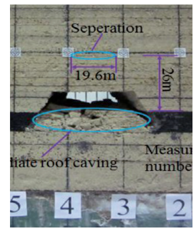
A study on the law of overlying strata migration and separation space evolution under hard and thick strata in underground coal mining by similar simulation



Un estudio sobre el principio de la migración de los estratos superpuestos y la evolución del espacio de separación bajo los estratos duros y potentes en la extracción subterránea de carbón mediante simulación similar

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RESUMEN

- La rotura de capas duras de espesor considerable puede causar desastres dinámicos con cierta facilidad, como los casos de fractura de rocas y sismicidad en minas, amenazando seriamente la seguridad minera. Para analizar las características de la rotura por sobrecarga y la ley de evolución de las grietas de separación en minas con estratos rocosos de cierto espesor, y para prever el proceso de aparición de desastres dinámicos, se analizan en este estudio, mediante simulación similar, las características de fractura de los estratos superpuestos durante las operaciones de minería. Se discuten, en base a la ley del desplazamiento de rocas superpuestas, las características del movimiento superficial y de la deformación antes y después de la rotura de los estratos duros. Finalmente, se presenta la ley del desarrollo de la fisura de separación en un estrato potente de roca. Los resultados muestran que las etapas clave del movimiento de los estratos superiores durante las operaciones de minería son la rotura inmediata del techo de la galería y de las rocas. Los estratos duros y potentes, que son los estratos clave, soportan el peso de los estratos superiores con un pequeño hundimiento antes de la rotura. El desarrollo de un estrato distinto se detiene en el fondo de los estratos duros y gruesos y mantiene una situación abierta durante mucho tiempo, proporcionando espacio en formación para la acumulación de gas y agua en la capa separada. Cuando la roca gruesa se rompe, el hundimiento de los estratos superiores aumenta dramáticamente, y el estrato separado se cierra rápidamente, produciendo fácilmente estallidos de gas, irrupciones de agua, hundimientos de la superficie y otros desastres en el frente. Los resultados de este estudio son relevantes para una minería segura en el frente de trabajo bajo condiciones geológicas similares.
- **Palabras clave:** estratos duros y potentes, simulación similar, movimiento de estratos superpuestos, estrato 30 separado, desastres dinámicos.

ABSTRACT

Fracture of the hard and thick key layer can easily cause dynamic disasters, such as the rock burst and mine seismicity, which seriously threatens the safety of underground coal mining. To analyze the characteristics of overlying strata fracture and law of evolution of separation fissures under hard and thick strata in underground coal mining, and further reveal the process of the occurrence of dynamic disasters, the fracture characteristics of overlying strata during underground coal mining were analyzed via similar simulation in this study. The characteristics of surface movement and deformation before and after the fracture of hard and thick strata were then discussed based on the law of overlying rock displacement. Finally, the development law of separation fissures under the hard and thick strata was revealed. Results show that the key stages of overlying strata movement during underground coal mining are immediate roof fracture, main roof fracture; main roof cycle fracture, and hard and thick rock fracture, respectively. Before the hard and thick strata are fractured, as the key layer, bearing the weight of the overlying strata and the overburden strata subsidence is small. The developmental height of the separated stratum stops at the bottom of the hard and thick strata, and the separated stratum stays in an unclosed state for a long time, which provides the incubation space for the accumulation of gas and water in the strata. After the hard and thick strata are fractured, the subsidence of the overlying strata increases dramatically, and the separated stratum is closed rapidly, inducing gas outburst, water inrush, dramatically surface subsidence, and other disasters in the working face. The research results of this study are of considerable significance to the safe mining of working face under similar geological conditions.

Keywords: hard and thick key strata, similar simulation, overlying strata movement, separated stratum, dynamic disasters.

1. INTRODUCTION

Dynamic disasters in mines, such as the mine seismicity and rock burst, have become increasingly prominent with the expansion of coal mining into the deep [1-5]. In particular, when hard and thick strata with high intensity, good integrity, and big limit span occur on the working face, it is easy to form a stable overburden space structure after mining, so that the surrounding rock of the stope is in high stress state. After the hard and thick strata are fractured, the structure of the overburden rock is changed, and the strong dynamic phenomenon is easily induced, even leading to dynamic disasters such as the mine shock and rock burst etc.

