt{\frac{\sigma_{\max}}{3q}} \tag{5}$$

The collapse of a cantilever beam structure occurs at one end of the beam, therefore, the spacing between cracks generated by periodic collapse is:

$$D_2 = L_s = 2h\sqrt{\frac{\sigma_{\max}}{3q}} \tag{6}$$

Although the spacing between cracks can be calculated theoretically, the height of crack development is influenced by many uncertain factors. Therefore, the development height of fracture zones is usually calculated using empirical formulas.

$$H_2 = \frac{100\sum m}{1.6\sum m + 3.6} \pm 5.6 \tag{7}$$

3. Materials and Methods

3.1. Geographical Location of the Study Area

The Majiazhuang mine is located in the southeast of Qinshui Coalfield, Majiazhuang, Quanzetou Village, Yonglu Township, Gaoping City, Jincheng City, Shanxi Province. The mining area is about 8km away from Gaoping City in Jincheng. The mine is located on the eastern edge of the Qinshui Block Depression, in the central southern section of the Jinhuo Fault Zone. The internal strata of the mining area are generally controlled by two sets of nearly east-west and northeast trending anticlinal fold structures, with an overall inclination to the northwest, as shown in Figure 1.

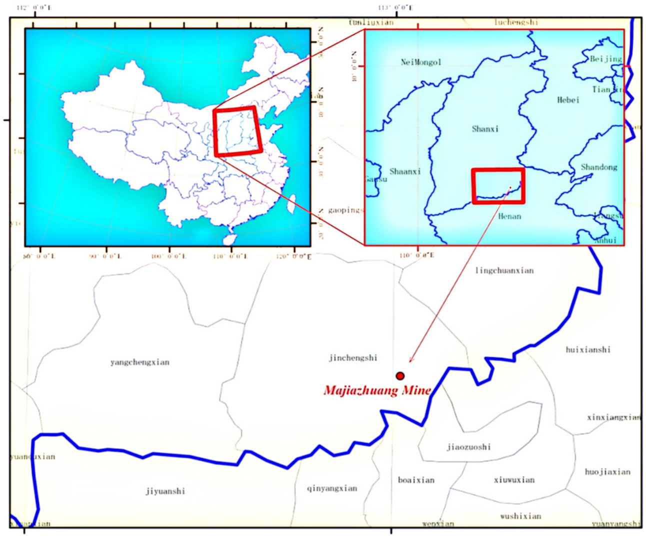


Figure 1. Geographical location of the study area

3.2. Physical Model Testing is a Simulation Test

Physical model testing is a simulation test method based on similarity theory, selecting suitable similar materials, and constructing a miniature model with physical parameters similar to actual engineering parameters according to a reasonable similarity ratio. It is used to study and analyze practical engineering problems. This experiment selected the geological conditions of Majiazhuang as the engineering background, and determined the geometric ratio of the model to be 1:130 based on the generalized thickness of each coal layer and the geometric dimensions of the model frame. Most of the other similarity ratios in the physical model experiment are related to the geometric ratio.

The physical model is made using cast-in-place method, laying each coal layer in sequence from bottom to top, and weighing according to the calculated values of each coal layer designed. Put the weighed river sand, calcium carbonate, gypsum, borax, and water into a mixer and mix thoroughly. Install protective plates on both sides of the model frame, and then pour the mixed material into the protective plate and fully compact it. When laying, it should be laid layer by layer according to the designed thickness of the coal layers. After the laying of each coal layer is completed, a layer of 1.0-1.5 mm thick mica sheet needs to be evenly spread to simulate the weak interlayer between the rock layers. The mining area adopts downward mining, and the position relationship of the coal seams is shown in Figure 2.

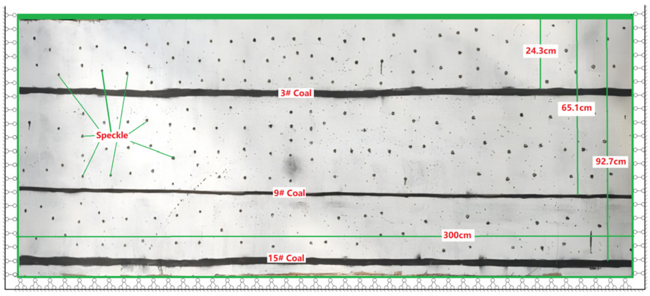


Figure 2. Physical model for mining of multi coal seam

3.3. DIC Observation of Deformation Process

In order to have a clearer understanding of the characteristics and patterns of overlying rock damage caused by multi seam mining, this physical model experiment adopts a combination of photography and digital speckle technology (DIC) observation method, as shown in figure. Using DIC's binocular high-speed CCD camera, continuously observe the changes in the rock layers of the physical model during the excavation process. After processing using professional image processing software, the entire physical model settlement field, strain field, and various yield state changes cloud maps were obtained as shown inFigure3.

