Roof Movement Characteristic and Pressure Relief Range Determination during the Lower Long-Distance Protective Seam Mining

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Abstract: Protective layer mining is an important technology for gas control, while long distance, the insufficient pressure relief, and borehole construction are the problems. It is important to clear roof movement laws and pressure relief range of the long-distance protective layer mining. By theoretical analysis and numerical calculation, the paper analyzed stress distribution laws and calculation formula of pressure relief range in the long-distance protective seam mining, and discussed the roof movement characteristics and pressure relief range during working face advancing in 9# seam. The results showed that any stress point in the protected seam underwent five stages with working face advancing of the protective seam: original rock stress - stress increasing - stress reduction - stress recovery - stability. With working face advancing, the pressure relief range of the protected seam constantly expanded, while the seam stress level did not reduce, and the stress began to recover with caving rock compacting, the stress in the protected seam showed the process from stress decreasing during rock movement to stress recovering during the compaction, and the maximum pressure relief of the protected seam was 13.7% of the original rock stress. In the pressure relief range, with the working face advancing, the maximum expansion deformation rate decreased gradually to 3.34‰. The effective protected range of seam 9 was 10~177m after the working face advancing. It was calculated that the pressure relief angles of seam 9 were 79°and 82°respectively after strike mining of seam 15. The upper pressure relief angle was 77°and the lower one 72°after dip mining. The research results provided a basis for gas extraction in long-distance protective layer mining.

Keywords: Long Distance; Lower Protective Seam Mining; Pressure Relief Range; Numerical Simulation.

1. Introduction

The technology of protective layer mining was one of the most common measures to prevent and control gas outburst. However, with the mining deepening in recent years, the factors such as high stress, high gas pressure and low permeability of coal seam have seriously restricted deep coal mining [1]. The distance between the 9# coal seam and the 15# coal seam was far in Qianjin Coal Mine. The lower 15# coal seam did not have gas outburst. The 9# coal could be liberated by mining the 15# coal, and the arrangement of cross-layer drilling was beneficial to the 9# coal seam, while the 15# coal seams are far from 9# one, so it was very important to study the pressure relief range and the development law of pressure relief cracks in long-distance protective layer mining.

In recent years, many domestic scholars have made a series of achievements in long-distance protective layer mining technology. Wang Zhonghua et al. [2] put forward the protective layers mining method for deep long-distance coal seam groups, and carried out engineering application research. He Aiping et al. [3] studied the quantitative relationship between the mining parameters of the lower protective layer and the protection effect by statistical analysis, and verified the analysis in numerical simulation. Qin Bing et al. [4] used FLAC3D software to simulate the overlapping mining of multiple working faces. Ma Jianhong et al. [5] studied the laws of stress distribution, vertical displacement and expansion deformation on the protected layer in the long-distance protective layer mining by numerical simulation. Liu Yingke [6] studied the pressure relief characteristics in lower long-distance protective layer mining. Liu Jun et al. [7] found that the mining operation could effectively relieve pressure and improve the permeability of the protected layer by extracting gas from the protected layer with upward grid through-bed borehole arranged in the floor roadway. Li Siqian [8] analyzed the stress variation and expansion deformation of the protected layer. Zhang Mingjie et al. [9] determined the expansion and deformation of the protective layer by analyzing the factors affecting the protection effect in the thin long-distance protective layer mining. Xiao Jiaping et al. [10] and Yang He et al. [11] studied the distribution characteristics of stress field, displacement field and fracture field in long-distance depressurization mining. Jia Fei et al. [12] and Sun Chengyu [13] monitored and analyzed the stress variation and pressure relief of the protected layer. Hao Tianxuan et al. [14] analyzed the characteristics of roof subsidence and expansion variation of the protected layer after the overburden pressure relief of the protective layer. Meng Xianzheng et al. [15] studied the evolutionary distribution law of floor stress field in upper middle-long-distance protective layer mining.

This paper divided the influence range partition of the long-distance protective seam mining by theoretical analysis and numerical simulation methods, determined the calculation method of the pressure relief range, and discussed the stress change characteristics and displacement one of the pressure relief range. The research results could provide references for determining the pressure relief range of long-distance protective layer mining and gas extraction parameters.