[6-7]. which seriously threatens the safe operation of the working face and result in casualties and economic losses [8-15]. At present, hard and thick strata are distributed in Huafeng, Huaibei, and Jining coal mines in China [16-18]. Production practice shows that when the working face is covered with hard and thick strata, as the mining range increases, when hard and thick strata reach the ultimate span, hard and thick strata fracture, resulting in strong shocks, which exerts different degrees of impact on the working face, resulting in different degrees of dynamic disasters on the working face.

At present, studies by domestic and foreign scholars on mining under hard and thick strata are mainly concentrated on the fractue law theory of hard and thick strata [19] and the abutment pressure distribution on the working face [20]. The researchers have analyzed the breaking span of hard and thick rock strata in the mining process, and the stress distribution characteristics of the surrounding rock before and after the fracture of hard and thick strata, which have played an important role in the study of the safe mining under the hard thick strata. However, the existing researches cannot directly observe the spatial structure of overlying strata and the developmental characteristics of separation fissures under the hard and thick strata, and in the actual mining, it is also difficult to detect the overlying rock movement and law of development of fissures in the field.

Based on this, aiming at the occurrence of high-position overlying hard and thick strata above stopes, this study applied similar material simulation to study the movement law of the overlying strata and the spatial evolution law of separation fissures under high-position hard and thick key strata, which are significant in revealing the process of occurrence of dynamic disasters and taking scientific prevention and control measures.

2. STATE OF THE ART

In recent years, domestic and foreign scholars have conducted extensive researches on dynamic disasters caused by mining under hard and thick strata. The causes and mechanicms of rock burst in North Africa over the past fifteen years. were studied by N. G. W. Cook [21]. He et al. [22] stated that based on the key theory of strata movement, the pressure of the mine reaches the maximum value when the overlying key strata fracture, easily leading to the occurrence of strong mine seismicity and rock burst. Hu et al. [23] analyzed the causes of dynamic disasters induced by the super-thick magmatic rock through FLAC3D numerical simulation. The relationship between the rock burst and mining blasting of a American coalmine was studied by Baumgardt D [24]. Golab A N et al. [25] proposed that the water inrush in the separated stratum was due to the uneven subsidence of the coal and rock seam under the entire blocky, hard and thick strata, which produced the separated stratum space, thereby leading to the accumulation of stratifugic water in the separated stratum and causing water disaster under the dynamic impact of the super-thick strata. In view of the coal and gas outburst events that occurred in Haizi Coal Mine. Yang [26] applied the similar material experiment, theoretical analysis, and numerical simulation to study the deformation failure of the overlying super-thick key strata and the bearing pressure variation characteristics of the working face. The mechanism and manifestation mode of the induction of the rock burst on the working face by the super-thick key strata was then analyzed. The aforementioned studies focus on the causes of dynamic disasters resulting from mining under hard and thick strata and point out the root causes of these disasters when the hard and thick strata are fractured. However, these studies fail to investigate the relationship among the movement of the overlying strata, the development law of the separated stratum, and the occurrence of dynamic disasters during the mining of working face. To understand the root causes of dynamic disasters under hard and thick strata, the relationship between the occurrence of dynamic disasters and the spatial structure of overlying strata must be discussed on the basis of the law of overlying rock movement and the characteristics of the development of the separated stratum.

Domestic and foreign scholars have conducted extensive research on the movement law of the overlying strata and the evolution law of the separated stratum in underground coal mining. Palchik, Howladar, and Bai [27-30] supposed that three different fracture movement zones existed in longwall mining. Li et al. [31] applied discrete element numerical simulation to study the influence of the overlying strata structure combination on the development law of water-flowing fractures for steep-inclined seam mining. The results suggested that the development height of water flowing fractures increased with seam thickness under various combinations of overlying strata structures in steep-inclined seam mining, and the ratio of the height of the fractured zone to the underground coal mining height showed a downward trend. Xu [32] applied theoretical analysis and numerical simulation to analyze the development location, height, evolution process, and influential factors of the separated stratum in the underground coal mining process of the working face and explained the isolated section-filling principle for the separated stratum to reduce subsidence based on the numerical simulation, which provided a reliable basis for the subsequent isolated section filling. Zhang [33] analyzed the distribution characteristics and evolution law of "three zones" of the overlying strata through similar material simulation and obtained the development pattern, location, and evolution characteristics of the separated stratum space. However, the movement law of the overlying strata and the development characteristics of the separated stratum under high-position hard and thick key strata have not been studied.