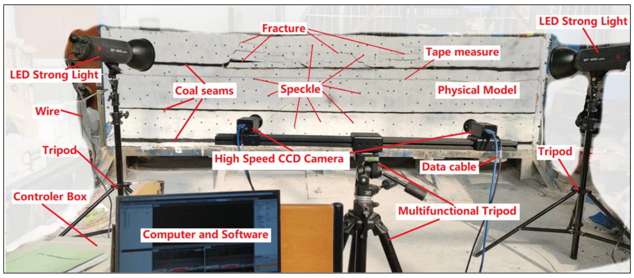


Figure 3. DIC system for observing the mining process of physical simulation

4. Results

4.1. Development Process of Overlying Rock Fractures

When simulating the mining of the upper 3 # coal seam, the direct roof of the upper coal seam is a thick sandstone layer with a thickness of 7.0m, which is not easy to collapse. When the working face is pushed forward by about 85cm, the key layer behind the direct roof collapse suddenly collapses, producing a loud noise and having a certain impact on the bottom plate. As the working face advances, the overlying rock above undergoes periodic collapse, forming a trapezoidal collapse form. Vertical cracks continue to develop towards the surface, resulting in the appearance of ground cracks on the surface and a continuous increase in surface basin subsidence. After the collapse of the overlying rock, horizontal and vertical cracks are interconnected, forming a relatively complex fracture connectivity structure. After the mining of the 9 # coal seam in the middle, the detachment state above continues to propagate upwards, reaching the floor of the 3 # coal seam. As the working face advances, the separation cracks generated by the bedrock between the 9 # coal seam and the 3 # coal seam gradually close. The overlying rock damage caused by the mining of the 9 # coal seam is not significant.

The mining thickness of the lower 15 # coal seam is relatively large, resulting in severe overburden damage. As the working face advances, the overlying rock undergoes periodic collapse, with a distance of about 22cm. The number and width of separation layers above the caving zone increase. The cracks develop upwards, reaching directly to the floor of the 9 # coal seam and the goaf. The length of the rock blocks in the lower coal seam mining caving zone is smaller and more fragmented, and the development of cracks leads to cracks in the middle coal seam floor. The mining of the lower coal seam induced secondary damage to the 3 # and 9 # coal seams. The development of overlying rock fissures directly connects the central goaf and connects with the upper coal seam goaf, ultimately reaching the surface, as shown in Figure 4

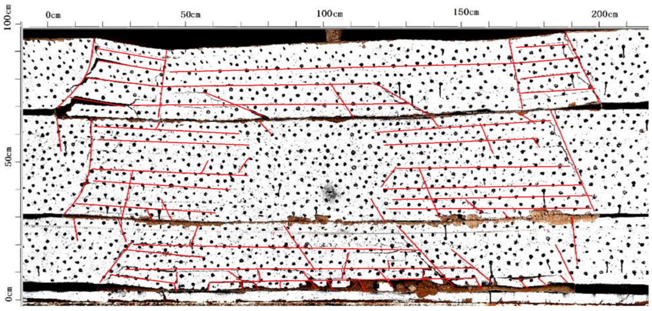


Figure 4. Development characteristics of overburden fractures in mining of lower coal seam

4.2. Analysis of Overburden Failure Height

The failure height of overlying rock is usually the sum of the height of the collapse zone and the height of the fracture zone. The spacing and separation of overlying rock collapse blocks are also important characteristics of overlying rock failure, mainly manifested as the spacing of collapse blocks and separation cracks. The size of the overlying rock collapse block is directly related to the characteristics of the rock layer itself. The collapse block is large, or its lithology is relatively hard, or the rock layer thickness is relatively large. This article does not discuss the impact of geological structure on overlying rock collapse, but only conducts research and analysis on overlying rock collapse caused by coal seam mining.

