

## Research Article

# Quantitative Evaluation of Top Coal Caving Methods at the Working Face of Extra-Thick Coal Seams Based on the Random Medium Theory

Shi Jiulin <sup>1,2</sup>, Zhang Quntao <sup>3</sup>, Gao Xiaojin <sup>1,2</sup> and Xue Jisheng <sup>1,2</sup>

<sup>1</sup>Beijing Mining Research Institute, China Coal Research Institute, Beijing 100013, China

<sup>2</sup>CCTEG Coal Mining Research Institute, Beijing 100013, China

<sup>3</sup>School of Energy and Mining Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China

Correspondence should be addressed to Shi Jiulin; [sjlin1210@163.com](mailto:sjlin1210@163.com)

Received 21 February 2021; Revised 21 March 2021; Accepted 31 March 2021; Published 10 April 2021

Academic Editor: Gaofeng Song

Copyright © 2021 Shi Jiulin et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Adopting an effective top coal caving method is the key to enhancing coal recovery and reducing gangue content for the fully mechanized top coal caving working face with extra-thick coal seams. In this study, the movement of coal particles generated during top coal caving is considered to follow a normal distribution. Then, the caving body and coal-rock settlement along the working face during the caving process are studied based on both the random media theory and probability theory. Accordingly, the optimal caving interval and caving sequences are determined, and a novel interval symmetrical coal caving method is proposed. The proposed method is systematically verified with results from physical similarity tests, and different caving methods are assessed by field tests. The results show the following: (1) The coal-rock settlement and the caving body demonstrate clear axial symmetrical features along the working face; the size of the caving body increases as the caving height grows and its shape turns progressively from semicircular to semielliptical with a lower foot of the coal-rock settlement. (2) The caving interval is derived using the sum of the radii of the coal-rock settlement curves formed by the two largest caving bodies. (3) The symmetrical caving approach provides a symmetrical space for the subsequent movement of the broken top coal, which enables a uniform development of the caving body. (4) Compared with the traditional sequential coal caving method with the same number of supports, the interval symmetrical caving method results in a 21.7% of coal production increase, 17% caving rate promotion, and a shortened caving time by 23.4%. (5) The interval symmetrical caving method is found to improve the controllability of the caving process at the fully mechanized top coal caving working face. In general, this work presents a theoretical approach to select the optimal caving methods for the fully mechanized caving working face in extra-thick coal seams for an improved production efficiency of the work face. The results of this study can also provide theoretical significance and referencing value for quantitative analyses of the coal caving methods for work faces with similar geological conditions.

## 1. Introduction

After 40 years of field application and practice, the fully mechanized top coal caving mining method has become the mainstream for mining thick and extra-thick coal seams in China. However, the loss of top coal during the mining process poses a major challenge for the further development of the method [1–6]. Larger mining height can lead to higher coal losses, and the key to reducing coal losses and improving recovery lies in the selection of a more effective caving method.

To find a caving approach that enables higher coal recovery and lower gangue content, many studies have analyzed the coal breaking and moving behavior and the evolution of the caving body and coal-rock boundary during the caving process. Wu and Zhang [5] proposed the coal caving ellipsoid theory based on field measurement and similar simulation experiments. In their study, the effects of the coal caving angle, coal caving height, and the distance between the caving and the top coal breaking line on the development of the strike coal caving ellipsoid and axial deflection were studied. Using the ellipsoid

theory, Tian et al. [7] analyzed the relationship between the theoretical coal caving ellipsoid, the actual caving ellipsoid, and the loose ellipsoid. A proper caving interval that can adapt to different top coal thickness was proposed by assuming that the initial coal-rock boundary is parabolic. Liu et al. [8] numerically analyzed the relationship between the caving interval and the coal recovery in a 17 m thick coal seam of the Zhungeer Coal Mine. It was found that a lower mining to caving ratio at twice the coal cutting can provide sufficient space for loosening the top coal, which is beneficial for top coal recovery. Wang and Zhang [9–12] proposed the “BBR” caving theory containing factors including top coal, recovery rate, and gangue rate, based on the granular media flow theory. A sectioned caving method with large intervals was developed, which can expand the coal caving area, reduce top coal losses between supports, and increase the overall coal recovery. Huang et al. [13–15] studied the flow field of coal gangue based on physical similarity tests of granular media in the strike direction and argued that the coal caving process is essentially the evolution process of the coal-rock boundary and the initial top coal boundary. They proposed the concept of the caving turning point by performing excessive top coal caving to improve the overall coal recovery. Yan et al. [16] studied the relationship between the flowing behavior of the broken coal and the quadrilateral/triangular piling patterns formed by the broken gangue and the top coal behind the support. They believed that the coal loss is inversely proportional to the piling angle of the gangue and is proportional to the distance between the rear scraper conveyor and the gangue pile. The coal loss was then quantified and the cause of residual coal in the goaf during top coal caving was analyzed. Zhu and Yu [17, 18] conducted physical similarity simulation tests and found that the tail beam and caving opening of the support in the inclined direction of the working face can cause the axial deflection angle of the caving body to decrease with the increase of the caving height, and the coal gangue boundary was found to appear at the coal caving opening. The top coal recovery rate in the direction of the coal seam was quantitatively analyzed using the relationship between the gangue settlement curve and the area of the caving body. Based on laboratory and field tests on the flowing behavior of the top coal using top coal caving method, numerous scholars proposed theoretical models for the caving process according to the coal caving, ellipsoid theory, and the granular dynamics. Moreover, it was found by controlling the caving body and coal-rock boundary that the top coal recovery can be increased with reduced coal losses. Liu et al. [19, 20] determined the sequence of coal caving and the interval time difference based on the coal-rock boundary line and the theory of inclined straight lines. In addition, the multiple top coal caving windows synergetic method with the principle of opening windows at the same time and closing the window in reverse was proposed. The proposed top coal caving method can optimize the coal gangue boundary to achieve increased top coal recovery by controlling the caving time of part of the coal caving supports.

