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Research Article

Analysis and Engineering Practice of Factors Affecting Top-Coal Recovery in a Large Dip Coal Seam

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The recovery of top coal in the caving face directly impacts the efficiency of mining coal resources. The geological conditions and mining parameters are well known to be significant influences on the recovery of top coal. This study focused on the 9-301 working face, which is located in a thick coal seam with a large dip angle. The influences of the coal seam's dip angle, mining direction, and coal caving mode and interval on the recovery were analyzed using PFC^{2D} simulation. Field trials were also carried out. The results of the numerical calculations show that the recovery of top coal is clearly affected by the dip angle, with recovery decreasing as the dip angle is increased. Mining from the top to bottom along the dip of the coal seam is beneficial to improve recovery. The top-coal recovery using the multicycle-sequence coal caving method is higher than when using single-sequence coal caving and single-interval coal caving modes. The top-coal recovery using "one cutting and one caving" (coal caving interval of 0.8 m) was higher than that under two cuttings and one caving (coal caving interval of 1.6 m). During the field trials, the recovery of top coal under different caving intervals and modes was measured. The results show that the recovery of top coal is optimal when using one cutting and one caving with multicycle-sequence coal caving modes. The field measurements are consistent with the simulation results. The results of this study can help guide additional research for optimizing the recovery of top coal from thick coal seams with large dip angles.

1. Introduction

As part of China's 14th five-year plan, the role of coal will change from being the country's primary energy source to that of a supporting role to guarantee energy security. The key developmental areas to improve coal processing include improved safety, efficient mining, and clean utilization. As coal is a nonrenewable resource, appropriate mining methods and parameters must be selected during mining to minimize the formation of waste material [1]. Coal seams with steep (>45°) dip angles account for approximately one-fifth of China's total coal reserves. Consequently, it is

important to improve the efficiency of mining these steep coal seams. During coal mining, the application of fully mechanized top-coal caving technology can optimize the mining process, improve efficiency and output, and significantly reduce or eliminate site accidents [2–4]. Top-coal caving technology is the primary and preferred method to mine thick coal seams in China, with the method being flexible and widely used [5, 6].

The caving properties of top coal are the key factors in the selection of fully mechanized cave-mining methods and also determine the resource recovery. The recovery of coal is directly related to the improvement of the caving properties

of the top coal present. Various studies have been conducted to investigate the relationship of top-coal caving at the working face [7–9] with various factors affecting the recovery. These can be summarized as being either geological or technical factors [10]. Geological factors include the coal strength, mining depth, and fracture development. Technical factors include the caving interval, mode, and sequence, mining/caving ratio, roof-control distance, support type, and end-head loss. To date, numerous studies have been carried out to qualify the influence of these factors on the recovery of top coal. Zhu and Wang [11], Ma [12], and Liang [13] summarized the geological and technical factors that affect the caving properties of top coal. These studies included the simulation of relevant technological parameters and selected mining schemes with improved recovery of top coal. Han and Bao [14], Wang [15], and Zu [16] all studied the mining/caving ratio. These studies considered the mining/caving ratio, along with the caving interval and mode, analyzing the recovery and gangue content under different conditions to select optimal process parameters to improve recovery. Some studies have individually focused on one of these factors. Liu et al. [17] conducted in-depth investigations into the top-coal caving properties under the conditions of different mining/caving ratios and caving intervals. This study established a numerical model that was used to analyze the impact of the mining/caving ratio and caving intervals on the top-coal recovery, obtaining the relationship between the mining/caving ratio and the recovery. Zhang et al. [18] conducted a discrete element simulation of the top-coal caving process under different dip angles, analyzing the caving volume and the recovery of top coal. The results demonstrated that the caving volume of top coal initially increased and then decreased as the dip angle of the working face was increased. Zhao [19] analyzed the influence of the coal caving sequence on the recovery of top coal. By comparing the recovery under "single-sequence," "single-interval," and "single-segmental interval" schemes, it was suggested that "single-segmental interval" caving modes could greatly improve the recovery at the working face. Li [20] reduced the strength and lumpiness of raw coal by injecting water to weaken a top-coal seam with a steep dip angle. This resulted in an increased recovery of top coal, improving from 13% to 22%. Chen et al. [21] undertook field- and laboratory-based investigations and conducted a theoretical analysis of the influence of gangue on the caving properties of top coal. The authors proposed measures to improve the caving properties of top coal based on these investigations. Various researchers have established systems for evaluating the caving properties of top coal. Jiang [22] undertook a theoretical analysis of the various factors that affect the caving properties, establishing a multifactor evaluation system. This provided a reference for other studies evaluating these properties. Du et al. [23] and Li [24] established functional models for simulating/evaluating top-coal caving using an analytic hierarchical process that provided guidance for improving the recovery of top coal.

In summary, various studies have investigated the factors that affect the recovery of top coal when utilizing a fully mechanized caving face. These studies have established

various models to evaluate the top-coal caving properties, providing a basis for determining the parameters to optimize the process. The geological conditions during mechanized caving are complicated, especially when mining thick coal seams with steep dip angles. Further in-depth research on improving the recovery of top coal under these conditions is required. This study used the theory of ellipsoid coal caving [25–28], and particle flow code (PFC) [29–34] was used to simulate and analyze the influence of factors including the dip angle, caving mode, caving interval, mining direction, and other factors on the recovery of top coal. Field trials were conducted to verify the accuracy of the model and determine the process parameters for the 9-301 working face of a steep, thick coal seam. This study provides a reference for improving the recovery of top coal under similar conditions.

2. Overview of the Project

The 9# coal seam is currently being mined in the 9-301 working face of a mining area located in Shanxi Province. The average depth of the coal seam from the surface is 460 m, with an average thickness of 11.8 m. The average dip angle of the coal seam is 35°. The inclined length of the working face is 200 m, and the strike length is 1490 m. Top-coal caving is currently used for a mining height of 3.2 m. The caving thickness is 8.6 m, and the coal cutting interval is 0.8 m. The immediate roof of the coal seam is argillaceous limestone, with a thickness of 5–7 m. The main roof is sandy mudstone, with a thickness of 6–9 m. The immediate floor is mudstone, with a thickness of 1-2 m. The north side of the working face is the western concealed inclined shaft system, and the south side is the boundary of the mine field. The west side is the 9-101 working face, and the east side is unmined coal. The layout of the working face is presented in Figure 1, while the roof and floor of working face are reported in Table 1.