(1) After calculating based on similarity ratio in this physical model experiment, the initial fracture distance obtained is 65-85cm(The spacing between cracks is also 32-43cm,equivalent to 42-56m of actual engineering), and the periodic fracture distance is 35-38cm(The spacing between cracks is also 35-38cm,equivalent to 45-50m of actual engineering).The length of the overlying rock collapse block in shallower buried coal seams is larger, while the length of the collapse block in the deep direct roof rock layer is smaller. The main reason may be that shallow burial results in lower ground stress, less prone rock beams to collapse, and larger collapse blocks. As the burial depth increases, the in-situ stress also increases, which in turn causes the cantilever beam structure to reach its ultimate fracture distance at a short distance, leading to periodic fracture.

According to the theory of rock mechanics and formula (4) and (6), collapse distance can be calculated. After calculation, the theoretical initial collapse distance is about 90m, the spacing between cracks is 45m. The periodic collapse distance is about 52m, the spacing between cracks is also 52m. Therefore, the fracture distance obtained from physical model experiments is consistent with the theoretical calculation of fracture distance.

As the collapse zone develops, separation layers and fractures continue to develop, ultimately forming a 3-D interconnected network structure of water channels. After the free space in the goaf is filled, the overlying rock is subjected to pressure, resulting in varying degrees of fractures in the rock layer, as shown in Figure 5.

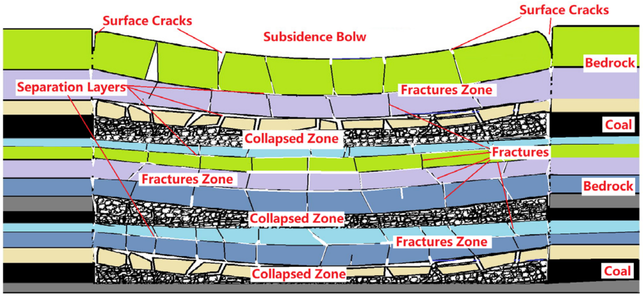


Figure 5. Schematic diagram of network formed by the development of fractures after multi seam mining

The height of crack development is directly related to the interlayer of the coal seam. The mining thickness of the 9 # coal seam is relatively small, and the interlayer of the 3 # coal seam is 50.4m. The height of crack development caused by mining is not connected to the 3 # coal seam. The mining thickness of the 15 # coal seam is 4.3m, and the interlayer between the 9 # coal seam is 34.9m. The development of cracks caused by mining directly connects with the 9 # coal seam and the 3 # coal seam, reaching the surface.

(2) Analysis of overburden failure height

In the early stages of mining, as the working face advances, the rock beams bend, resulting in separation cracks and no collapse phenomenon. At this stage, the overlying rock failure is in the incubation stage, and the main manifestations of overlying rock failure during the incubation stage are detachment and rock beam bending.

Table 1. Development height of overburden fractures in mining of different coal seams

Coal	Thickness /m	Actual Measurement /cm	Calculated Value/m	Actual Value /m
3#	2.9	24.2	40.8	31.5
9#	1.0	17.0	24.8	22.1
15#	4.3	92.8	46.6	120.7

After the rock beam reaches its maximum deflection, it collapses and the overlying rock failure enters a rapid development stage. This stage mainly manifests as the collapse of the rock layer, the formation of collapsed blocks, and the gradual upward development of cracks. When the lower coal seam with a larger thickness is mined, it will lead to the development of overlying rock failure height to the upper coal seam and goaf, causing repeated mining damage to the goaf of the upper coal seam. After the coal seam mining face is advanced to a certain distance, the height of overlying rock collapse reaches its maximum, and the development of cracks also reaches its maximum value. After that, the height of overlying rock failure no longer increases, and the overlying rock failure enters a relatively stable stage. At this stage, the height of overlying rock failure no longer increases, and the broadband gradually expands with the advancement of the working face, as shown in Figure 7.