In general, existing studies mostly focus on assessing the top coal recovery along the strike direction of the work face, whereas studies on top coal recovery along the dip direction of the work face are still lacking, especially in terms of selecting the coal caving method in the fully mechanized top

coal caving working face. The top coal caving method is a systematic combination of caving sequence and caving amount, and it possesses a major effect on the top coal recovery in the working face. The current selection process of top coal caving methods is mainly based on physical similarity simulation and empirical control from field tests. Therefore, this study aims to propose an effective approach to select the optimal caving method by quantitative analyses of the effect of different caving methods on the top coal recovery along the dip direction of the working face, based on the granular dynamic theory and stochastic theory.

## 2. Engineering Background

The 8222 work face of the Tashan Coal Mine has a buried depth of 467 m, an average thickness of 15 m, and a dip angle between 2 and 5°. The immediate roof mainly consists of mudstone and sandy mudstone, and the floor is generally of mudstone and sandy mudstone. The method of one cutting and one caving is adopted in the work face, with a mining height of 4 m, a caving height of 11 m, and a mining caving ratio of 1:2.75. The cutting cycle of the shearer and the caving interval of the hydraulic support are both 0.8 m. The ZF15000/27.5/42 four-column low-level coal caving support is adopted at the working face, with a center distance of 1.75 m. The overall support is divided into 3 sections (5#-50#, 51#-95#, and 96#-130#) along the direction of the working face, where single-port, sequential, and multiwheel caving is adopted in the section with three workers. According to the field measurements, the top coal recovery rate of the work face is 78.5%. To control the gangue content for improved production management, the top coal caving is stopped when the gangue appears during caving.

## 3. Theoretical Analysis of Top Coal Caving Law

During the top coal caving process, the broken top coal moves to the caving opening under the effect of gravity. The movement of a single broken coal is mostly random and discontinuous. However, by ignoring the effect of momentary loosening during the movement of the broken top coal, the bulk movement of the top coal can be considered continuous, and the entire moving process can be simplified to the flowing in a continuous medium [21, 22]. As the movement of the top coal is entirely continuous and locally discontinuous in the caving process, it is reasonable to study the flowing of the broken top coal using the random medium flow theory [18]. Therefore, the three following basic assumptions are made: (1) The top coal above the support and the immediate roof are considered fully broken before caving. (2) The broken top coal and the direct roof are flowing continuously during the caving process. (3) The friction coefficient remains unchanged during the caving process of the broken top coal.

*3.1. Analysis Based on the Random Media Theory.* Both sides of the broken top coal are subjected to almost the same external effects along the direction of the working face. When the coal caving port is opened, the top coal particles

move under the action of gravity to form a symmetrical settlement centered at the coal caving port. The space left when the top coal particles are released is supplemented by the upper coal particles. Considering the broken top coals that have not caved yet as shown in Figure 1, the volumes of blocks  $a$ ,  $b$ ,  $c$ , and  $d$  are all  $\Delta V$ , and the friction coefficient between the coal blocks is the same. When the  $d$  block is released, it is randomly supplemented by the upper  $a$ ,  $b$ , and  $c$  blocks. The probability of block movement is inversely proportional to the distance of movement. Therefore, the filling probabilities of blocks  $a$ ,  $b$ , and  $c$  to the vacancies of block  $d$  are  $1/4$ ,  $1/2$ , and  $1/4$ , respectively. Similarly, as the layer increases, the number of participating blocks in the movement increases, and the effect of each single influencing factor is trivial on the overall movement of the block, which approximately obeys a normal distribution [21–23]. According to the central limit theorem, when the number of block layers involved in the particle movement  $j$  is large enough, the motion probability density function of the blocks can be given by

$$p(i, j) = \frac{1}{\sqrt{\pi}j} \exp\left(-\frac{i^2}{j}\right), \quad (1)$$

where  $(i, j)$  are the centroid coordinates of the block.

A previous study [18] obtained a more practical probability density function of the movement of bulk particles by introducing the granular particle flow parameters based on a series of physical similarity tests, using the Cartesian coordinate system, and it takes the following form:

$$p(x, y) = \frac{1}{\sqrt{\pi\beta}y^\alpha} \exp\left(-\frac{x^2}{\beta y^\alpha}\right), \quad (2)$$

where  $\alpha, \beta$  are parameters related to the flow properties of granular particles.

