Research Article

Study on the Characteristics of Top-Coal Caving and Optimization of Recovery Ratio in Steeply Inclined Residual High Sectional Coal Pillar

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This paper is aimed at solving the technical problems such as low recovery ratio and frequent disasters in steeply inclined and extrathick coal seams at residual high sectional coal pillar. It takes the Wudong Coal Mine as an engineering background, a typical mine of steeply inclined and extrathick coal seams; the structural features of the top-coal caving at the steeply inclined residual high sectional coal pillar were analyzed using methods such as field monitoring and numerical simulation; a mechanical model of the top-coal arch structure was constructed, and the calculation method of top-coal caving height and related influencing factors was obtained. The results showed that the top-coal caving in the steeply inclined residual high sectional coal pillar was characterized as arch. Due to the existence of arch structure, the smooth caving of the top coal was hindered, resulting in a low top-coal recovery ratio, low support pressure at the working face, and differences detected by borehole television on the distribution of the top-coal cracks. With the advancement of the working face, the top-coal arch structure was in the process of dynamic evolution, as the old arch balance system was continuously replaced by the new arch balance system, and it continuously moved towards the upper top coal. The top-coal caving height was affected by factors such as length of the working face, bulk density of overlying coal rock, and cohesion of the top coal. The top-coal caving height increased with the length of the working face and the bulk density of the overlying coal rock mass but was inversely proportional to the cohesion of the top coal. Under the current mining conditions, the top-coal caving height was 39.8 m, which was much lower than the residual high sectional coal pillar height (71 m); the top coal cannot collapse completely. Based on the characteristics of the top-coal caving structure, the technology of sublevel advanced presplitting blasting was adopted to weaken the top coal in engineering practice, so that the top-coal caving structure moved up naturally. The daily coal production in the working face has increased by an average of 2419.6 tons, which has significantly improved the top-coal recovery ratio and production efficiency. The result provided a theoretical basis and application reference for similar residual high sectional coal pillar recovery.

1. Introduction

China is a large coal mining country with diverse coal resources. Diverse mining methods are applied in coal mining. Fully mechanized top-coal caving is a unique method for safe and efficient mining of complex and extrathick coal seams [1–5]. The top-coal caving property is the key to safe and efficient fully mechanized caving. In particular, for the hori-

zontal sectional fully mechanized caving in steeply inclined extrathick coal seams, the sectional height is large, and the top-coal recovery ratio accounts for more than 80% of the mine output. Whether the top coal can be recovered smoothly is the key to improving mine recovery ratio and ensuring safe and efficient production of the working face [6–8].

In recent years, scholars have studied the law of movement, caving property, and caving technology of the top coal

in fully mechanized working face. The research and practice of fully mechanized top-coal caving have made some new progresses, which have obtained great economic benefits and played an important role in promoting the development of fully mechanized top-coal caving technology in China. Wang et al. systematically studied the law of fully mechanized top-coal caving and established a four-element BBR research system, including the coal-rock interface, top-coal discharge body, top-coal recovery ratio, and gangue ratio. They improved the Berg-mark-Roos model in bulk medium mechanics and pointed out that the top-coal emissions are cutting variant ellipsoids [9, 10]. Wang et al. studied the effects of different machine mining heights on working resistance of support, top-coal caving law, and coal wall stability, in order to determine the reasonable machine mining heights for fully mechanized top-coal caving in extremely thick coal seams [11]. Yu et al. established the boundary line equations for top-coal discharge and coal gangue in fully mechanized top-coal caving based on random medium theory and similar simulation tests, taking into account the influence of fully mechanized caving support and coal outlet [12]. Chen et al. analyzed and compared the influence of mining depth, coal seam strength, horizontal stress, coal seam homogeneity, and original fracture on top-coal caving property, taking the damage parameter as a comprehensive index of top-coal caving property, by the basic principle of damage mechanics [13]. Kang et al. analyzed the structural characteristics and integrity of coal and rock masses through borehole television [14]. Wen et al. systematically studied the law of overburden movement in fully mechanized mining with large mining-height stopes, constructed the stope roof structure model, established the design criteria of stope roof control and the calculation method of support load, and optimized the coal pillar width and surrounding rock control technology of roadway driving along goaf [15, 16]. Alehossein and Poulsen divided the top coal into two parts, located in the front and rear of the coal body, and analyzed the top-coal stress state of the two parts [17]. Vakili and Hebblewhite used numerical simulation methods to study the top-coal destruction and release process and achieved top-coal caving grading through multivariate statistical analysis of the influencing factors [18]. Yasitli and Unver simulated the influence of support on top-coal caving characteristics and considered that the thickness of the top coal is a key factor affecting the caving performance [19].