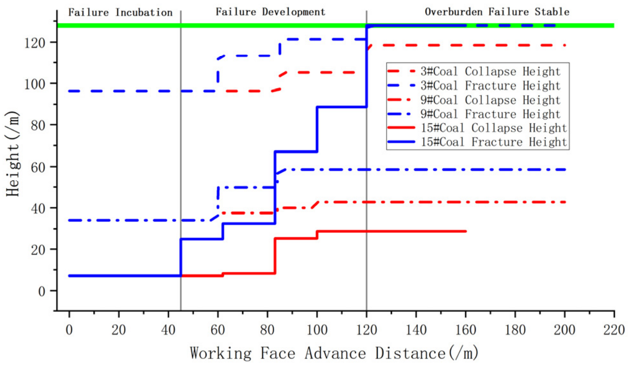


Figure 6. The process and law of overburden failure

5. Discussion

5.1. Analysis of Surface Subsidence

The research on the surface damage law of multi coal seam mining usually uses the surface settlement deformation curve to reflect. Based on the DIC monitoring results, an observation line is set at the boundary of the monitoring model to analyze the surface settlement law. After data processing, the surface settlement curve is obtained. The surface subsidence process reflected by the surface subsidence curve is very obvious. Firstly, the thickness of the upper coal seam mining is 2.9m, and the surface subsidence caused by it gradually develops with the advancement of the working face, forming a subsidence basin. The final form of the basin is shown as a "flat bottom pot" shape. The mining thickness of the central coal seam is only 1m, and the mining process leads to secondary subsidence of the overlying rock, as well as secondary subsidence of the surface. The surface forms a subsidence basin, which appears in the form of a "spoon". The mining thickness of the lower coal seam is 4.3m. As the mining face advances, the surface undergoes a third subsidence. When the mining face advances to the stop line, the surface subsidence reaches a stable state, and the surface subsidence basin appears as a "pointed bottom bowl" shape, as shown in Figure 6. By using DIC to observe the physical model, the variation curve of surface subsidence was obtained, and the trend of variation is very close to that of actual engineering.

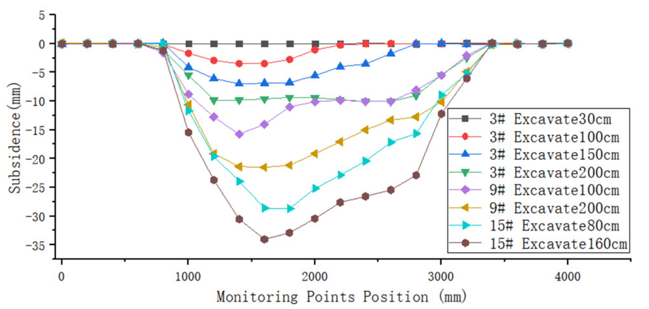


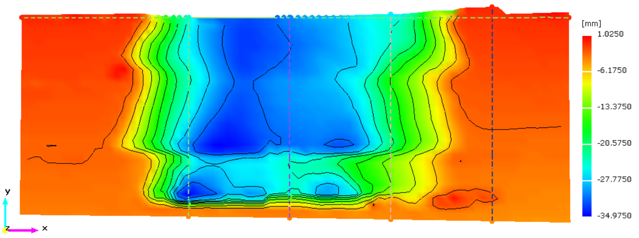
Figure 7. Surface subsidence curve

5.2. State of Overburden Failure

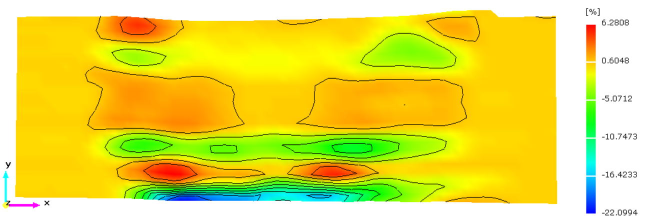
(1) Subsidence state of Overburden

The settlement state of the overlying rock is the vertical displacement characteristic caused by the overlying rock during the mining process, and is also an important reference for analyzing the failure of the overlying rock, as shown in

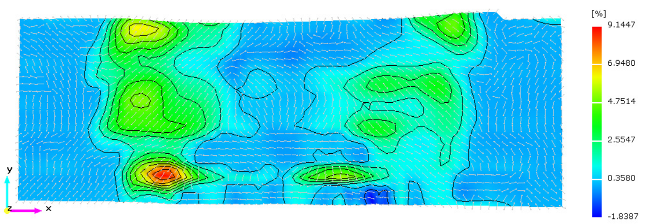
Figure 8(a). The mining of the 3 # coal seam caused subsidence of the overlying rock, resulting in the formation of surface subsidence basins and the generation of a large number of ground fissures at the edges of the basins. The mining thickness of the 9 # coal seam is relatively small, only 1m, which caused less severe damage to the overlying rock. However, it also led to secondary subsidence in the goaf and overlying rock of the 3 # coal seam. During the mining of the 15 # coal seam, significant secondary or tertiary subsidence occurred in the overlying rock and its two goaf areas above. Induced the "activation" settlement of the goaf above it. The vertical manifestation of overlying rock failure in multi seam mining is characterized by "two zones". With the increasing exploitation of coal seams, the overlying rocks and surface damage exhibit multiple cumulative subsidence characteristics.