Taking the center of the coal caving opening as the origin  $O$ , a two-dimensional plane coordinate system is established with the working surface direction in  $x$  and the vertical direction in  $y$ , as shown in Figure 2.

Considering the area with a width of  $\Delta l$  and  $A(x, y)$  as the center point as the target section, when opening the coal caving port, the probability of the caving particles to travel through the neighborhood section within a unit of time is

$$P(x, y) = \int p(x, y) d\Delta l. \quad (3)$$

It can be observed that when  $\Delta l \rightarrow 0$ ,  $P(x, y) = p(x, y)\Delta l$ .

When the quantity of discharged coal per unit time is  $q$ , the number of particles passing the neighborhood section is

$$Q_1 = qP(x, y) = qp(x, y)\Delta l. \quad (4)$$

Supposing that the falling speed of particles in the neighboring section is  $\bar{v}_y$ , the number of particles passing through the neighborhood section in unit time is  $Q_2 = \Delta l\bar{v}_y$ . According to the mass conservation with  $Q_1 = Q_2$ , the following expression can be obtained:

$$\bar{v}_y = qp(x, y) = -\frac{q}{\sqrt{\pi\beta}y^\alpha} \exp\left(-\frac{x^2}{\beta y^\alpha}\right). \quad (5)$$

In the continuous flow field, the inflow and outflow of the neighborhood section are the same; that is, the flow field of the incompressible continuous granular particles must meet

$$\text{div } \vec{v} = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0. \quad (6)$$

Combining equations (5) and (6), the particle moving speed can be obtained through integral calculation as

$$\begin{cases} v_y = -\frac{q}{\sqrt{\pi\beta}y^\alpha} \exp\left(-\frac{x^2}{\beta y^\alpha}\right), \\ x = \frac{\alpha\beta q y^{\alpha-1}}{2\sqrt{\pi}\sqrt[3]{\beta y^\alpha}} \exp\left(-\frac{x^2}{\beta y^\alpha}\right). \end{cases} \quad (7)$$

For any particle B  $(x_0, y_0)$  of the top coal at the  $y_0$  layer, the tangent of its moving path is along the velocity direction with  $dx/dy = v_x/v_y$ . From equation (7), one can obtain

$$\frac{dy}{dx} = \frac{2y}{\alpha x}. \quad (8)$$

Integrating both sides of equation (8), the moving path of granular particles obeys

$$\frac{x^2}{y} = \frac{x_0^2}{y_0}. \quad (9)$$

During the downward movement of the particle, the velocity field determines the change of the displacement field. The tangential direction of the movement path of the particle at any point is collinear with the velocity direction; that is,  $v_y = (dy/dx)$ . Combining equations (7) and (9), we obtain

$$\frac{dy}{dx} = -\frac{q}{\sqrt{\pi\beta}y^\alpha} \exp\left(-\frac{x_0^2}{\beta y_0^\alpha}\right). \quad (10)$$

By integrating equation (10), it can be found that when the particle B  $(x_0, y_0)$  moves to the point N  $(x, y)$ , the amount of top coal discharged from the caving port is

$$Q = \frac{2\sqrt{\pi\beta}}{\alpha+2} (y_0^{\alpha+2/2} - y^{\alpha+2/2}) \exp\left(-\frac{x_0^2}{\beta y_0^\alpha}\right). \quad (11)$$

Combining equations (9) and (11), the sedimentation motion trajectory equation of the top coal particles at the  $y_0$  layer can be expressed by the following equation:

$$x^2 = \beta y^\alpha \ln \left[ \frac{(\alpha+2)Q}{2\sqrt{\pi\beta} (y_0^{\alpha+2/2} - y^{\alpha+2/2})} \right]. \quad (12)$$

Since the settlement path of the top coal is symmetrical, the lowest point of the settlement curve of the upper broken

particles must be on the  $y$ -axis when the coal caving port is opened. Supposing that the lowest point is  $P(0, y_{\min})$  and substituting it into equation (12), the lowest point of the sedimentation curve of broken particles in the  $y_0$  layer is obtained as

$$y_{\min} = \left[ y_0^{\alpha+2/2} - \frac{(\alpha+2)}{2\sqrt{\pi\beta}} Q \right]^{\alpha+2/2}. \quad (13)$$

Supposing that the thickness of the coal seam is  $H$ , the top coal is released when the top coal particles of layer  $H$  reach the coal caving opening for the first time, that is, when the particle  $(0, H)$  reaches the coal caving opening. As the coal caving continues, mixed gangue will appear. According to the principle of closing the door, when the gangue occurs during the top coal caving process and when the particle  $(0, H)$  reaches the lowest coal caving opening, the caving opening is closed, and the coal caving process is terminated. The amounts of pure coal released are

$$Q_H = \frac{2\sqrt{\pi\beta}}{(\alpha+2)} H^{\alpha+2/2}. \quad (14)$$

From equations (11) and (14), the coal-rock settlement curve at a height of  $H$  is

$$x^2 = \beta y^\alpha \ln \frac{H^{\alpha+2/2}}{H^{\alpha+2/2} - y^{\alpha+2/2}}. \quad (15)$$

The amounts of coal and rock particles released from the caving port are equal to the number of particles contained in the released body during the release process. When the caving height  $H$  is obtained from equations (10) and (14), the caving particle body equation can be expressed by

$$x^2 = \frac{\alpha+2}{2} \beta y^\alpha \ln \frac{H}{y}. \quad (16)$$

**3.2. Selection of the Coal Caving Method at the Working Face.** An effective coal caving method is beneficial to increasing the coal recovery rate, reducing the gangue rate, and improving the production efficiency of the working face. The key to selecting the optimal coal caving method is to determine a reasonable coal caving interval and caving sequence.