To sum up, it was showed that the above research systematically analyzed the top-coal transport law and caving characteristics of thick coal seam fully mechanized caving and promoted the development of thick coal seam fully mechanized top-coal caving technology. However, the special geological conditions of the steeply inclined extrathick coal seams are quite different from those of the flat coal seams, and the related research on the structural characteristics of top-coal caving and the technology of improving recovery rate in the steeply residual high sectional coal pillar remain deficient; further studies are critically required. Therefore, in view of the technical problems such as low top-coal recovery ratio and frequent dynamic disasters in typical coal mines with steeply inclined and extrathick coal seams in China, the

structural characteristics of top-coal caving in residual high sectional coal pillar were comprehensively analyzed by means of theoretical analysis, field monitoring, and numerical simulation, and the technology of weakening top coal by sublevel presplitting blasting was proposed; an engineering design was then implemented based on the geological conditions of the Wudong Coal Mine. The findings provide theoretical basis and application reference for similar high sectional coal pillar recovery.

2. Engineering Background

The steeply inclined coal seams refer to the coal seams with an inclination angle of 45° – 90° . This kind of coal seam is hard to mine due to its complex occurrence, and this has been recognized as a public perception. The Urumqi mining area is a typical mining area with steeply inclined (45° – 87°) extrathick coal seams. There are more than 30 layers of steeply inclined coal seams with different thicknesses and different spacing. Large-scale mines with ten million tons of annual production have been established there, which are represented by the Wudong Coal Mine. The B_{3-6} coal seam is one of the main coal seams in the west mining area of the Wudong Coal Mine. Mine field geological exploration indicates that the B_{3-6} coal seams are the Xishanyao Formation of the Middle Jurassic, and the strata are distributed from northeast to southwest. The coal seams have an inclination angle of 85° – 89° , an average inclination angle of 87° , and an average coal seam thickness of 40 m. The roof and floor are all argillaceous cemented siltstone, with high strength, few cracks and joints, and not easy to collapse. Its special resource environment aggravates the complexity of stope structure and stress evolution on the working face. Different from the long-wall mining on gently inclined coal seams, the horizontal sectional fully mechanized top-coal caving face of the steeply inclined extrathick coal seams is a short-wall working face arranged along the thickness of the coal seam. The roof and floor are located on both sides of the working face. The stress of the working face transfers in the order of “residual coal gangue-top coal-support-coal body.” The top coal is the “roof” to be carried by the supports during recovery on the working face, and it is also the object to be mined [20–24].

At this mine, the +495 level of the B_{3-6} coal seams was being recovered. The sectional height of the working face was 25 m, the coal cutting height of the shearer was 3.5 m, and the coal discharge height was 21.5 m. When the working face was advanced to 1358 m, it was connected to the residual coal pillar in the closed Anning District. The residual coal pillar was 120 m long and 71 m high, forming a larger residual high sectional coal pillar as shown in Figure 1. When the working face passed through the residual high sectional coal pillar, the top-coal recovery ratio was low, and the pressure of the mine was strong. This situation was often accompanied by dynamic disasters such as “mining shock” and “coal burst.” Therefore, further study is needed on the structural features of top-coal caving and the technology for improving the recovery ratio in steeply inclined residual high sectional coal pillar.

With the development of computer and numerical simulation software, the numerical simulation analysis method has become one of the main research means to solve mining engineering problems [25–27]. In order to understand the movement law of the top coal in steeply inclined residual high sectional coal pillar under mining disturbance, the numerical calculation model was constructed according to the geological data and mining method of the B₃₋₆ coal seam +495 level working face of the Wudong Coal Mine, as shown in Figure 4. The numerical simulation was mainly used to study the migration characteristics of the top coal in the residual high sectional coal pillar after excavation at the +495 level working face. Therefore, the design model size was 140 m in the X direction, 10 m in the Y direction, and 140 m in the Z direction. In the model, brick units were adopted for coal and rock mass, generating 83,116 units

FIGURE 2: Characteristics of pressure change of hydraulic supports in the working face.