Therefore, considering the limitations of the existing research, this study applied similar material simulation to investigate the movement law of the overlying strata and the fracture evolution law of the separate stratum under high-position, hard and thick key strata in the underground coal mining field. This effort lays a foundation for the future mining under hard and thick strata research on the movement law of overlying rock and the characteristics of the development of the separated stratum.

The rest of the study is organized as follows. Section 3 expounds on the design of similar simulation. Section 4 studies the movement characteristics and migration law of the overlying strata and the evolution law of the separated stratum space based on mining under the high-position, hard and thick key strata. Section 5 summarizes the paper and presents relevant conclusions.

3. METHODOLOGY

3.1. EXPERIMENTAL DESIGN OF SIMILAR SIMULATED MATERIALS

Similar material simulation was conducted based on similarity theory, the geometric, time, bulk density, elastic modulus, and Poisson's ratio similarities must be followed between the similar model and the original field model. Supposing the sizes of three mutually perpendicular directions of the field original model were X_p, Y_p and Z_p, the sizes of the corresponding similar model were

X_m, Y_m, and Z_m.

1) Geometric similarity ratio was taken as

$$C_l = X_m / X_p = Y_m / Y_p = Z_m / Z_p \ . \ (1)$$

2) Time similarity. Time similarity was set as

$$C_t = T_m / T_p = \sqrt{C_l} \ . \ (2)$$

3) Bulk density similarity. The bulk density of the ith rock layer of the original model was γ_{pi}, and the bulk density of the rock was γ_{mi} in the similar model, then the similarity ratio of the bulk density was

$$C_\gamma = \gamma_{mi} / \gamma_{pi} \ . \ (3)$$

4) Strength similarity. The uniaxial compressive strength of each stratum in the original field model was σ_{cpi} and σ_{cmi}, the uniaxial compressive strength similarity ratio of the materials in each stratum was $c_{\sigma c}$, then,

$$C_{\sigma c} = \sigma_{cmi} \cdot \sigma_{cpi} = C_l \cdot C_\gamma \ . \ (4)$$

5) Elastic modulus similarity. The elastic modulus of each stratum in the original field model was E_{pi} and E_{mi}, then the elastic modulus similarity ratio was

$$C_E = E_m / E_p = C_l \cdot C_r \ . \ (5)$$

6) Poisson's ratio similarity. The Poisson's ratios of each stratum in the original field model was μ_{mi} and μ_{pi}. then the Poisson's ratio similarity coefficient was

$$C_u = \mu_{mi} / \mu_{pi} \ . \ (6)$$

Similar simulation in the study took the generalized geological section and rock mechanic parameters of the coal seam in 104 mining areas of the Yangliu mine of Huaibei Mining Group as reference to design the test model. The magmatic rock thickness of the model was 60 m; the space between the magmatic rock and mining coal seam was 80 m; and the mining thickness of the coal seam was designed to be 8 m. Then, 500 kg of iron was imposed above the model to simulate a part of unpaved strata. For similar parameters, the result is shown in Table 1 (see section: supplementary material). Then, 500 kg of iron was imposed above the model to simulate a part of the unpaved strata.

The simulation selected fine river sand as the aggregate and calcium carbonate and gypsum as the cement materials. Mica powder was selected as the inside of the simulated layer of the sandwich material. Different lithologies of various strata were obtained by different ratios of materials in the test. The proportioning parameters of the similar material test were determined by the proportioning test according to the confirmed similarity constants, and the result is shown in Table 2 (see section: supplementary material). The model construction process is described as follows: 1) The aggregates and cement materials required by different strata were weighed based on the calculation in Table 1 and then combined in the mixer. 2) The mixture on the support of the model was paved evenly and rammed by an iron. Then, the mica powders were evenly sprinkled on the strata to simulate the intraformational joint. 3) The other strata of the model were paved according to the preceding steps until the designed height was reached. 4) The weight of the overlying strata was determined, which couldn't be simulated above the model, by adding the counterweight. 5) The model was dried naturally for four days.