**3.2.1. Patterns of the Caving Body and Evolution of the Coal-Rock Boundary.** To determine the coal-rock settlement curve and the theoretical patterns of the top coal caving body during the caving process, the parameters  $\alpha$ ,  $\beta$  related to the flow properties of the granular caving body should be first calculated. Taking the 8222 working face of the Tashan Coal Mine as the engineering background, from the results of the physical similarity simulation and the curve fitting of the discharged body, the coal seam mining ratio is found to be 1 : 2.75, with  $a = 1.3$  and  $\beta = 0.3$ . From the working conditions of the 8222 working face and according to the above theoretical formulas (15) and (16), the coal-rock settlement curves and the evolution of the caving body with the increase

of the caving volume adopting the single-port caving are plotted using Matlab, as shown in Figure 3.

It can be seen from Figure 3 that the top coal particles move towards the caving opening under the action of gravity. With the increase of the discharged top coal, the slope of the settlement curve increases and rapidly approaches the centerline of the coal caving opening, with the foot of the curve decreasing along the axis. Moreover, as the coal caving height increases, the eccentricity  $e$  gradually decreases and the shape of the discharged body gradually changes from circular to elliptical, which differs from the traditional ellipsoid theory. The change of the geometry of the discharged body during the caving process is shown in Table 1.

When the coal caving height reaches 14.5 m, the endpoint of the top coal settlement curve reaches the coal caving opening, whereas the gangue reaches the critical mixing surface. As the coal caving continues, the end of the coal caving funnel damage and mixed gangue will occur. When the coal caving height is 15 m, the settlement curve of the fractured top coal develops outwards from the center of the caving opening, and the caving body exceeds the horizontal coal-rock boundary, resulting in an increased amount of mixed gangue.

**3.2.2. Determination of the Coal Caving Interval.** As discussed, the shape of the caving body changes from circular to elliptical with the increase of the amount of discharged coal, although it is always symmetrical with respect to the axis. The geometry of the discharged body is mainly controlled by the coal-rock settlement curve on both sides. A more developed caving body leads to a greater amount of top coal released, and the symmetrical coal-rock settlement curve can contribute to the full development of the top coal discharge. Therefore, by setting a reasonable coal caving interval and caving sequence, the coal-rock settlement curve can be controlled to ensure the integrity of the caving body and to maximize the amount of caved coal during the interval. The end of the coal caving interval is effectively the boundary of the coal and rock settlement curve after the previous caving. Therefore, the maximum amount of caved coal is observed at the two ends of the interval, and the maximum coal caving interval is determined by the distance between the settlement curves of two completely caved bodies. For the reasonable coal caving interval  $L$ , it contains  $n$  ( $n \geq 2$ ) supports, and the following expression can be obtained:

$$n = \frac{L}{l_f} = \left[ \frac{2X}{l_f} \right], \quad (17)$$

where  $l_f$  is the width of the coal caving opening, and we use  $l_f = 1.75$  m in this study.

Combining equations (15) and (17), the number of supports in the interval is

$$n = \frac{2\sqrt{\beta y^\alpha \ln H^{\alpha+2/2} / H^{\alpha+2/2} - y^{\alpha+2/2}}}{l_f}. \quad (18)$$

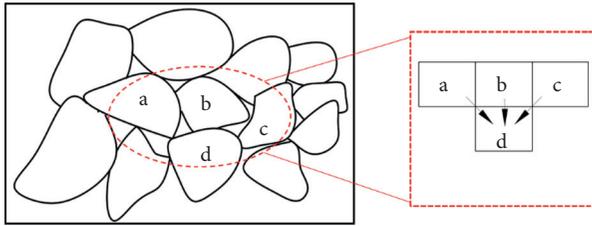


FIGURE 1: Movement of the broken block.

**3.2.3. Coal Caving Sequences within Each Interval.** To ensure a symmetric space for coal caving, the first step is to open the coal caving openings 1# and  $n$ # at both ends of the caving interval until the gangue appears. The same coal-rock settlement curves are formed above the two coal caving openings, which are symmetrical at  $m$ # and tangential to the horizontal coal-rock boundary. As shown in Figure 4(a), an inverted bowl-shaped coal body (shaded area with red boundaries) occurs between the two coal caving openings, surrounded by the coal-rock boundary and the floor. Then, the next step is to turn on the coal caving opening  $m$ # until the gangue appears, which forms a pure coal body similar to that at the end, as shown in the area with magenta boundaries in Figure 4(a). Within the interval, a symmetric solid coal area (surrounded by the coal-rock subsidence curve) is formed again, as shown in the shaded area in Figure 4(b). Due to the symmetry of the entire coal caving space, a symmetrical coal caving space will be formed again when the caving openings  $m-t$  and  $m+t$  are opened in the interval, as shown in the area with blue boundaries in Figure 4(b). A similar procedure is applied until the entire caving process is completed in the interval. The coal caving sequence in the interval follows 1 ( $n$ )- $m+t$  ( $m-t$ )-..., until all coal caving openings are opened and the coal caving in the interval is completed.