and 17,972 nodes. All regions in the mesh were Mohr-Coulomb constitutive models; the upper boundary surface was a free boundary surface, the bottom surface constrains vertical displacement, and the four sides constrain horizontal movement. At the same time, in order to realize the actual stress occurrence conditions in the field, a vertical stress of 5 MPa was applied on the upper boundary surface of the model, and a gradient stress was applied in the X direction to simulate the pressure of the roof and floor on the coal layer. The excavation plan was based on the field mining method and mining layout. First, roadways B3 and B6 were excavated on both sides of B₃₋₆ coal seam +495 level working face. After the model reaches equilibrium, excavate the +495 level working face. The cutting height of shearer was 3.5 m. Based on the coal face stepping distance of 1.2 m, three schemes of cumulative excavation distances of 1.2 m, 2.4 m, and 4.8 m were designed. Under the conditions of different driving distances of the working face, the top-coal movement and destruction characteristics were analyzed.

The mechanical parameters of coal and rock masses in the numerical simulation calculation model were determined by field sampling and rock mechanics test results, and certain corrections were made in consideration of the scale effect of coal and rock masses. The mechanical parameters of coal and rock masses used in the calculation are shown in Table 1.

In the method of horizontal sectional fully mechanized caving in steeply inclined extrathick coal seams, when the coal seam in the working face was not mined, the top coal supported by the bottom coal body was in a static equilibrium state. With the mining of the lower coal body and the migration of supports during the mining process, part of the top-coal mass was exposed on the free face of the goaf space. Due to the weight of the coal and rock mass, the compression on both sides of the roof and floor, and the repeated pressure from the supports on the working face, the mass on the boundary of the goaf first slid along a certain structural surface to lose the original static balance. Its instability caused a chain reaction of surrounding blocks and the top-coal body to break and collapse continuously. According to

the analysis of top-coal displacement cloud map under different advancing distances of the working face (Figure 5), after the coal seam in the working face was mined, the deformation and failure forms of the top and bottom coals were approximately arched. Affected by its own weight, the top-coal displacement field was significantly larger than the bottom coal body. With the advancement of the working face, the top-coal arch structure was in the process of dynamic evolution. The old arch balance system was continuously replaced by the new arch balance system, and it was constantly moving towards the upper top coal. As the top-coal caving arch structure continued to move upward, its carrying capacity gradually decreased. When the upward movement reached a certain height, the arch structure in the section of the top-coal body was finally unstable due to the heavy pressure of the coal gangue in the above goaf and the squeezing effect from the roof and floor. Coal gangue in the goaf above caved to the goaf below. Therefore, the instability of the top-coal arch structure was inevitable. This kind of arch structure is called “temporary balanced arch.”

Due to the existence of the top-coal caving arch structure, on the one hand, the arching action prevented the natural collapse of the top coal, resulting in the low extraction ratio of the top coal; on the other hand, under the protection of the arch structure, the working face supports bear only the gravity of the top coal inside the arch, which made the bearing load of the support decreased. With the advance of the working face and the influence of mining disturbance, the dynamic disaster induced by the instability of the top-coal arch structure seriously restricted the safe and efficient production of the mine, so it was very necessary to carry out reasonable engineering measures to ensure the natural upward movement of the top-coal arch structure, improve the extraction ratio of the top coal, and ensure the safe production of the working face.

5. Mechanical Model Analysis

Based on the results of field monitoring and numerical simulation, in the process of the horizontal sectional fully mechanized top-coal caving, the stress around the top coal is redistributed, the coal body bends and sinks, and tensile shear stress occurs. When the tensile and shear stress exceeds the load-bearing ultimate strength of the coal body, the top coal is unstable and caving. The caving shape is similar to an arch. The arch foot support near the roof and floor is constrained by the space size of rock mass. Regardless of the relative movement between the roof or the floor and top coal, the arch foot is simplified as a fixed-end constraint, and the nonuniformly distributed load acting on the top-coal arch structure is q . The mechanical model of the top-coal arch structure constructed is shown in Figure 6.

Assume that the distance from the arch foot to the surface is H , the arch height is h , the length of the working face, i.e., the span of the arch structure, is L , the volume weight of the overlying coal rock is γ , the calculated width is b , the gravity of the arch itself is ignored, the friction angle in the coal body is φ , and the cohesive force is c .