3. Simulations of the Factors Influencing the Top-Coal Recovery

3.1. Establishment of the Model. Particle flow code (PFC^{2D}) and the discrete element method were utilized to simulate the movement and interaction of particle aggregates. The trend and strike models were established according to the conditions measured at the 9-301 working face. The strike model of section I-I and the trend model of section II-II in Figure 1 were established. The length and width of the model were 50 m × 50 m. Field investigations and laboratory testing determined the mechanical parameters of the coal and rock mass used in the model (Table 2). The size of the coal seam block was set as 100–200 mm. Considering the Gaussian random distribution, large or small blocks were discarded to reduce the calculation time and speed up the model convergence. The stress state of the coal seam was displayed via particle cluster mode. In the case of non-mining, the coal body was in an integral state without granular flow medium [35]. The trend model was used to study the influence of the dip angle, mining direction, and caving mode on the recovery of top coal. The strike model was used to analyze the influence of the caving interval on the recovery of top coal.
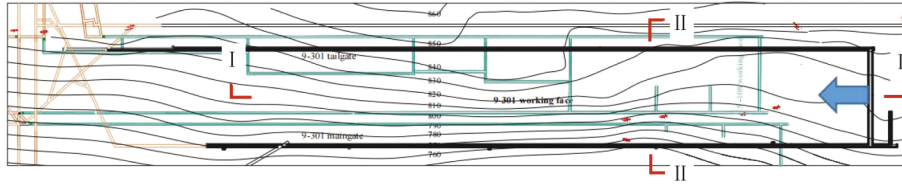
Figure 1: 9-301 working face layout.

Table 1: Roof and floor of the working face.

Roof and floor	Lithology	Thickness (m)
Main roof	Sandy mudstone	6–9
Immediate roof	Limestone	5–7
Immediate floor	Mudstone	1-2
Main floor	Fine sandstone	1–3

Table 2: Mechanical parameters of the coal and rock.

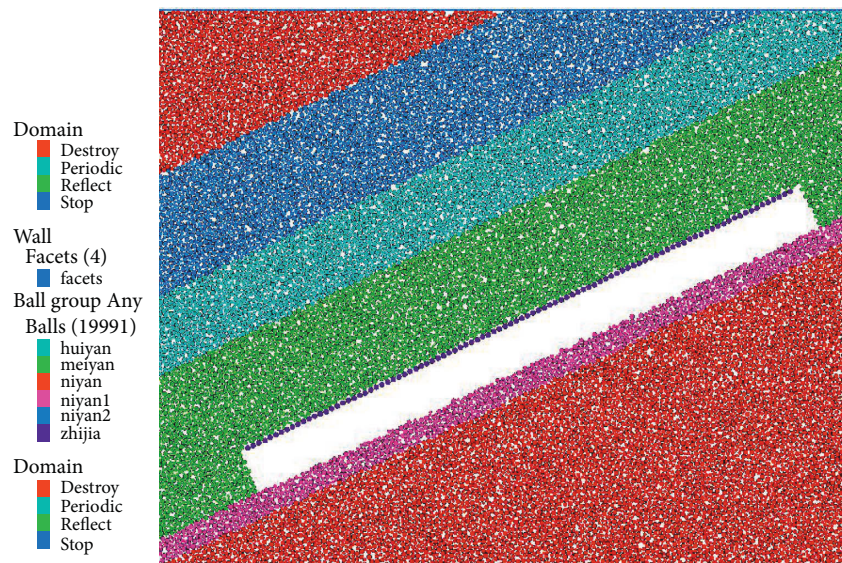| Rock	Thickness (m)	Density (kg/m^3)	Compression strength (MPa)	Tensile strength (MPa)	Friction angle (°)	Elastic modulus (MPa)	Poisson's ratio
Sandy mudstone	7.60	2598	63.22	4.05	36	10233	0.26
Limestone	5.70	2688	76.02	5.10	29	11279	0.23
9# coal	11.80	1420	2.72	0.57	35	3865	0.33
Mudstone	1.89	2623	61.12	3.26	34	8179	0.29

Figure 2: Trend model of the 9-301 working face.

The trend and strike models are reported in Figures 2 and 3, respectively.

Both sides and the top boundary of the model were fixed horizontally, and the vertical direction was free. The bottom of the model was fixed horizontally and vertically. According to the field stress testing, a horizontal force of 20.5 MPa was applied to both sides of the strike model, and 26.3 MPa was applied to both sides of the trend model, while 10.3 MPa was applied to the top of the model to replace the weight of the upper overburden.

3.2. Influence of the Coal Seam's Dip Angle on the Top-Coal Recovery. The dip angle of the coal seam significantly influences the mining efficiency of top-coal caving. When the dip angle is large, the gravitational influence of the coal body is increased, potentially leading to the collapse of the coal body. However, with continuous increase in the dip angle, the recovery decreases [36]. During this study, top-coal caving simulation tests were carried out with the dip angle of coal seam set to 15°, 25°, and 35°(Figures 4–6, respectively). The coal caving direction during the simulations was from
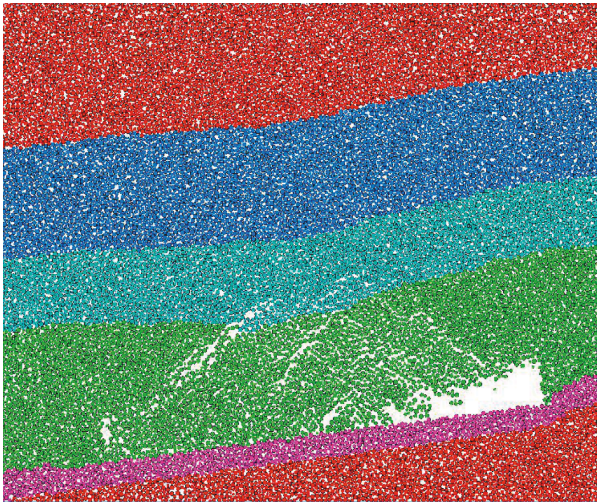
FIGURE 3: Strike model of the 9-301 working face.