Based on the above analysis, under the engineering background of the 8222 working face, the optimal caving interval  $n=7$  is obtained by substituting the relevant parameters into equation (18), and the caving sequence is found to be 1-7#, 4#, 2-6#, and 3-5#.

## 4. Verification Using the Physical Similarity Simulation

**4.1. Model Development.** In this study, two-dimensional physical similarity simulation experiments were conducted based on the mining and geological conditions of the studied working face. The dimension of the test bench was  $150 \times 17 \times 50$  cm with the geometric similarity ratio at 1:87. Caving openings of the support were formed using  $2 \times 4$  cm square steel to represent the 1.74 m caving opening in the mine, and a total of 29 supports were placed in the model (with an actual distance of 50.46 m). Coal caving was simulated by withdrawing the square steel to open the coal caving port of the support, and 7 square steels were placed on both sides to ensure a stable boundary condition. The supports in the experimental area are numbered 1#~15# from left to right in Figure 5. In the experiment, black stones

(5 cm in layer thickness) with a particle size between 6 and 12 mm were used to simulate the broken top coal with a height of 12 cm, which contained two layers of white stones (1 cm in layer thickness) with the same particle size as the marking layer, and the total weight was 29.58 kg. Black stones with a particle size between 15 and 25 mm were used to simulate the immediate roof with a height of 25 cm, and white stones with the same particle size were used as the marking layer, with a total weight of 61.63 kg. The initial state of the physical similarity model is shown in Figure 5.

**4.2. Experiment Setup.** To verify the rationality of the symmetrical sequential caving method, the tests conducted in this study compared both the top coal recovery rate and the gangue rate of the two different sequential caving approaches. The details of the coal caving sequence of the studied caving method are summarized in Table 2.

**4.3. Results and Analysis.** Development of the coal settlement curve reflects the changes in the top coal caving condition. The effectiveness of the selected caving method is evaluated by comparing the shape of the coal-rock settlement curve and the evolution of the remaining space of the two different interval coal caving methods. The coal-rock settlement curves of the two caving methods are shown in Figure 6.

It can be seen from Figure 6 that, following the principle of closing the door when gangue appears, the coal caving outlets 1#, 7#, and 15# were all opened at the same time. The coal-rock settlement curves of the coal caving openings 1# and 7# of Scheme 1 intersected with each other, forming a relatively symmetric area of pure coal. In Scheme 2, the coal-rock settlement curves of the coal caving openings 7# and 15# also intersected, but the coal area was inclined to the coal caving port 7#. According to the analysis in Section 4, the symmetrical coal area can contribute to the full development of the discharged body. Then, opening caving ports 4# and 11# and following the principle of closing the door when gangue appears, after closing the coal caving port, the coal-rock settlement curve of the interval is shown in Figure 7.

The coal-rock settlement curve generally descends after opening coal caving port 4. The coal-rock settlement curves between coal caving ports 1#-4# and 4#-7# form two identical coal areas depicted by the white-dotted line in Figure 7. However, the coal-rock settlement curves between coal caving ports 7#-11# and 11#-15# form two relatively symmetrical coal areas with different sizes, as shown by the red-dashed lines in Figure 7.

As the coal caving port continues to be opened, the coal-rock settlement curves continued to descend for the two schemes of sequential interval coal caving method. In Scheme 1, the coal-rock settlement curve always maintains symmetry above the support, which is beneficial to maximizing the top coal recovery and improving the management of subsequent workers. However, the size of the coal-rock settlement curve above the support becomes inconsistent in the subsequent caving process, due to the asymmetric coal-rock settlement curve formed after the first coal

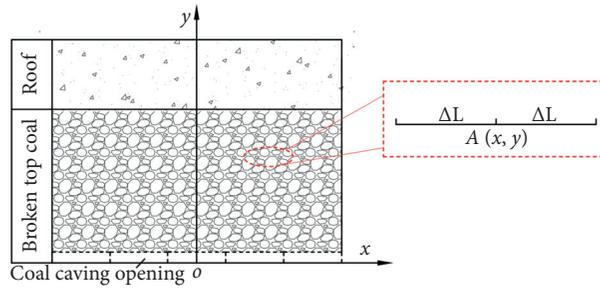


FIGURE 2: Two-dimensional coordinate system along the working face.

