

Article

Optimizing Simulation and Analysis of Automated Top-Coal Drawing Technique in Extra-Thick Coal Seams

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Abstract: A particle element approach based on continuum-discontinuum element method (CDEM) is applied to optimize the automated top-coal drawing techniques in extra-thick coal seams. Numerical models with 100 drawing openings are created according to the field engineering geological conditions of Tongxin coal mine in China. An automated coal drawing control approach in numerical modelling based on time criterion is proposed. The rock mixed rate, top-coal recovery rate and the variance of the drawn top coal amount are counted and set as the statistical indicators to evaluate the top-coal drawing techniques. The traditional top-coal drawing criterion, “rocks appear, close the opening”, leads to low recovery of top coal and waste of coal resources in extra-thick coal seams, significantly weakening the transport stability and efficiency of the scraper conveyer. A three-round unequal time top-coal drawing technique is proposed for automated top-coal drawing. Three drawing openings, corresponding to the three top-coal drawing rounds respectively, are working at the same time; in each round, the top-coal drawing sequence is from the first drawing opening at one end of the working face to last drawing opening at another end; the drawing time of each round is not equal and increases with the round number. The numerical inversion approach of iteration steps can be used for real top-coal drawing time estimation and automated drawing process design to achieve a better top coal drawing effect, while the exact time for each drawing round still needs to be corrected by engineering practice.

Keywords: extra-thick coal seams; automated top-coal drawing; particle element method; optimization analysis

1. Introduction

The reserves and production of thick coal seams account for about 45% of underground coal resources and output in China. As a major mature mining method used in thick coal seams, the longwall top-coal caving technique (LTCC) has been used in China for over 30 years for industrial testing and large-scale application [1–3]. However, because of the complex environment of underground longwall working face, LTCC process can only be achieved by manual operation for a long time, which greatly restricts the standardization of LTCC process flow and top-coal caving efficiency. The traditional LTCC process is shown in Figure 1. In Figure 1, top-coals are continually drawn out from the drawing opening until all fractured top coals are recovered and the waste rocks appear on scraper conveyer, then the tail canopy of hydraulic support will be adjusted and the drawing opening will be closed. For the traditional top-coal caving technique, the coal drawing termination condition is “close coal

drawing opening once rocks appear”, but that is very difficult for underground workers to control it accurately due to the poor resolution of coal-rock boundary behind hydraulic supports.

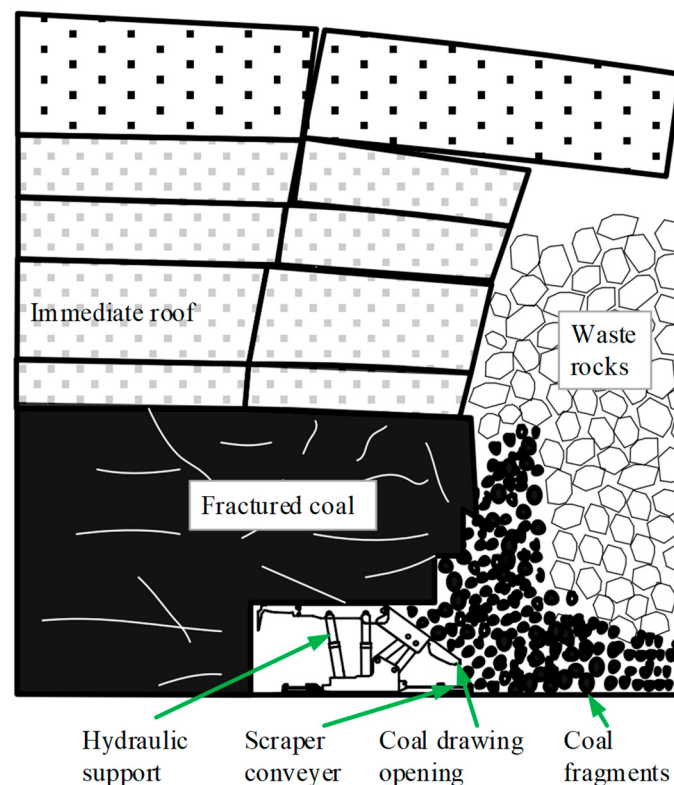


Figure 1. Schematic of the top-coal fracturing and drawing process in LTCC.

Currently, with the development of artificial intelligence and automated control technology, great progress has been made in automated top-coal caving technology. Some automated top-coal caving working faces have been established in China for mining extra-thick seams, such as Tongxin coal mine and Tashan coal mine. In automated LTCC, the opening and closing action of drawing openings is carried out according to the pre-given automation program. To facilitate management, these actions are set as a function of time, so the traditional criterion, “rocks appear, close the opening”, is no longer used as the top-coal drawing criterion. Naturally, an important issue should be raised, that is, how to optimize the automated top-coal drawing process and determine the automated operation time of opening and closing of drawing openings scientifically to ensure the improvement of top-coal drawing efficiency, reduce the waste rock content and improve the top-coal recovery rate.