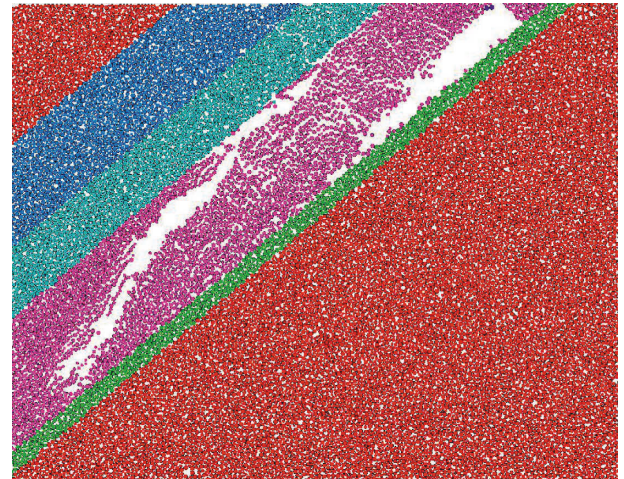FIGURE 4: Effect of the coal seam's dip angle (15°) on coal caving.

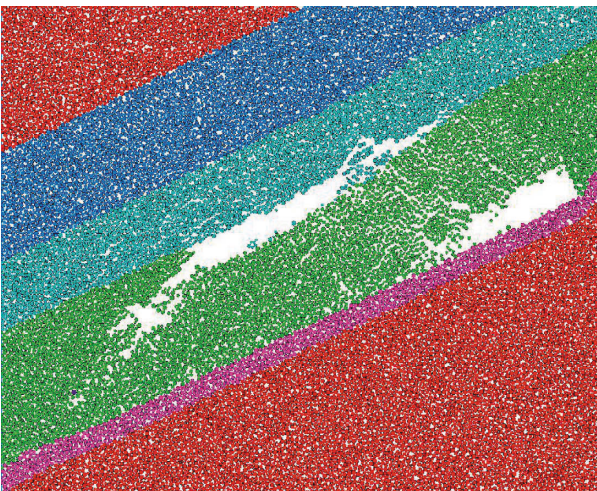FIGURE 6: Effect of the coal seam's dip angle (35°) on coal caving.

the bottom to the top along the dip angle of the coal seam. The effect of coal caving is shown in Figures 3–5. When the dip angle of the coal seam was 15°, the recovery was calculated to be 79.2%. When the dip angle was increased to 25°, the recovery was 76.3%, and when the dip angle was 35°, the recovery was 74.2%. The simulation results clearly demonstrate that the recovery rate decreases as the dip angle of the coal seam rises.

3.3. Influence of the Mining Direction on the Top-Coal Recovery. The influence of downward and upward mining on the top-coal recovery was examined using a dip angle of 35°. Upward mining refers to the shearer cutting coal and hydraulic support caving coal from bottom to top along the inclination of the coal seam. Downward mining refers to the shearer cutting coal and hydraulic support caving coal from top to bottom along the inclination of the coal seam. According to the simulations (Figures 7 and 8), the recovery of top coal was 82.5% during upward mining and 83.1%
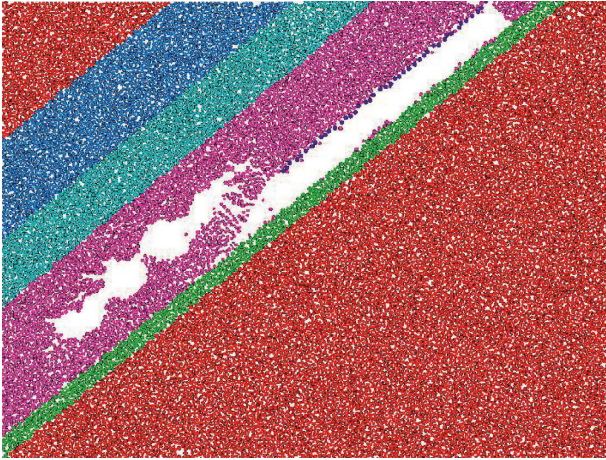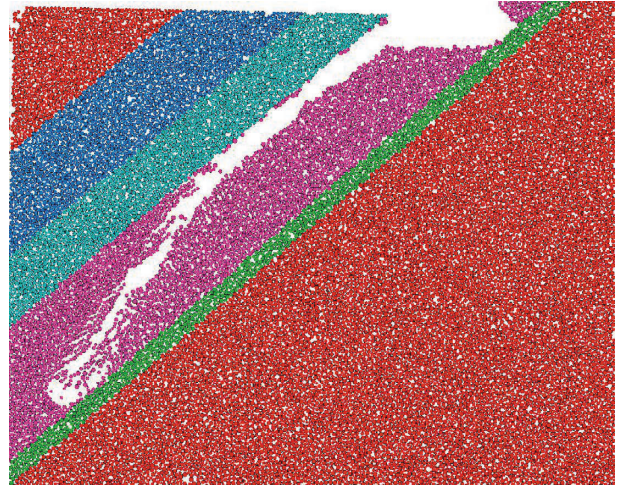

FIGURE 5: Effect of the coal seam's dip angle (25°) on coal caving.

FIGURE 7: Upward mining and coal caving.

FIGURE 8: Downward mining and coal caving.