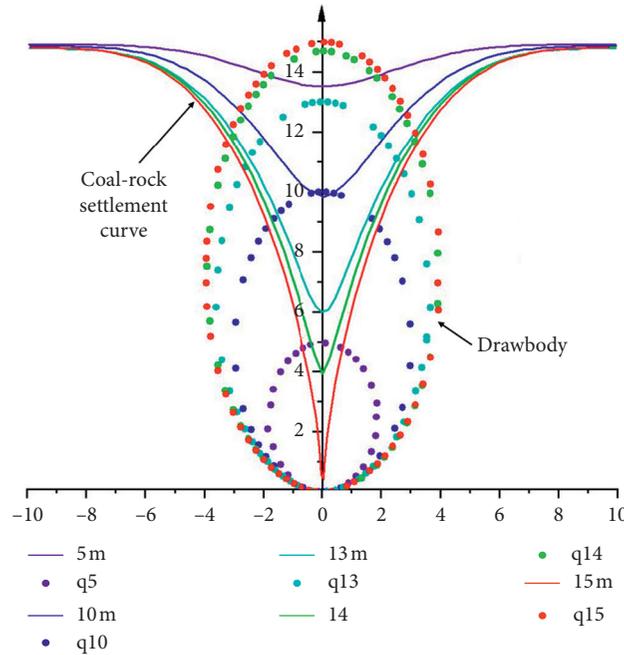


FIGURE 3: Coal-rock settlement curves and the evolution of the caving body. The solid line indicates the evolution of the settlement path of the top coal particles, and the dotted line represents the evolution of the caving body during the coal caving process.

TABLE 1: Geometric parameters of the caving body.

Height $H$	5	10	13	14	15
Width $l$	3.8	6	6.8	7.4	7.8
Eccentricity $e$	0.760	0.600	0.523	0.529	0.520

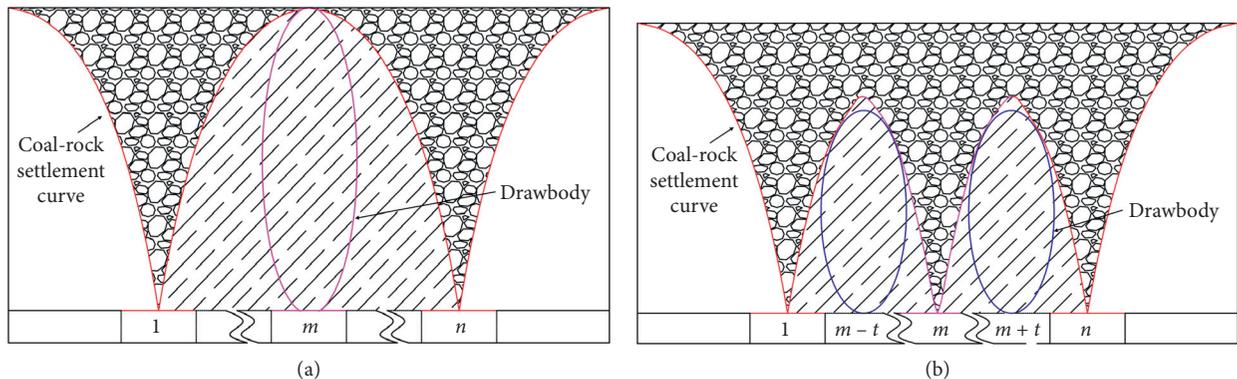


FIGURE 4: Illustration of the sectional interval symmetrical coal caving method.

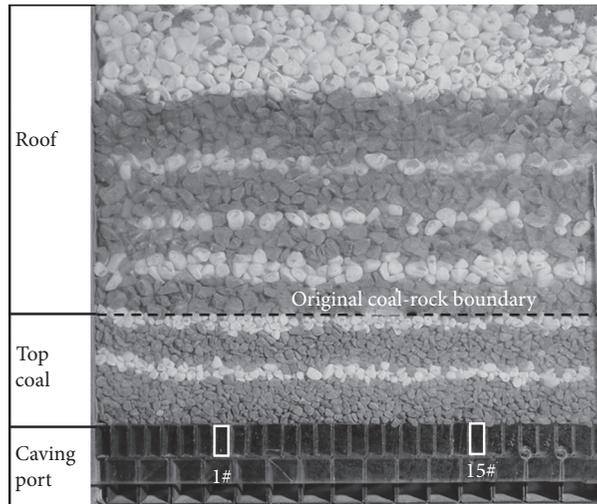


FIGURE 5: Initial state of physical similarity model.

TABLE 2: Caving sequences of different coal caving methods.

Serial number	Coal caving interval	Caving sequence of support
Scheme 1	7 supports	1-7#, 4#, 2-6#, 3-5#
Scheme 2	9 supports	7-15#, 11#, 3-7#, 2-8#, 4-6#

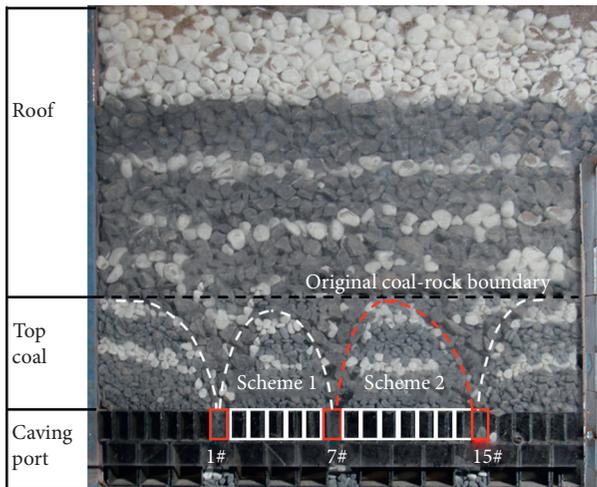


FIGURE 6: Coal-rock settlement curves for the two coal caving schemes (1#, 7#, and 15#).

caving in Scheme 2. The coal-rock settlement curve between the two coal caving openings turns symmetric as the coal caving interval decreases. Since the two coal areas are inconsistent in size above the support, the amount of caved coal is uneven during each caving, resulting in coal waste in the coal caving process and becomes difficult to control in practice.