3.2. OBSERVATION OF MOVEMENT AND DISPLACEMENT OF OVERLYING STRATA

Grids, which was 100 mm long and 100 mm wide, were arranged on the surface of the test model to observe the movement characteristics of the overlying strata in the underground coal mining process of the model. The dimension of the model was 3 m x 0.4 m x 1.8 m (length x width x height). Detection lines and monitoring points were set on the surface of the model to effectively observe the movement law of the overlying strata in the underground coal mining process ; the result is shown in Fig. 1 (see section: supplementary material). The model had 5 detection lines, namely, 12.5, 32.5, 37.5, 42.5, and 112.5 cm from the coal seam, respectively. A total of 29 monitoring points (numbered from 1 to 29) were set on each line.

The total station, the result is shown in Fig. 2 (see section: supplementary material) was applied to measure the displacements of the monitoring points. A digital camera was used to record the breaking process of the overlying strata in the underground coal mining process of the model.

4. RESULT ANALYSIS AND DISCUSSION

4.1. MOVEMENT CHARACTERISTICS OF OVERLYING STRATA UNDER HARD AND THICK KEY STRATA

A 25 m coal pillar was left on each side to eliminate the boundary effect before the excavation of the model. The model was excavated 10 m each time. After each excavation, the overlying strata movement and displacement of the measuring points were recorded by digital camera and total station.

As shown in Fig. 3, when the working face advances to 40 m, the hanging area of the immediate roof is large. At this instance, the span length reaches the limit value and the immediate roof cave. The caved rocks accumulate in the goaf area in a disorderly manner. The size of the goaf area increases continuously with the advancement of the working face. The main roof breaks when the working face advances to 70 m, as shown in Fig. 4. After breaking, the rock blocks are large and regularly shaped, which can maintain the original strata falling down in order on the immediate roof and form the front and rear articulated transferring rock beam. Fig. 5 shows that the main roof suffers periodic breakage when the underground coal mining scope of the working face increases. The rock blocks are roughly quadrilateral in shape after breaking. The caved overlying strata also form the articulated structure with a certain bearing capacity.

Figs. 6 and 7 show that the caved rocks are gradually compacted with the advancement of the working face. The overlying strata breakage continues to develop upward. The separated stratum begins to develop to the bottom of the hard and thick magmatic rock when the working face advances to 160 m. The hard and thick strata can play a shielding role in the height development of the separated stratum because they remain stable due to considerable strength and good integrity. Figs. 7 to 9 show the height of the separated stratum ends at the bottom of the magmatic rock before the breakage of the hard and thick magmatic rock.

With the joint effects of the overlying pressure and the elastic foundation effect of the weak strata below, fracture cracks occur on the lower surface in the middle of the magmatic rock, as shown