FIGURE 9: Single-sequence coal caving.
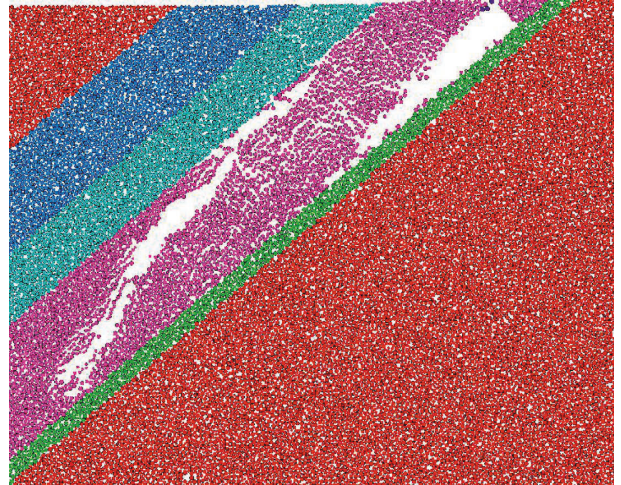
FIGURE 10: Single-interval coal caving.

FIGURE 11: Multicycle-sequence coal caving.

during downward mining. Downward mining and caving had a greater impact on the roof, but the area impacted was relatively weak. Consequently, downward mining along the dip of the coal seam is recommended for improved economic benefits.

3.4. Influence of the Caving Mode on the Top-Coal Recovery. There are three caving modes utilizing a fully mechanized caving face. These include single-sequence coal caving, single-interval coal caving, and multicycle-sequence coal caving [37]. Eight groups of supports were arranged in the model. The simulations were carried out according to the three modes, with the effects compared: (1) single-sequence coal caving refers to coal caving in the order of 1#, 2#, 3#... supports, with the caving opening closed after contacting the gangue. (2) Single-interval coal caving refers to coal caving in the order of 1#, 3#, 5#... supports initially and closing after finding gangue. After a certain period, the coal outlets of the 2#, 4#, 6#... supports are opened to discharge the ridge coal. (3) Multicycle-sequence coal caving refers to opening the outlets of the 1# and 2# supports at the same

FIGURE 12: Migration characteristics of top coal during the simulation of "one cutting and one caving."

FIGURE 13: .Migration characteristics of top coal during the simulation of "two cuttings and one caving."

FIGURE 14: Layout of the monitoring sections and measuring points (unit: (m)).

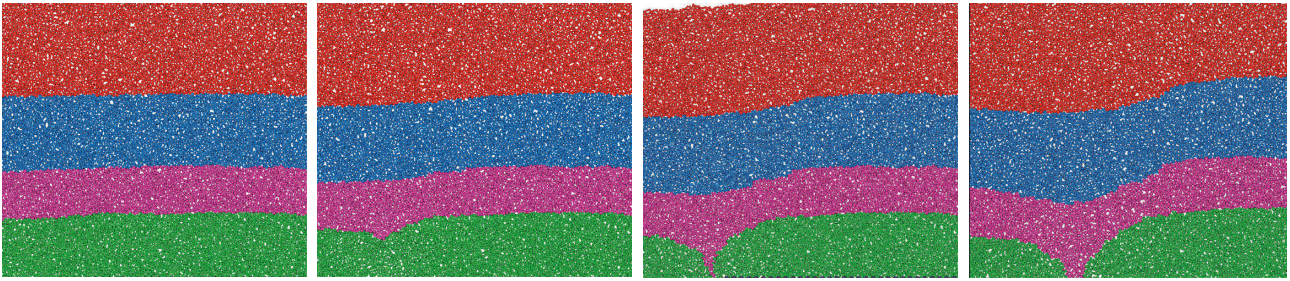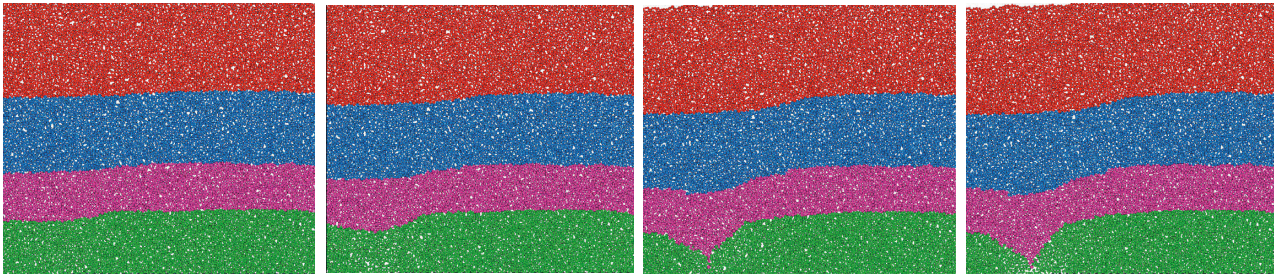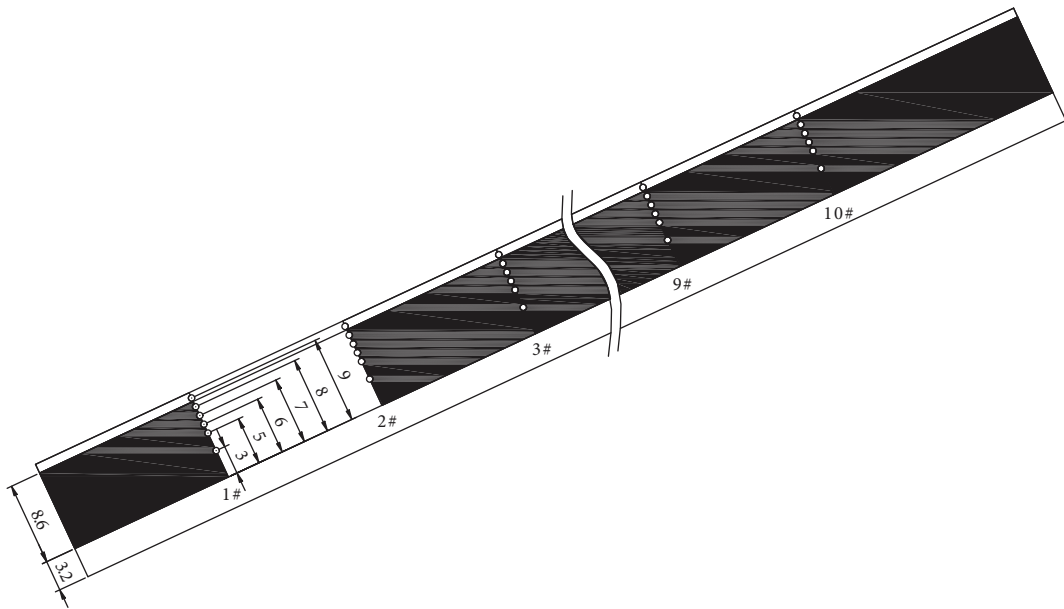FIGURE 15: Measuring point device before installation.