### 5. Optimization of the Coal Caving Method at the 8222 Working Face

From the above analysis, the interval symmetrical caving method was adopted in the 8222 working face. The coal

caving interval was set to be the width of 7 supports (8.75 m), and the symmetrical coal caving is adopted during each interval. The amount of caved top coal for two different caving methods is listed in Table 3. It can be shown that the largest amount of caved coal was observed at the support on both ends and in the middle, whereas the amount of caved coal gradually decreases for the remaining caving openings according to the opening sequence. Based on the field measurement, the top coal caving rate of the interval symmetrical caving is 95% with a caving time of 12,960 s; the top coal caving rate of traditional caving is 78% and the caving time is 10,502 s.

From the results of the caving volume of the interval symmetrical caving method, the amount of caved coal in the first two coal cavings accounts for 68% of the total caving volume, whereas the amount of caved coal in the last coal caving only accounts for 12%. To improve the caving efficiency and reduce the overall gangue content rate, excessive caving can be adopted during the first two cavings to shorten the coal caving time of the last caving. Compared with the traditional coal caving method, the interval symmetrical coal caving method increased the amount of caved coal by 21.7%, and the coal recovery rate increased by 17%. With the same coal caving interval, the caving time is shortened by 23.4% for the interval symmetrical caving, compared with the sequential caving. In general, the interval symmetrical coal caving always maintains the symmetry of the coal-rock settlement curve, enables a full development of the top coal caving bodies, effectively reduces coal losses during coal caving, and greatly improves the recovery rate of top coal. Moreover, the method is also convenient for on-site manual operation, which enhances the controllability of the coal caving process.

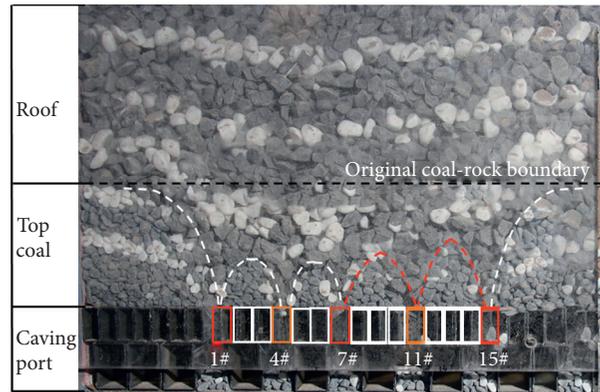


FIGURE 7: Coal-rock settlement curves for the two coal caving schemes (4# and 11#).

TABLE 3: Performance of different coal caving methods.

	Interval symmetrical caving	Single-port multiround sequential caving
Top coal discharge/kg	67.41	50.35
Recovery rate/%	95%	78%
Caving time/s	105024 s	129600 s

## 6. Conclusions

The following conclusions can be drawn from this study:

- (1) The broken top coal discharges as the caving port opens in the fully mechanized caving mining. Although the movement of single particles in the caving process is random and disordered, the movement of a large number of particles generally obeys the normal distribution. By combining the statistical probability theory and random medium flow theory, the top coal caving body and coal-rock settlement curve equations are established along the direction of the fully mechanized caving working face. According to the derived equations, the settlement curves of the caving body and coal rock are axial symmetrical, and the foot of the coal-rock settlement curve decreases during the caving process; as the amount of coal caving increases, the shape of the caving body gradually changes from circular to elliptic.
- (2) According to the coal settlement curve and the caving body equation described in this study, the interval symmetrical coal caving is found to be the optimal mining method. The coal caving interval  $L$  is defined as the sum of the radii of the coal and rock settlement curves formed by the two largest caving bodies. In practice,  $L$  is normally multiple times of the support number. The symmetrical coal-rock settlement curve also leads to a symmetrical subsequent caving space, which is conducive to a fully developed caving body. The caving sequence is symmetrical on both sides during each interval, which results in a consistent shape for the top coal caving body, and is beneficial to manual control

during the coal caving process for improved top coal recovery.

- (3) Compared with the single-port multiround sequential caving method, the proposed interval symmetrical caving can increase the amount of caved coal and the top coal caving rate by 21.7% and 17%, respectively, reducing effectively the coal losses at the working face. In addition, the coal caving time is shortened by 23.4% with the same interval supports. According to the characteristics of interval symmetrical coal caving, the coal caving time may be shortened in the later stage of coal caving to improve the production efficiency of the working face.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that there are no conflicts of interest.

## Acknowledgments

This work was supported by the special fund project for technology innovation and entrepreneurship of Tian Di Science & Technology Co., Ltd. (2020-TD-ZD016), National Key Research and Development Program (2018YFC0604506), and Technology Innovation and Entrepreneurship Fund Special Project of Tian Di Science & Technology Co., Ltd. (2019-TD-QN006).