(a)



(b)



(c)

Figure 8. State of Overburden Failure (a)subsidence state of overburden (b)Strain state of overburden (c)Maximum principal stress state of overburden

As shown in Figure 8 (b), the variation of strain field in multi seam mining is much more complex than that in single seam mining. Different burial depths of coal seams, different mining thicknesses, and changes in geological strata can all lead to complex changes in strain distribution and state. The main deformation areas are the overlying rock and crack positions during the mining of Coal Seam 3 #, and the strain is mainly concentrated in the goaf position, mainly manifested as tensile deformation. The crack location above the goaf is a small deformation zone, mainly manifested as compression deformation. After the mining of the 9 # coal seam, the main deformation area of the overlying rock underwent significant changes, with two obvious tensile deformations appearing above the coal pillars on both sides of the 9 # coal seam. The goaf and overlying rock layer showed a compressive state. The 3 # coal seam exhibits significant tensile deformation on the surface above the cutting hole, and a certain compressive deformation state near the stop mining line. After the mining of the 15 # coal seam, the goaf is the main deformation area, and the main deformation is compression deformation. Two stretching zones were generated above both sides of the coal pillar, while the goaf of the 3 # and 9 # coal seams also underwent certain deformation.

The principal strain is a direction in which the strain state of a point exists, as shown in Figure 8 (c). After any segment of the element is subjected to force in that direction, the strain only elongates and shortens in that direction, which is the principal direction and its strain is the principal strain. The maximum principal strain is a method of reflecting whether a material will undergo fracture in material mechanics. In this experiment, it is mainly used to analyze the range of rock fracture. After the mining of the upper coal seam, the strain state changes, and the maximum principal strain is mainly concentrated in the rock layers near the surface. After the mining of the central coal seam, the main deformation zone of the maximum principal strain is located in the stretching zone of each coal seam in the model after mining. After the mining of the lower coal seam, the maximum principal strain is concentrated in the tensile zone above the lower coal pillar, and shows a certain degree of compression and realization in the floor near the stop mining line.

6. Conclusion

This article mainly conducts a similar simulation test on the overlying rock of shallow buried multi coal seam mining under the geological conditions of Majiazhuang, revealing the characteristics and laws of overlying rock movement caused by multi coal seam mining.

(1) The characteristics of overlying rock failure mainly include the height of failure and the spacing between collapsed blocks. The height of overlying rock failure can be calculated by the height of the collapse zone and the development height of the fracture zone. The theoretical calculation values and physical simulation values have good consistency. The length of the overlying rock collapse block can be inferred by establishing a mechanical model. The physical simulation of the collapse block spacing is about 32-50m, and the theoretical calculation value is 45-52m.

(2) This article studies the characteristics and laws of overlying rock fracture caused by multi coal seam mining through physical simulation experiments, and elucidates the characteristics and laws of overlying rock and surface damage caused by multi coal seam mining. The vertical manifestation of overlying rock failure in multi seam mining is characterized by "two zones", and the settlement characteristics of overlying rock failure are manifested as multiple cumulative states.

(3) The characteristics and laws of the development of overlying rock fractures have been revealed. The vertical and horizontal fractures of overlying rock in multi coal seam mining are interconnected, forming a three-dimensional network structure. The development of fractures runs through the goaf of each coal seam and directly connects to the surface.

Acknowledgments

Funding: This work was supported by Liaoning Provincial Department of Education Service Local Project [Grant No. LJKFZ20220282].

References

[1] Sun D.C., Wei X.P., Lu N. Energy Resource Extraction When the Future New Energy Has an Uncertain Cost. J. Technical Economics & Management, 2010, 6: 23-26.

[2] Liu, G.C; Zou, Y.F; Zhang, W.Z; Chen, J.J. Characteristics of Overburden and Ground Failure in Mining of Shallow Buried Thick Coal Seams under Thick Aeolian Sand. Sustainability 2022, 14, 4028.

[3] Liu, G.C.; Zhang, W.Z.; Zou, Y.F.; Chai, H.B.; Xue, Y.A. Numerical Study on Characteristics of Bedrock and Surface Failure in Mining of Shallow-Buried MCS. Energies 2022, 15, 3446.