2. Movement Characteristics of Overburden Strata in Long-Distance Protective Seam Mining

2.1. Analysis of Engineering Geological Conditions

The inclined shaft development and central parallel ventilation were adopted in Qianjin Coal mine, a coal and gas outburst mine. The strike length of the mine field was 4 ~ 4.5km, the inclination length 2 ~ 5km, the mine field area 9.25km^2, the mining depth +1550 ~ +1100m. The gas content of the 9# coal seam was obviously influenced by the thickness of mudstone roof. Gas content and the outburst difficulty on working face of the coal 9# were particularly high due to concentrated stress in Jiantang syncline axis. The 9# commercial coal seam had outburst risk, while the 15# coal seam no outburst risk in the identification range. The average thickness of 9# coal seam was 1.81m, the average thickness of 15# coal seam 2.4m, the average distance between 9# coal seam and 15# coal seam 64m, and the average inclination of coal seam 8°. The gas extraction design of 9# coal seam was realized by drilled through strata to the mined 15# coal seam (Figure 1).

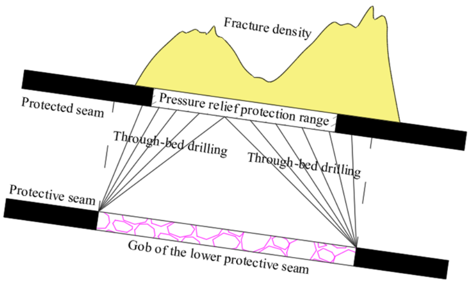


Figure 1. Borehole layout of the lower protective seam

2.2. Movement Characteristics of Overburden Strata in the Lower Protective Seam

When the near horizontal coal seam was mined, the gob roof bent downward to the rock strata limit, the roof failed, the overburden strata bent and fracture to the upper rock strata, and this range could continue to expand until the gob was filled. In the near horizontal coal seam, when the gob was filled, the overlying rock didn't move further, and finally the caving form of "vertical three zones" was formed above the gob, which were respectively from bottom to top: caving zone, fissure zone and bending subsidence zone.

When the inclined coal seam with large inclination angle was mined, the lower space in the gob was rapidly filled due to the rolling slide of caving rock, which restricted the upward development of caving zone and fracture zone, especially in the coal seam with inclination angle greater than 45° even extending to the floor rock. In addition, in the upper of the gob, the height of caving zone and fracture zone developed continuously, which greatly exceeded the upper boundary of the gob. The outline shape of the fracture zone, an "ear" shape or an asymmetric "arch" shape with large upper and small lower, was similar to that of the caving zone.

2.3. Analysis on Pressure Relief Range of the Protected Seam

In 3DEC simulation, the displacement measurement line was laid on the top and bottom of the protective layer, the expansion deformation of coal 9 after each advancing was monitored, and the pressure relief and gas permeating improvement effect of the long-distance protected coal seam 9 was studied. The coal seam deformation obtained from the simulation test could be converted into the normal deformation value:

$$\varepsilon_0 = \varepsilon / \left(\cos\gamma\cos\beta\sin\alpha + \sin\gamma\cos\alpha\right)^2 \qquad (1)$$

Where: ε_0 was the normal expansion deformation of coal seam; ε the relative deformation of coal seam in any direction; α the inclination angle of coal seam, (°); β the angle between the borehole and the vertical coal seam line, (°); γ the borehole elevation angle, (°).

The test model was a two-dimensional model, and the normal deformation of the protected seam was taken as the research object. Therefore, $\beta = 90°$, $\gamma = 90°$, that was:

$$\varepsilon_0 = \varepsilon_y / \cos^2\alpha \qquad (2)$$

$$\varepsilon_y = \Delta S / m \qquad (3)$$

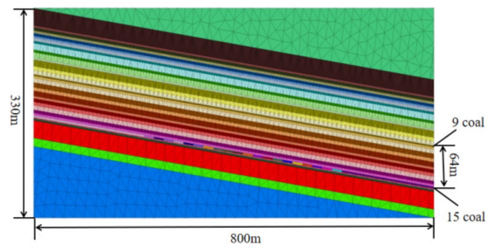
Where: ε_0 was the relative deformation of coal seam in *y* direction (vertical direction); ΔS The difference between floor subsidence and roof subsidence, m; *m* the thickness of the protected seam, m.