TABLE 3: Distribution of measuring points on different monitored sections.

Section number	Point position						
	3 m	5 m	6 m	7 m	8 m	9 m	Installation location (the number of hydraulic supports)
1#	1-3#	1-5#	1-6#	1-7#	1-8#	1-9#	10#
2#	2-3#	2-5#	2-6#	2-7#	2-8#	2-9#	20#
3#	3-3#	3-5#	3-6#	3-7#	3-8#	3-9#	30#
4#	4-3#	4-5#	4-6#	4-7#	4-8#	4-9#	40#
5#	5-3#	5-5#	5-6#	5-7#	5-8#	5-9#	50#
6#	6-3#	6-5#	6-6#	6-7#	6-8#	6-9#	60#
7#	7-3#	7-5#	7-6#	7-7#	4-8#	7-9#	70#
8#	8-3#	8-5#	8-6#	8-7#	8-8#	8-9#	80#
9#	9-3#	9-5#	9-6#	9-7#	9-8#	9-9#	90#
10#	10-3#	10-5#	10-6#	10-7#	10-8#	10-9#	100#

FIGURE 16: Measuring point device after recovery.

time, and simultaneously opening the outlets of the 3# and 4# supports after closing the outlets of the 1# and 2# supports. The mode described is followed until all supports have completed caving. The coal caving direction in the above model is from top to bottom along the dip of coal seam.

The simulation process is presented in Figures 9–11. The recovery of top coal was 85.7% when multicycle-sequence coal caving was used, 82.7% in the case of single-interval coal caving, and 83.1% when single-sequence coal caving was utilized. Multicycle-sequence coal caving is the most effective method to improve the top-coal recovery. However, due to the simultaneous caving of multiple supports, the roof is impacted and the top coal is thrust from the top to the bottom. This leads to the roof sinking towards the coal caving space, making it more difficult to control.

3.5. Influence of the Caving Interval on the Recovery of Top Coal. The coal caving interval refers to the advancing distance of the working face between coal caving. A reasonable coal caving interval is crucial to improve the recovery and maintain roof stability [38, 39]. The caving interval is an important factor that affects the top-coal recovery and the gangue content of the working face. If the caving interval is too long or too short, the recovery will decline and the mining quality will be reduced [40–42]. At present, there are two commonly used technologies for coal caving, namely, "one cutting and one caving" (coal caving interval of 0.8 m) and "two cuttings and one caving" (coal caving interval of 1.6 m). The numerical simulation of these two coal caving processes is presented in Figures 12 and 13, respectively.

When the coal caving interval is larger than the short axis of the caving ellipsoid, the gangue above the support reaches the caving opening before the top coal within the interval range. This results in "backbone" coal loss and reduces the recovery of top coal. Conversely, if the coal caving interval is smaller than the short axis of the caving ellipsoid, then gangue in the goaf is discharged earlier than the top coal, resulting in the retention of the coal, which affects the quality of the coal mined [43–46]. The results of the simulations (Figures 11 and 12) show that the "one cutting and one caving" method (coal caving interval of 0.8 m) is more economical than the "two cuttings and one caving" method (coal caving interval of 1.6 m). The top coal and gangue can reach the coal discharge port at the same time, assisting in recovering the top coal and improving control of the support to the roof.

4. Field Trials

4.1. Monitoring the Top-Coal Recovery. The 9-301 working face was selected as the site for undertaking the industrial field trials. The migration monitoring points of the top coal were arranged, with boreholes installed in different areas of the working face. A total of 10 sections were arranged for monitoring. The 10# support was used as the starting point, with each monitoring section arranged at an interval of 10 supports. Six measuring points were arranged in the top coal for each section, at depths of 3, 5, 6, 7, 8, and 9 m, respectively. The measuring point at 9 m was located in the roof (Figure 14). The measuring point in the hole was equipped with a fixed barb device (Figure 15). During field construction, boreholes were drilled between the adjacent supports, with a diameter of 42 mm and a depth of 9 m. The drill rod was used to push the monitoring device to a predetermined depth. The arrangement of measuring points for each section is presented in Table 3. After the top coal was discharged, an iron suction device at the head of the scraper conveyor and transfer machine was used to recover the measuring point device (Figure 16), which was used to count the maximum coal caving height (i.e., the actual coal caving height). The ratio of the actual coal caving height to the theoretical coal caving height was used as a comparative

Table 4: Monitoring data of top coal recovery under the condition of one cutting and one caving with single-sequence coal caving ("√" means the monitoring point has been recovered, "×" means the monitoring point has not been recovered).

Date	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#
2018.11.3	1-3# √	2-3# √	3-3# √	4-3# √	5-3# √	6-3# √	7-3# √	8-3# √	9-3# √	10-3# √
	1-5# √	2-5# √	3-5# √	4-5# √	5-5# √	6-5# √	7-5# √	8-5# √	9-5# √	10-5# √
	1-6# √	2-6# √	3-6# √	4-6# √	5-6# √	6-6# √	7-6# √	8-6# √	9-6# √	10-6# √
	1-7# √	2-7# √	3-7# √	4-7# √	5-7# √	6-7# √	7-7# √	8-7# √	9-7# √	10-7# √
	1-8# √	2-8# ×	3-8# √	4-8# ×	5-8# √	6-8# √	7-8# √	8-8# √	9-8# √	10-8# √
	1-9# ×	2-9# ×	3-9# ×	4-9# ×	5-9# √	6-9# ×	7-9# ×	8-9# ×	9-9# √	10-9# √
Recovery	0.93	0.81	0.93	0.81	1.00	0.93	0.93	0.93	1.00	1.00
Average recovery	0.93									