## References

- [1] S. Yan, Y. U. Lei, and Q. Liu, *Full-mechanized Top Coal Caving: Forming Mechanism and Application of "Combined Short Hanging Beam-Hinged Beam Structure"*, China Coal Industry Publishing House, Beijing, China, 2017.
- [2] J. Wang, *The Theory and Technique on the Thick Coal Seam Mining*, Metallurgical Industry Press, Beijing, China, 2009.
- [3] J. Wang and Q. Fu, "Low top-coal caving off the loose medium flow theory and application," *Journal of China Coal Society*, vol. 27, no. 4, pp. 337–341, 2002.
- [4] J. Wang, Z. Li, Y. Chen, and H.-F. Zheng, "The experimental study of loose medium flow field on the longwall top-coal caving," *Journal of China Coal Society*, vol. 29, no. 3, pp. 260–263, 2004.
- [5] J. Wu and Y. Zhang, "Study on the basic theory of longwall top-coal caving system," *Journal of China University of Mining and Technology*, vol. 27, no. 4, pp. 332–335, 1998.
- [6] J. Zhang, *Simulation Study on the Three-Dimensional Caving Mechanism of Loose Top-Coal in Longwall Top-Cpal Caving Mining Panel*, China University of Mining & Technology, Beijing, China, 2017.
- [7] D. Tian, S. H. I. Hao-yu, E.-J. Fu et al., "Study on relationship between coal caving step distance and top coal caving step distance and top coal caving recovery rate based on ellipsoid theory," *Coal Science and Technology*, vol. 43, no. 5, pp. 51–53, 2015.
- [8] Q. Liu, M. Tu, and B. Fu, "Study on mining and caving ratio of fully mechanized top coal caving mining face affected to top coal recovery rate," *Coal Science and Technology*, vol. 41, no. 3, pp. 55–58, 2013.
- [9] J. Wang, W. Chen, and J. Zhang, "Optimization study on drawing technique of longwall top-coal caving in extra-thick coal seam based on BBR system," *Coal Engineering*, vol. 48, no. 2, pp. 1–4, 2016.
- [10] J. Wang, S. Yang, G. Huang et al., "Research on top coal tracker of fully mechanized top coal caving mining and measurement of top coal recovery rate," *Coal Science and Technology*, vol. 41, no. 1, pp. 36–39, 2013.
- [11] J. Wang, J. Zhang, and C. Yi, "Research on technology of improving top-coal recovery in longwall top-coal caving mining based on BBR system," *Journal of Mining Science and Technology*, vol. 1, no. 1, pp. 38–48, 2016.
- [12] J. Wang, W. Wei, and J. Zhang, "Theoretical description of drawing body shape in an inclined seam with longwall top coal caving mining," *International Journal of Coal Science & Technology*, vol. 7, no. 1, pp. 182–195, 2020.
- [13] B.-X. Huang, C.-Y. Liu, and Q.-Y. Cheng, "Relation between top-coal drawing ratio and refuse content for fully mechanized top coal carving," *Journal of China Coal Society*, vol. 32, no. 8, pp. 789–793, 2007.
- [14] B.-X. Huang, C.-Y. Liu, H. Niu et al., "Research on coal-gangue flow field character resulted from great cutting height fully mechanized top coal caving," *Journal of Mining & Safety Engineering*, vol. 25, no. 4, pp. 415–419, 2008.
- [15] N. Zhang and C. Liu, "Arch structure effect of the coal gangue flow of the fully mechanized caving in special thick coal seam and its impact on the loss of top coal," *International Journal of Mining Science and Technology*, vol. 26, no. 3, pp. 593–599, 2016.
- [16] S. Yan, H. Zhang, Q. Liu et al., "The theoretical study on loss rate of top coal and quantitative characteristics of piled waste," *Journal of China Coal Society*, vol. 34, no. 11, pp. 1441–1445, 2009.
- [17] D. Zhu, Z. Chen, Y. Chang et al., "Study on top coal caving law of fully-mechanized top coal caving mining based on random medium theory," *Coal Science and Technology*, vol. 46, no. 1, pp. 167–174, 2018.
- [18] B. Yu, D. Zhu, and Z. Chen, "Top-coal drawing law of LTCC mining based on stochastic medium theory," *Journal of China Coal Society*, vol. 42, no. 6, pp. 1366–1371, 2017.
- [19] C. Liu, H. Li, Y. Zhou et al., "Method of synergetic multi-windows caving in longwall top coal caving working face," *Journal of China Coal Society*, vol. 44, no. 9, pp. 2632–2640, 2019.
- [20] C. Liu, *Research on the Method of Synergetic Multi-Windows Top Coal Caving and the Mechanism of Coal-Gangue Identification in Longwall Top Coal Caving Working Face*, Henan University of Engineering, Zhengzhou, China, 2018.
- [21] Y.-C. Zhang and F. Gao, *Congtinuum Mechanics Fundamentals and Application*, China University of science and Technology Press, Shanghai, China, 2019.
- [22] Y. Ren, *Random Medium Drawing Theory and its Application*, Metallurgical Industry Press, Beijing, China, 1994.
- [23] J. Cheng, S. Xie, and C. Pan, *Probability Theory and Mathematical Statistics*, Higher Education Press, Beijing, China, 2008.