In combination with the formulas (2) and (3), ε_0 was obtained:

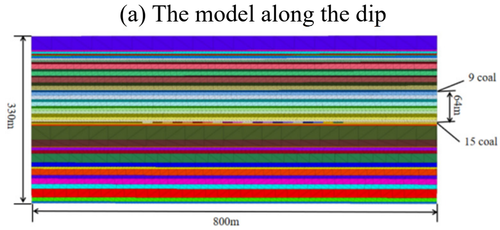
$$\varepsilon_0 = \frac{\Delta S}{m\cos^2\alpha} \qquad (4)$$

3. Numerical Model Construction

3.1. Model Building



(a) The model along the dip



(b) The model along the strike

Figure 2. The model unit division

Combined with the actual situation, the numerical calculation software was used to establish the inclination model, the size of the model was length × height × width =800m×330m×1m, and the coal seam and rock strata were constructed according to lithological mechanical parameters. In order to obtain the displacement and deformation of the rock strata near coal seam and realize the expected research purpose, the density of rock strata unit near coal seam was added, and the one away from coal seam was reduced, meanwhile the solution speed could be improve (Figures. 2).

3.2. Boundary Condition

(1) According to the principle of model design, the left and right sides of the model were single constrained boundaries, that was, the horizontal displacement was limited, and the boundary nodes could move in the vertical direction.

(2) The bottom of the model was the fully constrained boundary, that was, there was no displacement in the horizontal and vertical directions of the bottom boundary.

(3) The upper part of the model was the load boundary. The load applied to the upper part of the model was calculated according to the buried depth and the self-weight stress of the original rock.

$$\sigma = \gamma H \tag{5}$$

Where: σ was the self-weight stress of the original rock, MPa; γ the rock bulk density, taking 0.025MN/m^3; H the vertical distance between the model boundary and the surface.

The buried depth of 15# coal seam was about 390m, and the distance between the middle of the upper boundary of the model and the surface H=160m, then the load applied to the upper boundary 160×0.025=4MPa.

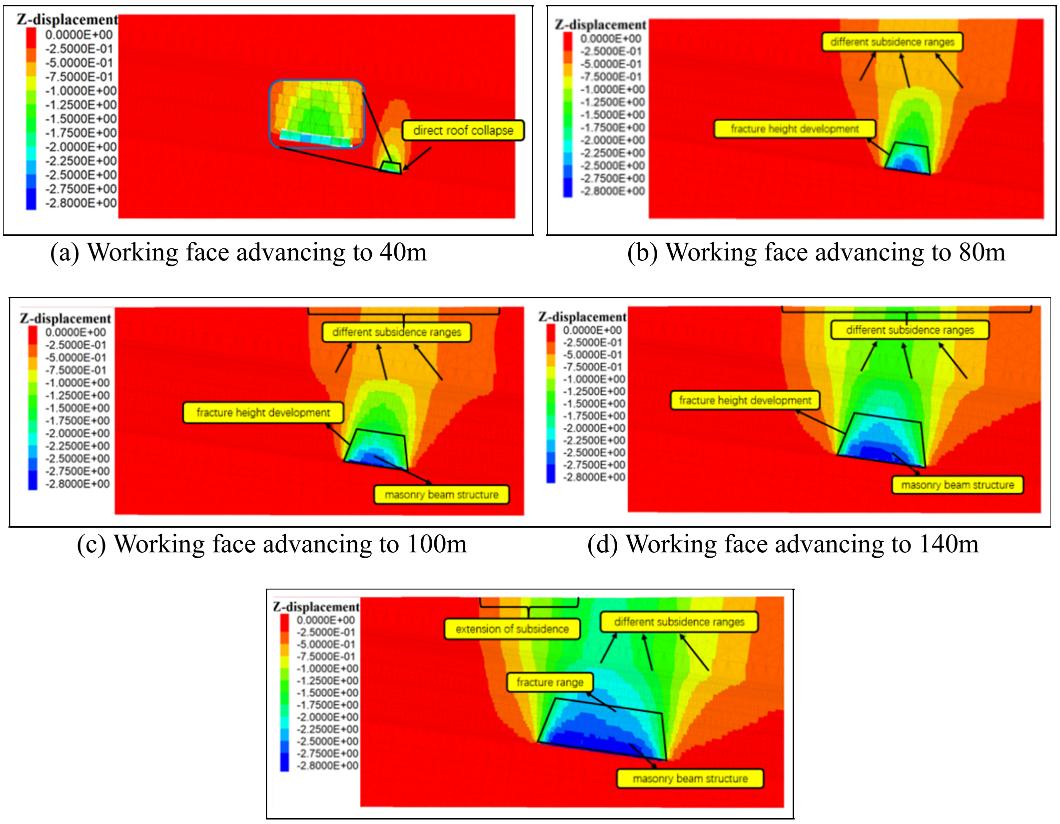
3.3. Simulation Step

The strike length of 15# coal seam was taken to 800m, and the initial modeling and simulation were carried out to the stress equilibrium state. The working face was advanced 20m each time from left to right, and the model was calculated to the equilibrium state; The simulation results were analyzed.