Date	1#	2#	3#	4#	5#	6#	7	8#	9#	10#
2018.11.6	1-3# √	2-3# √	3-3# √	4-3# √	5-3# √	6-3# √	7-3# √	8-3# √	9-3# √	10-3# √
	1-5# √	2-5# √	3-5# √	4-5# √	5-5# √	6-5# √	7-5# √	8-5# √	9-5# √	10-5# √
	1-6# √	2-6# √	3-6# √	4-6# √	5-6# √	6-6# √	7-6# √	8-6# √	9-6# √	10-6# √
	1-7# √	2-7# √	3-7# √	4-7# √	5-7# √	6-7# √	7-7# √	8-7# √	9-7# √	10-7# √
	1-8# ×	2-8# √	3-8# √	4-8# √	5-8# ×	6-8# √	7-8# √	8-8# √	9-8# √	10-8# √
	1-9# ×	2-9# ×	3-9# ×	4-9# ×	5-9# ×	6-9# ×	7-9# ×	8-9# √	9-9# √	10-9# √
Recovery	0.81	0.93	0.93	0.93	0.81	0.93	0.93	1.00	1.00	1.00
Average recovery	0.93									

Date	1#	2#	3#	4#	5# 6#	7# 8#	9# 10#	5# 6#	7# 8#	9# 10#
2018.11.10	1-3# √	2-3# √	3-3# √	4-3# √	5-3# √	6-3# √	7-3# √	8-3# √	9-3# √	10-3# √
	1-5# √	2-5# √	3-5# √	4-5# √	5-5# √	6-5# √	7-5# √	8-5# √	9-5# √	10-5# √
	1-6# √	2-6# √	3-6# √	4-6# √	5-6# √	6-6# √	7-6# √	8-6# √	9-6# √	10-6# √
	1-7# √	2-7# √	3-7# ×	4-7# √	5-7# √	6-7# √	7-7# √	8-7# √	9-7# √	10-7# √
	1-8# √	2-8# √	3-8# ×	4-8# √	5-8# √	6-8# √	7-8# √	8-8# √	9-8# √	10-8# √
	1-9# ×	2-9# ×	3-9# ×	4-9# ×	5-9# √	6-9# ×	7-9# ×	8-9# ×	9-9# √	10-9# √
Recovery	0.93	0.93	0.81	0.93	1.00	0.93	0.93	0.93	1.00	1.00
Average recovery	0.94									

Table 5: Monitoring data of top coal recovery under the condition of two cutting and one caving with single-sequence coal caving ("√" means the monitoring point has been recovered, "×" means the monitoring point has not been recovered).

Date	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#
2018.11.15	1-3# √	2-3# √	3-3# √	4-3# √	5-3# √	6-3# √	7-3# √	8-3# √	9-3# √	10-3# √
	1-5# √	2-5# √	3-5# √	4-5# √	5-5# √	6-5# √	7-5# √	8-5# √	9-5# √	10-5# √
	1-6# √	2-6# √	3-6# √	4-6# √	5-6# √	6-6# √	7-6# √	8-6# √	9-6# √	10-6# √
	1-7# √	2-7# √	3-7# √	4-7# √	5-7# √	6-7# √	7-7# √	8-7# √	9-7# √	10-7# √
	1-8# ×	2-8# ×	3-8# √	4-8# ×	5-8# √	6-8# √	7-8# ×	8-8# √	9-8# √	10-8# √
	1-9# ×	2-9# ×	3-9# ×	4-9# ×	5-9# ×	6-9# ×	7-9# ×	8-9# ×	9-9# ×	10-9# √
Recovery	0.81	0.81	0.93	0.81	0.93	0.93	0.81	0.93	0.93	1.00
Average recovery	0.90									

Date	1#	2#	3#	4#	5#	6#	7	8#	9#	10#
2018.11.20	1-3# √	2-3# √	3-3# √	4-3# √	5-3# √	6-3# √	7-3# √	8-3# √	9-3# √	10-3# √
	1-5# √	2-5# √	3-5# √	4-5# √	5-5# √	6-5# √	7-5# √	8-5# √	9-5# √	10-5# √
	1-6# √	2-6# √	3-6# √	4-6# √	5-6# √	6-6# √	7-6# √	8-6# √	9-6# √	10-6# √
	1-7# √	2-7# √	3-7# √	4-7# √	5-7# √	6-7# √	7-7# √	8-7# √	9-7# √	10-7# √
	1-8# ×	2-8# √	3-8# ×	4-8# √	5-8# √	6-8# √	7-8# √	8-8# √	9-8# √	10-8# √
	1-9# ×	2-9# ×	3-9# ×	4-9# ×	5-9# ×	6-9# ×	7-9# ×	8-9# ×	9-9# √	10-9# ×
Recovery	0.81	0.93	0.81	0.93	0.93	0.93	0.93	0.93	1.00	0.93
Average recovery	0.91									

Date	1#	2#	3#	4#	5# 6#	7# 8#	9# 10#	5# 6#	7# 8#	9# 10#
2018.11.23	1-3# √	2-3# √	3-3# √	4-3# √	5-3# √	6-3# √	7-3# √	8-3# √	9-3# √	10-3# √
	1-5# √	2-5# √	3-5# √	4-5# √	5-5# √	6-5# √	7-5# √	8-5# √	9-5# √	10-5# √
	1-6# √	2-6# √	3-6# √	4-6# √	5-6# √	6-6# √	7-6# √	8-6# √	9-6# √	10-6# √
	1-7# √	2-7# √	3-7# √	4-7# √	5-7# √	6-7# √	7-7# √	8-7# √	9-7# √	10-7# √
	1-8# √	2-8# √	3-8# ×	4-8# √	5-8# ×	6-8# ×	7-8# √	8-8# √	9-8# √	10-8# √
	1-9# ×	2-9# ×	3-9# ×	4-9# ×	5-9# ×	6-9# ×	7-9# ×	8-9# ×	9-9# ×	10-9# ×
Recovery	0.93	0.93	0.81	0.93	0.81	0.81	0.93	0.93	0.93	0.93
Average recovery	0.89									

TABLE 6: Monitoring data of top coal recovery under the condition of one cutting and one caving with single-interval coal caving ("√" means the monitoring point has been recovered, "×" means the monitoring point has not been recovered).