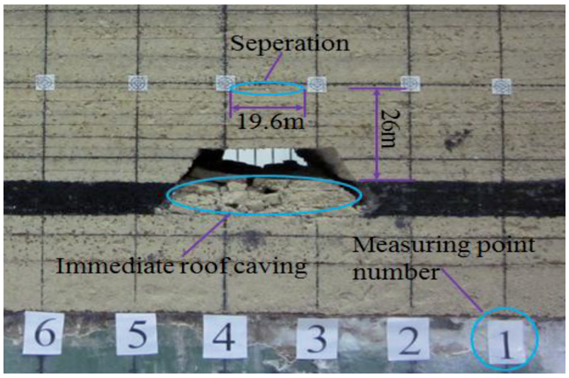

Fig. 3. Advancement 40m

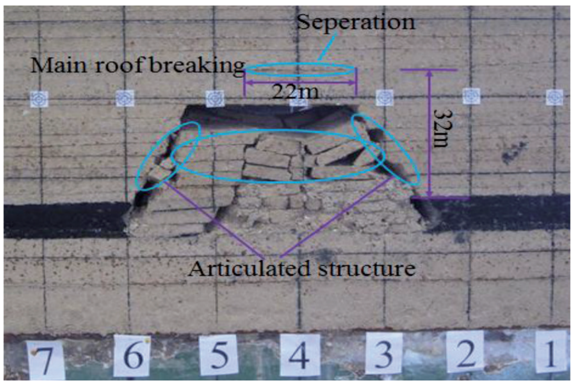

Fig. 4. Advancement 70m

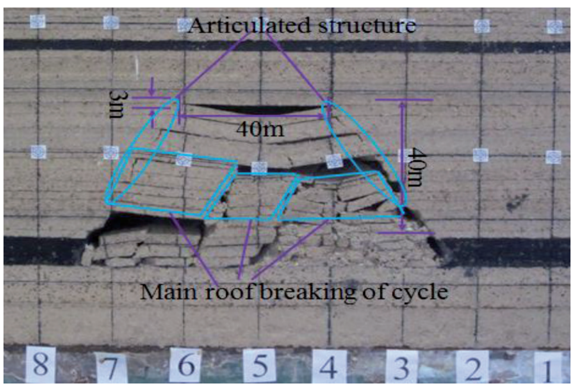

Fig. 5. Advancement 100m

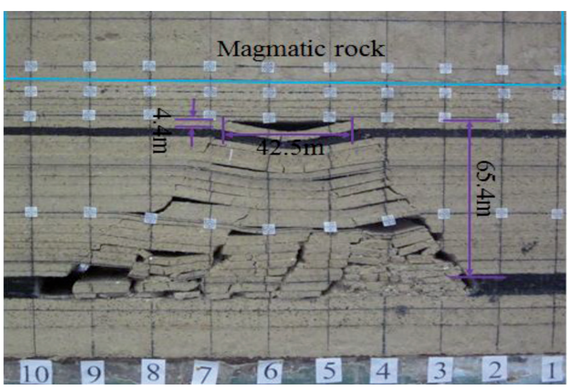

Fig. 6. Advancement 130m

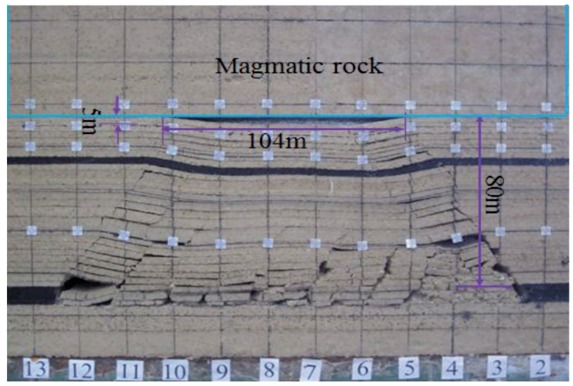

Fig. 7. Advancement 160m

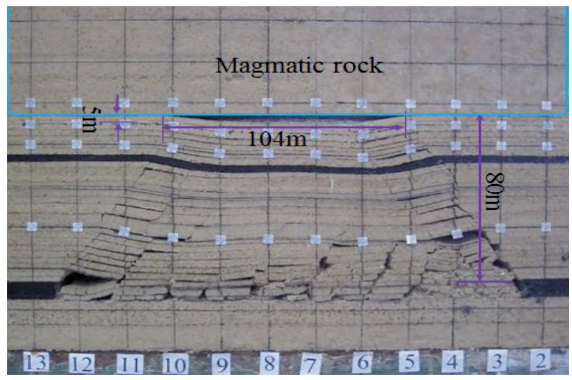

Fig. 8. Advancement 200m

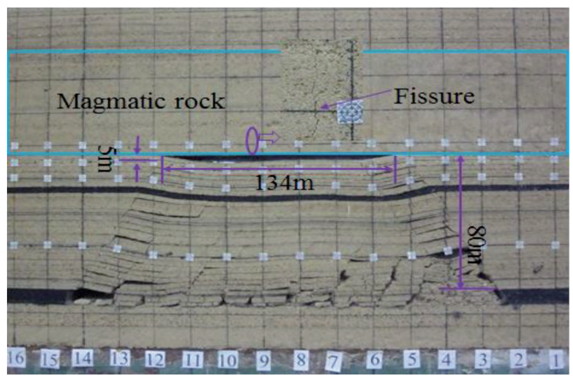

Fig. 9. Advancement 240m

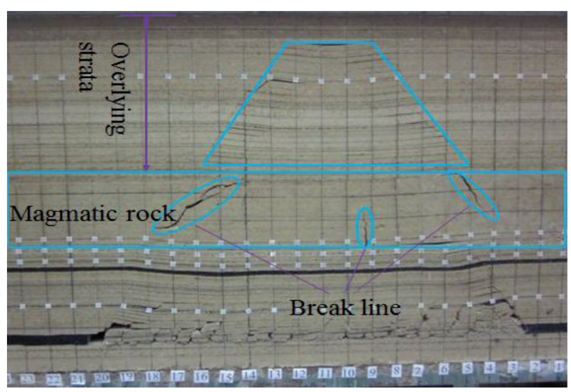

Fig. 10. Advancement 340m

in Fig. 9. The fractures on the lower surface of the magmatic rock continues to expand, and inclined fractures occur on the upper surface of the end with the advancement of the working face. The separated stratum below the magmatic rock also continues to expand. The magmatic rock breaks and moves when the inclined fractures pass through the magmatic rock. The separated stratum below it closes and the overlying strata settle overall. The fractures then develops to the top of the model, as shown in Fig. 10.

4.2. MOVEMENT LAW OF OVERLYING STRATA UNDER HARD AND THICK KEY STRATA

For the displacement subsidence curves of five detection lines during the underground coal mining process of the working face, the results are shown in Fig. 11 to 14 (see section: supplementary material). When the working face advances to 70 m, the maximum amount of subsidence of line no. 1 is 4.28 m after the main roof breaks. The displacement of other detection lines does not settle, and the result is shown in Fig. 11 (see section: supplementary material). Thus, the main roof is in a growing state, and the hard and thick magmatic rock and its overlying strata are stable without subsidence. Fig. 11 (see section: supplementary material) shows that the overlying strata continue to cave as the goaf area increases. The subsidence of detection line no. 1 continues to increase to 6.02 m. The subsidence of detection line nos. 2 and 3 have no apparent change. The maximum amounts of subsidence of line nos. 2 and 3 in the central part of the goaf are 4.67 m and 4.4 m, respectively, and are distributed symmetrically. The strata in the high position begin to bend and settle with the constant upward development of the separated stratum. The overlying strata have no noticeable change in displacement because of the shielding role of the magmatic rock.