4. Numerical Result Analysis

4.1. The Overburden Displacement Laws of the Lower Protective Seam in Inclination Mining

In the lower protective seam dip mining, the distribution law of vertical stress in overburden rock was obtained with working face advancing in numerical simulation calculation. The overburden rock caving and strata displacement of the protective seam were shown in Figure 3 in the simulated working face advancing to 40m, 80m, 100m, 140m, 200m respectively.



(a) Working face advancing to 40m (b) Working face advancing to 80m

(c) Working face advancing to 100m (d) Working face advancing to 140m

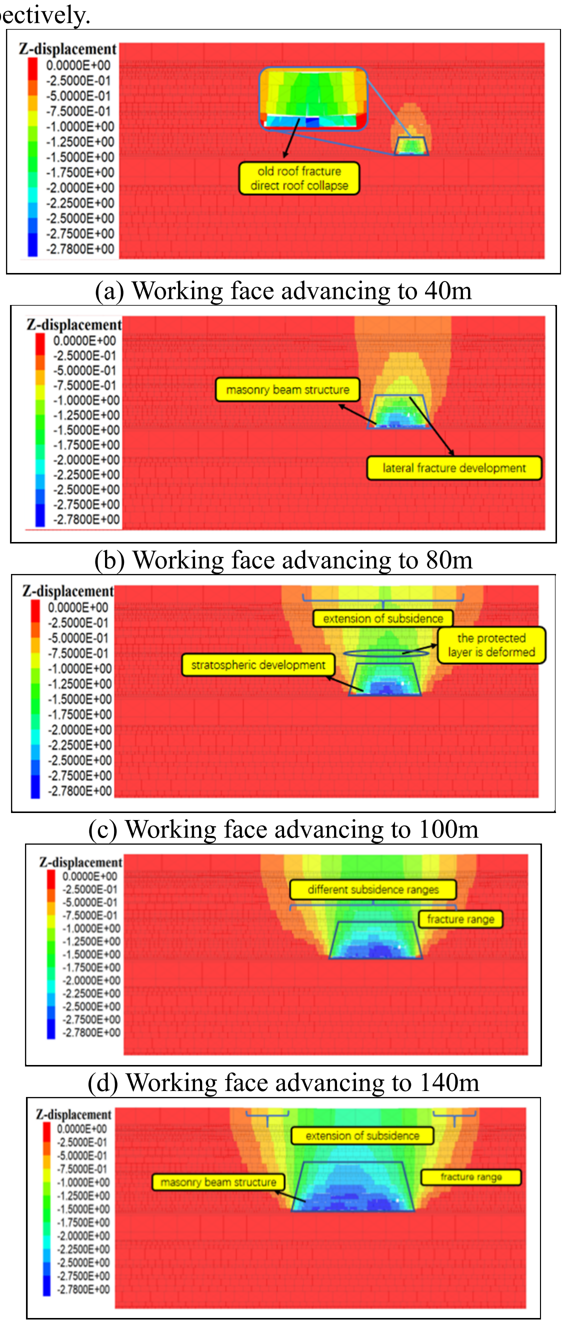
(e) Working face advancing to 200m

Figure 3. The law of overburden displacement during the working face advancing along the inclination

When the working face was advanced to 40m, the direct roof fell, the basic roof appeared cracks and broken, and the maximum bending subsidence value of the basic roof reached 1.54m. During the working face advancing to 60 m ~ 80 m, the overburden cracks developed rapidly and the roof caving occurred in a large range. When the working face was advanced to 100m, the fracture zone developed to the protected seam, and the bending subsidence above the protected seam mining was obvious. With the mining scope expansion, the working face affecting range on rock strata expanded, strata movement continued to transfer upward, the vertical displacement of some lower strata reached the maximum, and the vertical displacement of upper strata gradually increased. With the continuous advancing of working face, the movement range of the upper strata continued to expand, and the maximum vertical displacement of each strata would no longer increase.