Date	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#
2018.12.3	1-3# √	2-3# √	3-3# √	4-3# √	5-3# √	6-3# √	7-3# √	8-3# √	9-3# √	10-3# √
	1-5# √	2-5# √	3-5# √	4-5# √	5-5# √	6-5# √	7-5# √	8-5# √	9-5# √	10-5# √
	1-6# √	2-6# √	3-6# √	4-6# √	5-6# √	6-6# √	7-6# √	8-6# √	9-6# √	10-6# √
	1-7# √	2-7# √	3-7# √	4-7# √	5-7# √	6-7# √	7-7# √	8-7# √	9-7# √	10-7# √
	1-8# ×	2-8# ×	3-8# √	4-8# ×	5-8# ×	6-8# √	7-8# ×	8-8# ×	9-8# √	10-8# √
	1-9# ×	2-9# ×	3-9# ×	4-9# ×	5-9# ×	6-9# ×	7-9# ×	8-9# ×	9-9# ×	10-9# ×
Recovery	0.81	0.81	0.93	0.81	0.81	0.93	0.81	0.81	0.93	0.93
Average recovery					0.86					
Date	1#	2#	3#	4#	5#	6#	7	8#	9#	10#
2018.12.7	1-3# √	2-3# √	3-3# √	4-3# √	5-3# √	6-3# √	7-3# √	8-3# √	9-3# √	10-3# √
	1-5# √	2-5# √	3-5# √	4-5# √	5-5# √	6-5# √	7-5# √	8-5# √	9-5# √	10-5# √
	1-6# √	2-6# √	3-6# √	4-6# √	5-6# √	6-6# √	7-6# √	8-6# √	9-6# √	10-6# √
	1-7# √	2-7# √	3-7# √	4-7# √	5-7# √	6-7# √	7-7# √	8-7# √	9-7# √	10-7# √
	1-8# √	2-8# ×	3-8# ×	4-8# ×	5-8# √	6-8# ×	7-8# √	8-8# √	9-8# √	10-8# √
	1-9# ×	2-9# ×	3-9# ×	4-9# ×	5-9# ×	6-9# ×	7-9# ×	8-9# ×	9-9# ×	10-9# ×
Recovery	0.93	0.81	0.81	0.81	0.93	0.81	0.93	0.93	0.93	0.93
Average recovery					0.88					
Date	1#	2#	3#	4#	5# 6#	7# 8#	9# 10#	5# 6#	7# 8#	9# 10#
2018.12.10	1-3# √	2-3# √	3-3# √	4-3# √	5-3# √	6-3# √	7-3# √	8-3# √	9-3# √	10-3# √
	1-5# √	2-5# √	3-5# √	4-5# √	5-5# √	6-5# √	7-5# √	8-5# √	9-5# √	10-5# √
	1-6# √	2-6# √	3-6# √	4-6# √	5-6# √	6-6# √	7-6# √	8-6# √	9-6# √	10-6# √
	1-7# √	2-7# √	3-7# √	4-7# √	5-7# √	6-7# √	7-7# √	8-7# √	9-7# √	10-7# √
	1-8# √	2-8# √	3-8# ×	4-8# ×	5-8# ×	6-8# √	7-8# ×	8-8# √	9-8# √	10-8# √
	1-9# ×	2-9# ×	3-9# ×	4-9# ×	5-9# ×	6-9# ×	7-9# ×	8-9# ×	9-9# ×	10-9# ×
Recovery	0.93	0.93	0.81	0.81	0.81	0.93	0.81	0.93	0.93	0.93
Average recovery					0.88					

TABLE 7: Monitoring data of top coal recovery under the condition of one cutting and one caving with multicycle-sequence coal caving ("√" means the monitoring point has been recovered, "×" means the monitoring point has not been recovered).

Date	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#
2018.12.13	1-3# √	2-3# √	3-3# √	4-3# √	5-3# √	6-3# √	7-3# √	8-3# √	9-3# √	10-3# √
	1-5# √	2-5# √	3-5# √	4-5# √	5-5# √	6-5# √	7-5# √	8-5# √	9-5# √	10-5# √
	1-6# √	2-6# √	3-6# √	4-6# √	5-6# √	6-6# √	7-6# √	8-6# √	9-6# √	10-6# √
	1-7# √	2-7# √	3-7# √	4-7# √	5-7# √	6-7# √	7-7# √	8-7# √	9-7# √	10-7# √
	1-8# √	2-8# √	3-8# √	4-8# √	5-8# √	6-8# √	7-8# √	8-8# √	9-8# √	10-8# √
	1-9# ×	2-9# ×	3-9# ×	4-9# √	5-9# √	6-9# ×	7-9# ×	8-9# √	9-9# √	10-9# √
Recovery	0.93	0.93	0.93	1.00	1.00	0.93	0.93	1.00	1.00	1.00
Average recovery					0.97					
Date	1#	2#	3#	4#	5#	6#	7	8#	9#	10#
2018.12.17	1-3# √	2-3# √	3-3# √	4-3# √	5-3# √	6-3# √	7-3# √	8-3# √	9-3# √	10-3# √
	1-5# √	2-5# √	3-5# √	4-5# √	5-5# √	6-5# √	7-5# √	8-5# √	9-5# √	10-5# √
	1-6# √	2-6# √	3-6# √	4-6# √	5-6# √	6-6# √	7-6# √	8-6# √	9-6# √	10-6# √
	1-7# √	2-7# √	3-7# √	4-7# √	5-7# √	6-7# √	7-7# √	8-7# √	9-7# √	10-7# √
	1-8# √	2-8# √	3-8# √	4-8# √	5-8# √	6-8# √	7-8# √	8-8# √	9-8# √	10-8# √
	1-9# ×	2-9# √	3-9# ×	4-9# √	5-9# √	6-9# √	7-9# ×	8-9# √	9-9# √	10-9# √
Recovery	0.93	1.00	0.93	1.00	1.00	1.00	0.93	1.00	1.00	1.00
Average recovery					0.98					
Date	1#	2#	3#	4#	5# 6#	7# 8#	9# 10#	5# 6#	7# 8#	9# 10#
2018.12.23	1-3# √	2-3# √	3-3# √	4-3# √	5-3# √	6-3# √	7-3# √	8-3# √	9-3# √	10-3# √
	1-5# √	2-5# √	3-5# √	4-5# √	5-5# √	6-5# √	7-5# √	8-5# √	9-5# √	10-5# √
	1-6# √	2-6# √	3-6# √	4-6# √	5-6# √	6-6# √	7-6# √	8-6# √	9-6# √	10-6# √
	1-7# √	2-7# √	3-7# √	4-7# √	5-7# √	6-7# √	7-7# √	8-7# √	9-7# √	10-7# √
	1-8# √	2-8# √	3-8# √	4-8# √	5-8# √	6-8# √	7-8# √	8-8# √	9-8# √	10-8# √
	1-9# ×	2-9# ×	3-9# √	4-9# √	5-9# √	6-9# √	7-9# √	8-9# ×	9-9# √	10-9# √
Recovery	0.93	0.93	1.00	1.00	1.00	1.00	1.00	0.93	1.00	1.00
Average recovery					0.98					