Fig. 13 (see section: supplementary material) shows that the overlying strata break and move repeatedly before the hard and thick strata is fractured. The displacements of detection line nos. 1 to 3 settle fully to form a basin shape, and the magmatic rock and its overlying strata show an apparent subsidence. The magmatic rock hangs in a large area, which obstructs the longitudinal development of the separated stratum. However, the separated stratum space continues to develop horizontally, providing sufficient space for the breakage of the magmatic rock. Fig. 14 (see section: supplementary material) shows that the hard and thick strata breaks and becomes unstable. The subsidence of detection line nos. 4 and 5 increase noticeably with maximum values of 5.2 and 4.02 m, respectively. The displacements of detection line nos. 1 to 3 are basically stable. The magmatic rock loses the original bearing capacity after breaking, leading to the bending and subsidence of the upper strata and the large range of movement and deformation on the surface.

The hard and thick magmatic rocks bear the weight of the upper strata and form a separated stratum between the lower and key strata before breaking. The deformation of the upper strata is small. After breaking, the upper strata bend and settle, and the lower separated stratum of the hard and thick strata is closed rapidly, leading to the movement and deformation, and increasing subsidence of the upper strata. Under general geological conditions, the movement and deformation of the overlying strata is a process of continuous development with underground coal mining of the working face, but the mining under hard and thick strata shows a significant difference. Thus, the movement and deformation exhibit the mutation phenomenon. Surface movement and deformation begin to increase rapidly when the hanging length of the magmatic rocks reaches the limit span. In the underground coal mining process, strengthening the ground deformation observation is necessary to perform a good job in prediction and forecasting and prevent a sharp subsidence of the surface.

4.3. EVOLUTION LAW OF SEPARATED STRATUM OF OVERLYING DISRUPTED STRATA BY EXTRACTION

The similar simulation test can visually display the entire evolution process of the separated stratum under the hard and thick key strata, as shown in Figs. 3 to 10.