4.2. The Laws of Overburden Displacement in Strike Mining on the Lower Protective Seam

The caving and displacement of overburden rock above the protective seam were shown in Figure 4 when working face was advanced to 40m, 80m, 100m, 140m and 200m, respectively.



(a) Working face advancing to 40m

(b) Working face advancing to 80m

(c) Working face advancing to 100m

(d) Working face advancing to 140m

(e) Working face advancing to 200m

Figure 4. The law of vertical overburden displacement during the working face advancing along the strike

When the working face was advanced to 40m, the direct roof began to fall, the separation fracture developed to 21m above the roof, and the basic roof broke during the advancing. When the working face advanced to 80m, the fracture developed laterally, the separation height developed to 30m, the range of vertical and cross fractures in the lower layer expanded, and pressure relief and expansion deformation of the protected seam appeared. When the working face advanced to 100m, the protected coal seam above the gob occurred obvious bending deformation. As the working face advancing, expansion deformation and pressure relief of the protected seam increased. When the fracture below the protected coal seam was fully developed, the expansion deformation of the protected coal seam would not increase, while some re-compaction came under the overburden pressure. With the continuous advancement of the protective seam, the displacement of the protected seam changed constantly from not obvious to obvious. The protected seam 9# was in the mining pressure relief range of the protective seam 15#, and the pressure relief effect was remarkable.

4.3. Stress Distribution in Surrounding Rock of the Protected Seam

When the working face was advanced to 40m along the inclination, the protected seam was disturbed due to the overburden rock caving, and the internal vertical stress decreased to 3.5MPa, 38% of the original rock stress. As the working face advancing, the protected scope expanded, and the degree of pressure relief continued to increase. After the working face advanced to 100m, the vertical stress reached the minimum 1.27MPa, about 13.7% of the original rock stress. With the working face advancing again, the relief range of the protected seam expanded again, but the stress level of the coal seam did not continue to be unloaded, and the compaction stress began to recover with rock continuous caving and accumulation. When the advancing distance of the working face was long enough, the stress in stress recovery area closed to the original rock stress (Figure. 5).

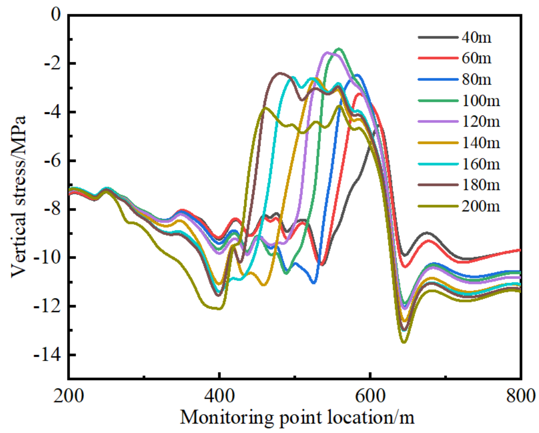


Figure 5. Vertical stress distribution of the protected seam during the working face advancing along the inclination

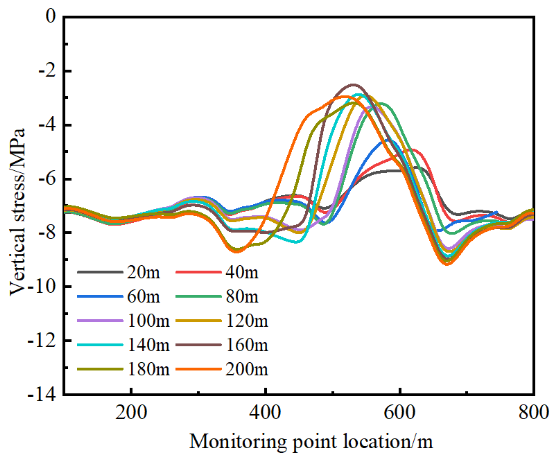


Figure 6. Vertical stress distribution of the protected seam during the working face advancing along the strike

When the working face advancing to 40m along the strike, the protected seam above the gob began to release pressure, and the seam stress decreased to 74.19% of the original rock stress (7.67MPa). As the working face advancing, the degree and the range of pressure relief expanded gradually. When the working face advancing to 100m, the protected seam stress (3.02MPa) was 39.37% of the original rock stress. When working face advancing distance was long enough, the caving rocks in the middle of the relief range above the gob of the protective seam were gradually compacted. When the working face advancing to 200m, the protected seam stress at the highest relief degree (2.78MPa) was 36.25% of the original rock stress, and the vertical stress in the stress recovery area (5.19MPa) was 67.67% of the original rock stress (Figure.6).