TABLE 8: Statistics of recovery of top coal under different coal caving intervals.

Caving interval/m	1	2	3	Average
0.8	0.93	0.93	0.94	0.93
1.6	0.90	0.91	0.89	0.90

TABLE 9: Recovery of top coal using different coal caving modes.

Coal caving mode	1	2	3	Average
Single interval	0.86	0.88	0.88	0.87
Single sequence	0.93	0.93	0.94	0.93
Multicycle sequence	0.97	0.98	0.98	0.98

TABLE 10: Output of the working face from January to February 2019.

Coal caving modes	Production duration (days)	Working face advanced distance (m)	Theoretical coal output (t)	Actual output (t)	Recovery of top coal (%)
"One cutting and one caving" with single-sequence caving	25	80	251104	227284	90.5
"One cutting and one caving" with multicycle-sequence caving	20	62	194606	186822	96.0

index to determine the recovery of top coal. The method used is based on the stability of top-coal's occurrence with a consistent thickness along the working face.

4.2. Analysis of Monitoring Data

4.2.1. Recovery of Top Coal under Different Coal Caving Intervals. A comparison was carried out between the processes of "one cutting and one caving" (caving interval of 0.8 m) and "two cuttings and one caving" (caving interval of 1.6 m). The original monitoring data are attached at the end of the article (Tables 4–7). The statistical data of the recovery under these conditions are reported in Table 8. The caving method used was single-sequence coal caving. Three measurements were made under each condition. Using the process of "one cutting and one caving," the recovery of top coal was 0.93, 0.93, and 0.94, with an average of 0.93. Using the conditions of "two cuttings and one caving," the recovery of top coal was 0.90, 0.91, and 0.89, with an average of 0.90. The recovery of top coal with the process of "one cutting and one caving" was significantly higher than that of "two cuttings and one caving." The industrial test results were consistent with the simulation data.

4.2.2. Recovery of Top Coal with Different Coal Caving Modes. Different coal caving modes were compared under the condition of "one cutting and one caving." The coal caving modes included single-sequence coal caving, single-interval coal caving, and multicycle-sequence coal caving. The results from the monitoring data are reported in Table 9. It is evident that the multicycle-sequence coal caving was the best, with the recovery of top coal reaching 98%. The recovery of top coal using the single-sequence coal caving was 93%, with single-interval coal caving having 87% recovery.

Therefore, the recovery of top coal can be improved using multicycle-sequence coal caving.

To verify the experimental results, field industrial tests lasting two months were carried out. Assuming that all of the coal within the cutting height of the coal shearer was recovered, the theoretical coal output, the actual output, and the recovery of top coal were determined. These data are reported in Table 10, with the effects of different caving modes on the recovery of top coal compared. The results demonstrate that the recovery of top coal was the highest under the condition of "one cutting and one caving" with a multicycle-sequence coal caving, reaching 96%. The recovery of top coal was 90.5% under the condition of "one cutting and one caving" with single-sequence coal caving. The optimal choice of methodology resulted in an increase of 5.5% in the recovery.

5. Discussion

(1) There are many factors affecting the recovery of top coal, and the interaction of multiple factors makes the movements of top coal more complicated. This study only analyzes factors such as the dip angle, mining direction, coal caving intervals, and coal caving modes. Thus, further analysis is required.

(2) At present, there is still no effective method to observe the recovery of top coal. The method used in this study is based on the stability of top-coal's occurrence with consistent thickness, so there is still an error with respect to the actual situation.

6. Conclusion

(1) A numerical model was established to investigate the dip of the 9-301 working face. The effects of the coal seam's dip angle, the mining direction, and the

caving mode on the recovery were analyzed. The simulation results showed that the dip angle of the coal seam has a strong influence on the recovery. The recovery decreased as the dip angle increased. Downward mining from the top to the bottom along the dip of the coal seam is conducive to improving the recovery of top coal. The recovery of top coal using the multicycle-sequence caving method is higher than that using single-sequence or single-interval caving.

(2) The influence of the coal caving interval on the recovery of top coal was analyzed, with simulation results demonstrating that the recovery under "one cutting and one caving" (coal caving interval of 0.8 m) was higher than that under "two cuttings and one caving" (coal caving interval of 1.6 m).

(3) The recovery of top coal under different caving intervals and caving modes was measured during field trials. Site monitoring results showed that the recovery of top coal was greatest under the condition of "one cutting and one caving" with the multicycle-sequence caving. The field measurements were consistent with the simulation results.

Data Availability

Some or all data, models, or codes generated or used during the study are available from the corresponding author by request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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