FIGURE 3: Typical borehole images of the top-coal structure.

FIGURE 4: FALC^{3D} numerical model.

TABLE 1: Coal and rock mechanical parameters.

Lithology	Bulk modulus (GPa)	Shear modulus (GPa)	Cohesion (MPa)	Tensile strength (MPa)	Internal friction angle (°)	Density (kg/m ³)
Siltstone	7.89	5.27	3.6	2.39	37	2768
Medium sandstone	5.72	4.33	3.5	2.87	35	2660
Carbon mudstone	2.13	1.09	2.8	1.23	32	2250
B ₃₋₆ coal seams	1.98	0.97	2.5	1.12	30	1270
Coal gangue	0.80	0.27	0.50	38.0	0.31	2000

FIGURE 5: Top-coal displacement nephogram.

FIGURE 6: Mechanical model of the top-coal arch structure.

The arch curve is assumed to be a quadratic parabola. It is known through the boundary conditions that

$$\begin{cases} x = 0, & y = 0, \\ x = \frac{L}{2}, & y = h, \\ x = L, & y = 0. \end{cases} \quad (1)$$

Let the arch curve equation be

$$y(x) = \frac{4h}{L^2}x(L-x), \quad (0 \leq x \leq L). \quad (2)$$

The vertical pressure is

$$q(x) = \gamma b(H-y) \quad (0 \leq x \leq L). \quad (3)$$

At any depth Z surface, the lateral pressure of the micro unit is

$$\sigma = k_0 \gamma z \tan^2 \left(45 - \frac{\varphi}{2} \right), \quad (4)$$

where $k_0 = \tan^2(45 - \varphi/2)$ is the pressure coefficient of the single medium.

The shear strength of coal is

$$\tau = \sigma \tan \varphi + c. \quad (5)$$

The ultimate equilibrium theory shows that the shear stress at the arch foot (A or B) is the largest and its shear resistance is as follows:

$$F = \int_0^H b \tau dz = \frac{1}{2} \gamma b H^2 \tan^2 \left(45 - \frac{\varphi}{2} \right) \tan \varphi + c g H. \quad (6)$$

The vertical reaction of the arch foot (A or B) is

$$R_v = \frac{1}{2} \int_0^L q(x) dx = \frac{1}{2} \gamma b L \left(H - \frac{2}{3} h \right). \quad (7)$$

From $F = R_v$,

$$h = \frac{3}{2} \left[H - \frac{\gamma H^2 \tan^2(45 - (\varphi/2)) \tan \varphi + 2cH}{\gamma L} \right]. \quad (8)$$

It can be seen from formula (8) that under the condition of natural caving of the top coal, the height of the arch structure was affected by factors such as the length of the working face, the bulk density of the overlying coal rock body, and the cohesion of the top coal. The height of the arch structure increased with the length of the working face and the bulk density of the overlying coal rock mass, which was inversely proportional to the cohesion of the top coal. The ground elevation of the west mining area of the Wudong Coal Mine is +800 m, the mining level elevation was +495 m, the working face length was 40 m, the overlying coal and rock mass was $2.5 \times 10^4 \text{ KN/m}^3$, the coal body cohesion was $1 \times 10^5 \text{ Pa}$,

and internal friction angle was 68° . Using formula (8), the top-coal caving height under the current mining conditions was calculated to be 39.8 m, while the B_{3-6} coal seam +495 level residual high sectional coal pillar height was 71 m (as shown in Figure 1). The theoretically calculated caving height was much lower than the height of the residual high sectional coal pillar. This indicated that the B_{3-6} coal seam +495 level residual high sectional coal pillar cannot cave completely under natural collapse state.

6. Optimized Techniques of Recovery Ratio

Based on the above research and analysis, the top-coal caving of steeply inclined extrathick coal seams at the residual high sectional coal pillar is in an arch form. The arching action not only prevents the natural collapse of the top coal, making the top-coal recovery efficiency low, but the instability of the top-coal structure severely restricts the safety and efficiency of the working face. Therefore, artificial auxiliary measures need to be applied to reduce the overall strength of the coal body, increase the number of cracks and structural faces, so as to achieve the smooth top-coal releasing, increase the top-coal recovery ratio, and ensure the safe mining of the working face.