4.4. The Pressure Relief Range Determination of the Protected Seam

The roof displacement and bottom one of 9# coal seam, the thickness and the inclination angle of the protected seam were substituted into formula (5) to obtain the normal expansion deformation of the protected seam after the protective seam mining (Figures. 7 and 8).

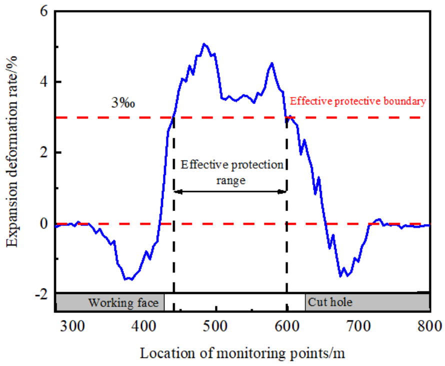


Figure 7. Deformation expansion rate of 9# coal during the working face advancing along the inclination

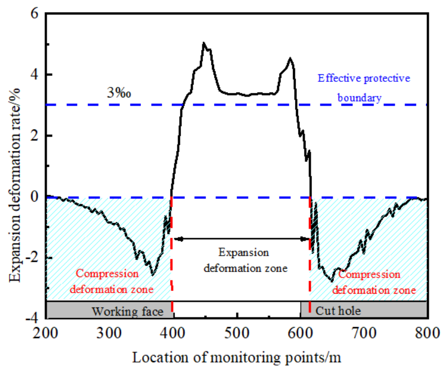


Figure 8. Deformation expansion rate of 9# coal during the working face advancing along the strike

(1) The deformation of the protected seam presented the law of compression-expansion - expansion reduction - deformation stability with the working face of the protective seam advancing. In the relief range of the protected seam, the maximum expansion deformation rate appeared in 48 ~ 100m behind the working face, and the expansion deformation of the protected seam was "M" shape in general.

(2) When the working face of the protective seam advancing to 200m along the inclination, the maximum expansion deformation rate of 9# coal seam reached 5.08‰. In the pressure relief range, the maximum expansion deformation rate gradually decreased with the working face advancing, and finally stabilized at about 3.5‰, and the pressure relief degree remained at the higher level.

(3) After working face advancing to 200m along the strike, two peak points appeared in the pressure relief range with the highest expansion rate 5.04‰. In the re-compacting area, the expansion deformation rate was stable at about 3.34‰, which was in the effective pressure relief range. The peak expansion deformation rates of coal pillars on both sides of the gob were 2.58% and 2.78%, respectively.

(4) The stress in the protected seam redistributed due to the protective seam mining. The maximum compressive deformation rate of the coal seam reached to 1.58‰ in the protected coal pillar at the open-off cut side of the protective seam, and the maximum compressive deformation rate of the protected seam in front of the working face of the protective seam reached to 1.49‰, and the deformation rate of the protected seam on both sides of the gob was roughly symmetric.

(5) According to the effective protection principle of the seam expansion less than 3‰, the normal distance between the protective seam and the protected one was 64m. It could be obtained by the trigonometric function that the pressure relief angle of the upper part of 9 coal seam was 77° and the one of the lower parts 72° with coal 15# mining along the inclination. The pressure relief angles along the strike were 79° and 82° respectively.

5. Conclusion

(1) As working face advancing of the protective seam, any stress point in the protected seam underwent five stages: original rock stress - stress increasing - stress reduction - stress recovery - stability.

(2) With the mining scope expanding, the strata effective range of working face mining continued to expand, strata movement transferred upward, and the vertical displacement of some lower strata reached to the maximum value, while the vertical displacement of upper strata gradually increased.

(3) With the mining scope expanding, the stress in the protected seam showed the process from stress decreasing during rock movement to stress recovering during the compaction, and the maximum pressure relief of the protected seam was 13.7% of the original rock stress.

(4) The deformation of the protected seam presented the law of compression - expansion - reduced - deformation stability. The expansion deformation of coal mass in the middle of the gob was smaller than that on both sides, and the expansion deformation rate in the re-compacted area was stable at about 3.34‰.

(5) The effective protection range of 9 coal seam was 10~177m after the working face advancing. The pressure relief angles of coal 9 were 79°and 82°respectively after strike mining of 15 coal seam. The upper pressure relief angle was 77°and the lower one 72°along mining along inclination.

Acknowledgments

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