Fig. 3 shows that the caving immediate roof cannot completely fill the goaf area when the working face advances to 40 m. Thus, the lower part of the non-caving roof bends and settles because of the loss of support. The bending and subsidence of the roof strata occur asynchronously because of the difference in lithology, leading to the formation of the separated stratum at the siltstone–mudstone interface (upper hard–lower soft overlying strata structure), which is 26 m above the coal seam. The separated stratum spans 19.6 m.

Fig. 4 shows that the main roof of the working face is weighting when the working face advances to 70 m. The separated stratum moves upward to 32 m above the coal seam. The span slightly increases, but its shape is unchanged. With the increase in the underground coal mining area, the working face undergoes periodic weighting when it advances to 100 m.

As shown in Fig. 5, when the working face advances to 100 m, the roof of the working face breaks and moves in a large area. The height of the separated stratum space (that is, the maximum difference in the displacements between the upper and lower strata at the maximum separated stratum) and the morphology change rapidly. The height of the separated stratum space immediately increases to 3 m, the span reaches 40 m, and the separated stratum develops on the area 40 m above the coal seam.

Figs. 7 and 8 show that the overlying rocks break and move in groups when the working face advances to 130 and 160 m. The morphology of the separated stratum gradually develops on the higher-position stratum and on the bottom of the magmatic rocks. The height of the separated stratum space is 4.6 m and it spans 66 m. The morphology of the separated stratum does not change.

As shown in Fig. 8 and Fig. 9, when the working face advances to 200 m and 240m, the overlying rock is collapsed in a large area, and the collapsed rock strata are gradually compacted in the middle part of the goaf. The height of the separated stratum space beneath the magmatic rocks increases to 5 m, and the span reaches 104 and 134 m. The morphology of the separated stratum is changed.

As shown in Fig. 10, when the working face advances to 340 m, the magmatic rocks break and become unstable. The magmatic rocks and upper strata begin to settle, and the separated stratum is closed beneath the magmatic rock. For the development process of the morphology of the separated stratum under the hard and thick strata, the result is shown in Fig. 15 (see section: supplementary material).

For the development height of the separated stratum, Fig. 16 (see section: supplementary material) shows that the evolution of the height of the separated stratum is divided into two stages before the breakage of the hard and thick key strata. At stage I, the development height of the separated stratum increases as the mining width increases before the separated stratum develops into the hard and thick key layer. However, the development height of the separated stratum is not linearly related to the advancing distance but develops rapidly to the bottom of the hard and thick key strata based on the overlying subcritical layer on the working face. The development height of the separated stratum is 0.4 to 0.65 times more than the advancing length. At stage II, the development height of the separated stratum is unchanged from developing to the bottom to breakage of the hard and thick key strata.

Based on the morphology of the roof of the working face before and after the hard and thick strata break, the breakage of the magmatic rocks can easily induce water inrush at the working face, dynamic load on the support, and other disasters. Before the breakage, a huge space of separated stratum is formed between the magmatic rocks and the lower strata without communication with the fracture, thereby providing a good space carrier for the accumulation of the stratifugic water. Once the magmatic rocks break and settle, a significant effect can be seen observed on the stratifugic water. Thus, the stratifugic water floods into the working face along with the O-type fracture zone, leading to the water inrush at the working face. A large amount of energy is released when the magmatic rocks break. In addition, the rapid subsidence and movement of the magmatic rocks convert the gravitational potential energy into kinetic energy, which results in the strong, dynamic action of magmatic rocks on the lower strata. This condition induces the mine seismicity, and leading to the instability of the support, rock burst, coal and gas outburst, and other accidents. The evolution of the developing morphology and height of the separated stratum provide a good development space for gas accumulation at the bottom of the hard and thick key strata. If the separated stratum beneath the magmatic rocks communicates with the penetrating fracture of the stratum under the magmatic rocks, then a natural channel and space for gas accumulation is provided. Once the magmatic rocks become unstable, the huge energy produced will cause the gas accumulated in the separation zone to pour into the working face rapidly through the O-type fracture zone, thereby resulting in gas outburst accidents.