6.1. Sublevel Advanced Presplitting Blasting of the Top Coal. It is proved that advanced presplitting blasting is one of the effective methods for recovery of the top coal in engineering practice [28, 29]. According to the characteristics of the top-coal caving structure in steeply inclined high sectional coal pillar, three sublevels were divided in the vertical direction, and advanced presplitting blasting was used to weaken the top coal, as shown in Figure 7(a), respectively, at the +495 level, the +518 level, and the +541 level.

Top-coal advanced presplitting blasting was carried out in the recovery roadways B3 and B6 on the +495 level. The full-section hole arrangement was adopted, as shown in Figure 7(b). Each row was arranged with 7 blast holes, the diameter of each hole was 108 mm, the row spacing was 4 m, and the presplitting blasting was 30.0 m. In order to avoid the impact of blasting on the stability of the working face and mining roadway, the top-coal thickness of the protective layer and the blasting buffer layer of the working face were all 3.0 m. At this level, the cumulative length of blasting holes of each row was 182.7 m, the cumulative length of the charge was 114.4 m, and the charge of each row was 972.4 kg.

The coal pillar of the +518 level and the +541 level had the same size, and the same advanced presplitting blasting scheme was adopted, as shown in Figure 7(c). The arrangement of blasting holes was fan-shaped. 10 blasting holes have a diameter of 108 mm in each row, the hole sealing section was 4.0 m, the cumulative drilling depth was 359.0 m, the cumulative length of the powder charge was 319.0 m, and the amount of explosives used in each row was 2711.5 kg. A total of 9 rows were arranged along the roof to the floor, with clearance of 4.0 m, and the first row and the ninth row were 6.0 m from the inside of the roof and the floor.

FIGURE 7: Sublevel advanced presplitting blasting scheme for the top coal in the residual high sectional coal pillar.

6.2. Effectiveness Evaluation. The implementation effect of program was analyzed, by recording the daily production of the top coal in the residual high sectional coal pillar of B₃₋₆ coal seams at the +495 level prior and post the implementation of sublevel presplitting blasting program. The statistics of the top-coal recovery are shown in Figure 8. It can be seen from the figure that prior the implementation of the sublevel presplitting blasting, the average daily coal mining volume of the working face was 5075.6 tons, with a maximum of 5594.8 tons. Post the implementation of the sublevel presplitting blasting, the average daily production of the working face was 7495.2 tons, with a maximum of 7855.7 tons, which showed an average increase of 2419.6 tons compared with the daily production of coal prior the implementation of the blasting program. The statistical analysis of the mining amount of the working face showed that the top-coal recovery ratio and production efficiency were effectively improved and the safety production of the working face was guaranteed after the sublevel presplitting blasting of the top coal in the residual high sectional coal pillar of B₃₋₆ coal seams at the +495 level.

7. Conclusions

(1) Due to the existence of the top-coal arch structure, the smooth caving of the top coal was hindered, resulting in a low top-coal recovery ratio, low support pressure at the working face, and differences detected by borehole television on the distribution of the top-coal structure. With the advancement of the working face, the top-coal arch structure was in the process of dynamic evolution, as the old arch bal-

FIGURE 8: Characteristics of daily coal production at the working face.

ance system was continuously replaced by the new arch balance system, and it continuously moved towards the upper top coal

(2) Analysis of the mechanical model of the top-coal arch structure has shown that the top-coal caving height was affected by factors such as the length of the working face, the bulk density of the overlying coal rock mass, and the cohesion of the top coal. It increased with the length of the working face and the bulk density of overlying coal rock mass but was inversely proportional to the cohesion of the top coal.

The top-coal caving height under the current mining conditions was 39.8 m, which was much lower than the residual high sectional coal pillar height (71 m). Therefore, the top coal cannot collapse completely.

(3) The daily production of the working face increased by an average of 2419.6 tons, significantly improving the top-coal recovery ratio and production efficiency, after the sublevel pre-splitting blasting technology was adopted to weaken the top coal. This provided theoretical basis and application references for residual high stage top-coal recovery in similar programs.

Data Availability

The test data used to support the findings of this study are included within the article. Readers can obtain data supporting the research results from the test data table in the paper.

Disclosure

I would like to declare on behalf of my coauthors that the work described was an original research that has not been published previously and not under consideration for publication elsewhere, in whole or in part.

Conflicts of Interest

No conflict of interest exists in the submission of this manuscript.

Authors' Contributions

All the authors listed have approved the manuscript that is enclosed for publication.

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