[4] Zhang, J.; Zhuo, Q.; Yang, S.; Yang, T.; Wang, B.; Bai, W.; Wu, J.; Xie, S. Study on the Coal Pillar Weakening Technology in Close Distance Multi-Coal Seam Goaf. Energies 2022, 15, 6532.

[5] Ma F.H., Hou J.H., Zuo C. Knowledge Structure Analysis of International Mining Subsidence Research. China Mining, 2013, 22, (2):96-100.

[6] Chen CM., Ibekwe SanJuan F., Hou J.H.. The Structure and Dynamics of Co Citation Clusters: A Multiple Perspective Co Citation Analysis. Journal of the American Society of Information Science and Technology, 2010, 61: 1386-1409.

[7] Liu Z.K., Liu B.L.i, Wang R.R.. The main research methods and application of mining subsidence in domestic mines. Western Exploration Engineering, 2011,1: 176-178.

[8] Li, B.; Wang, X.; Liu, Z.; Li, T. Study on multi-field catastrophe evolution laws of water inrush from concealed karst cave in roadway excavation: A case of Jiyuan coal mine. Geomat. Nat. Hazards Risk 2021, 12, 222-243.

[9] Cui F., Jia C., Lai X.P., Yang Y.B., Dong, S.. Study on the Law of Fracture Evolution under Repeated Mining of Close-Distance Coal Seams. Energies. 2013.22.6064.

[10] Li, Q.; Wu, G.; Kong, D. Study on Stability of Stope Surrounding Rock under Repeated Mining in Close-Distance Coal Seams. Geofluids. 2022,9630942.

[11] He, Fulian; Liu, Bingquan; Li, Liang; Xu, Xuhui; Lv, Kai; Zhai, Wenli; Song, Jiayu; Wang, Deqiu. Study on the Key Factors of Terminal Mining Line Layout in Repeated Mining of Close-Distance Thick Coal Seams. Advances In Materials Science And Engineering.2022.9724275.

[12] Liu, H.; Jiang, Y.; Misa, R.; Gao, J.; Xia, M.; Preusse, A.; Sroka, A.; Jiang, Y. Ecological environment changes of mining areas around Nansi lake with remote sensing monitoring, Environmental Science And Pollution Research, 2021, 28, 32, 44152-44164.

[13] Nie, X.; Hu, Z.; Ruan, M.; Zhu, Q.; Sun, H. Remote-Sensing Evaluation and Temporal and Spatial Change Detection of Ecological Environment Quality in Coal-Mining Areas. Remote Sensing,2014,2,345.

[14] Qin, Y. Research on Rock Movement Law in Multi Coal Seam Mining.; China University of Geosciences: Beijing, China, 2021.

[15] Dong, C. Research on Overlying Rock and Surface Movement and Deformation under Repeated Mining; Taiyuan University of Technology. Taiyuan China ,2020.

[16] Li, Z.C.; Li, L.C.; Wang, S.R.; Ma, S.; Zhang, Z.L.; Li, A.S.; Huang, B.; Zhang, L.Y.; Wang, Z.L.; Zhang, Q.S. Formation of X-shaped hydraulic fractures in deep thick glutenite reservoirs: A case study in Bohai Bay Basin, East China. J. Cent. South Univ. 2021, 28, 2814-2829.

[17] Xie, S.R.; Pan, H.; Chen, D.D.; Gao, M.M.; He, S.S.; Song, B.H. Equivalent basic roof structure between layers and its activity law in multi coal seam mining. J. China Univ. Min. Technol. 2017, 46, 1218–1225.

[18] Zhao, X.L.; Wang, Y.Q.; Gao, G.Q.; Wu, Y. Safety analysis of coal mining pavement under expressway based on UDEC and settlement prediction. Coal Technol. 2020, 39: 123–127.

[19] Li, S.H.; Wang, J.G.; Liu, B.S.; Dong, D.P. Analysis of criticalexcavation depth for a jointed rock slope using a face-to-face discrete element method. Rock Mech. Rock Eng. 2007, 40: 331-348.

[20] Sawamura, Y.; Ishihara, H.; Otani, Y.; Kishida, K.; Kimura, M. Deformation behavior and acting earth pressure of three-hinge precast arch culvert in construction process. Undergr. Space ,2019,4:251-260.