4.4. THEORETICAL ANALYSIS OF HARD AND THICK FRACTURE

In the process of working face mining, the overlying hard and thick strata can be considered as solid supported beams. According to the theory of key strata, the calculation formula for the initial breaking span of hard and thick strata is as follows:

$$L = h\sqrt{\frac{2R_T}{q}} \quad (7)$$

where, L is the initial breaking span of hard and thick strata, h is the thickness of hard and thick strata, R_T is the tensile strength of hard and thick strata, q is the load of hard and thick strata.

The tensile strength of hard and thick rock measured in the laboratory was 6.8 MPa, and the corresponding value was substituted into the formula (7), and the initial breaking span of the hard rock was 380.8 m. The theoretical calculation of the initial breaking span of hard and thick rock was in agreement with the results of similar simulation test.

It can be seen from the above analysis that as the working face continues to be mined, when the hard and thick rock strata reach the limit span, it will break. Before hard and thick strata fracture, the lower rock strata will fracture first owing to the different strengths between the hard-thick rock and the lower rock. As the working face continues to advance, the breaking height and the separated stratum height develop gradually. When the height of the separated stratum develops to the bottom of the hard and thick strata, under the shielding effect of the hard ahd thick key strata, the separated stratum doesn't continue to develop upward, and the lower strata continue to fracture. When the length of the separated stratum reaches the limit span of the hard and thick strata, the hard and thick strata fracture and the abscission development is closed. The theoretical calculation gives a good explanation of the fracture characteristics of the overlying rock movement and the evolution law of the separated stratum space during the similar simulation.

5. CONCLUSION

This study applied the similar simulation test to analyze the breakage characteristics and movement law of the overlying strata, as well as the law of evolution of separation fissures under hard and thick strata, to investigate the movement law of the overlying disrupted strata by extraction and the development characteristics of the separated stratum under hard and thick strata. The following conclusions are drawn:

1) The key stages of overlying strata movement when the hard and thick key strata occur on the working face are immediate roof fracture, main roof initial fracture, main roof cyclic fracture, and hard and thick strata–magmatic rock fracture.

2) Before fracture, the hard and thick magmatic rocks bear the weight of the upper strata as the key strata, and the deformation of the upper strata is small. After fracture, the upper strata bend and settle, showing movement and deformation and the subsidence amount rapidly increases. The movement and deformation of the overlying strata under the hard and thick strata show significant discontinuity and exhibit mutation. When the hanging length of the hard and thick magmatic rocks reaches the limit span, the hard and thick strata fracture and the surface movement and deformation begin to increase rapidly. In the underground coal mining process, strengthening the ground deformation observation is necessary for effective prediction and forecasting to prevent sharp subsidence of the surface.

3) Before the fracture of the hard and thick key strata, the development height of the overlying separated stratum and the advancing distance develop upward nonlinearly. The development height of the separated stratum is cut off by the hard and thick magmatic rocks and ends at its bottom. The separated stratum remains unclosed for a long time. The long-term expansion of the separated stratum space at the bottom of the hard and thick magmatic rocks provides the development space for the accumulation of gas and water in the separated bed. Gas outburst and water inrush can easily be induced once the hard and thick key strata break.

4) The research results provide a valuable reference to prevent the separation water, gas flow to the working surface enriched in the separated stratum, coal and gas outburst produced by the separated layer gas, rock burst caused by the fracture of hard and thick strata, and large subsidence of the ground for mining under hard and thick strata. The results provide a reliable basis for in-situ slurry grouting, which is essential for safe mining under hard and thick strata.

This study applied the similar simulation test to intuitively observe the entire process of overlying strata fracture, caving, and separated stratum development after underground coal mining. The test is characterized by a small amount of work, short cycle, low cost, and minimal influence by external environmental factors. Thus, the outcome of this study is significant to the safe underground coal mining of the working face under similar geographical conditions and the adoption of scientific prevention measures. However, the test model takes artificial excavation without the influence of underground coal mining, thereby possibly affecting the test results. Therefore, future research must consider the influence of the underground coal mining factor on the fracture of the overlying strata to improve the accuracy of the test results.

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SUPPLEMENTARY MATERIAL

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