Optimization of the automated top-coal drawing technique depends on the theory of top-coal caving and top-coal movement law. The ore-drawing ellipsoidal theory was adopted to explain the movement characteristics of top-coal caving in the early stage. Thereafter, the variant ellipsoid theories based on experimental measurement of top-coal particle movement were put forward [4–6]. A loose medium flow field theory was developed to reveal the movement process of top-coal, indicating the quadratic curve can fit the moving coal and rock boundary [7,8]. 3-D experiments and numerical simulations were conducted to investigate the movement and flow law of top-coal under caving mining technique [9,10]. A boundary-body-ratio (BBR) research system for top-coal caving mining was developed to reveal the top-coal flow mechanism under the condition of lower drawing opening. In the BBR system, a simplified parabolic model was proposed to describe the development process of the top-coal boundary in normal top-coal drawing cycles; to improve the recovery ratio and reduce the rock mixed ratio of top-coal, a method for selecting reasonable drawing technique parameters and controlling the shape of the boundary of top-coal was given [11]. A longwall top-coal cavability

assessment criterion based on top-coal cavability rating (TCCR) was proposed by Vakili [12] to improve the overall understanding of the caving mechanism in LTCC technology. TCCR system incorporated the top-coal recovery (TCR) for estimating the potential top-coal recoverability and the main caving distance (MCD) for predicting an approximate span length for the initial top-coal caving. Besides, an ultrasonic-based method integrating fracture detection system and ultrasonic wave velocity was developed to characterize top-coal cavability [13]. However, few theoretical studies focus on automated top-coal drawing at present.

It is difficult to monitor the movement of top-coals and waste rocks in gob or behind the hydraulic support due to the restriction of coal mine safety regulations and the complex underground environment. Moreover, physical similarity simulation experiments in laboratory can only be conducted to investigate the top-coal drawing process under simple boundary conditions. Therefore, numerical simulation has become an effective means to study the top-coal drawing mechanism. A case study of top-coal caving in Omerler underground mine based on FLAC3D developed by Itasca International Inc in Minnesota of America was studied by Yasitli and Unver [14]. Moreover, a mine-scale analysis was performed by COSFLOW developed by CSIRO Exploration and Mining of Australia to evaluate various LTCC parameters for a mine [15]. The continuum methods show good accuracy in calculating stress distribution of intact geological rock body, but is difficult to simulate the progressive fracture of rock mass, especially the whole process of top-coal damage, fracture, loosening and flow. Discontinuum methods are more adopted to simulate the flow process of top-coal, such as the particle flow code (PFC) and the universal distinct element code (UDEC) developed by Itasca International Inc in Minnesota of America. By PFC2D, Xie [3] proved that an arch structure can be formed under gravity conditions but can be easily destroyed by vibration during the top-coal caving process. Besides, the continuum-discontinuum element method (CDEM) was developed recently, which conducts finite element calculation in the continuous domain and conducts discrete element calculation in the discontinuous domain [16–18]. CDEM has been used in modelling the progressive failure of rock samples in meso-scale and civil and underground engineering problems in large scale [19–21]. Moreover, CDEM also is used in simulating the overburden strata movement in coal mine longwall panel, and the simulation results are very close to the field measurements [22]. CDEM also shows good application prospects in simulating top-coal caving. Zhang et al. proposed a new CDEM model to study top-coal caving in extra-thick coal seams, which integrates continuous block elements and cohesive particle elements to simulate the dynamic mining pressure induced by periodic breaking of overlying strata and the top-coal flow, respectively [23].

In this study, CDEM is conducted to evaluate and optimize the automated top-coal drawing techniques in extra-thick coal seams. Numerical models with 100 drawing openings are created according to the field engineering geological conditions of Tongxin coal mine in China. The top-coal drawing process under single drawing opening is modeled to investigate the top-coal drawing mechanism and verify the numerical approach of top-coal drawing compared to the top-coal caving theory. Then, the top-coal drawing process under different top-coal thicknesses are studied to clarify the effect of the top-coal thickness on top-coal recovery rate and rock mixed rate. The automated collaborative coal drawing process under multiple coal drawing openings is developed based on Bergmark-Roos model, and an automated coal drawing control approach in numerical modelling based on time criterion is proposed. The rock mixed rate, top-coal recovery rate and the variance of the drawn coal amount are automatically counted and set as the statistical indicators to evaluate top-coal drawing techniques in extra-thick coal seams. Finally, an optimal automated coal drawing technique is proposed. This study is of significance to provide a numerical approach for top-coal drawing technique optimization in extra-thick coal seams.

2. Numerical Approach for Modeling Top-Coal Drawing

2.1. Theories of Particle Element in CDEM

A linked bar model is built between two particle elements to simulate the top-coal caving process from initial intact state to fragmentation [24,25]. As shown in Figure 2, the linked bar model is regarded as a rectangle, by which the contact force or cohesive force between two particle elements can be calculated. The long edge of the rectangle is the sum of the radius of the two particles, while the short edge is equal to the diameter of the smaller particle. Based on the linked bar model, a surface contact relationship is established between the two particle elements, in which the equivalent contact area A_c is the projected area of the smaller particle. A_c is mainly used for calculating the contact stiffness between two particle elements. The parameters of contact stiffness can be obtained by:

$$\begin{cases} K_i = E_i A_c (R_1 + R_2), i = 1, 2 \\ A_c = \min\{2R_1, 2R_2\} \end{cases} \quad (1)$$

where K_i and $\tilde{E}_i$ are the contact stiffness and modulus tensors, respectively; variable X_i represents normal components when the subscript $i = 1$ and represents tangential components when subscript $i = 2$; R_1 and R_2 are the radius of the two particle elements, respectively.

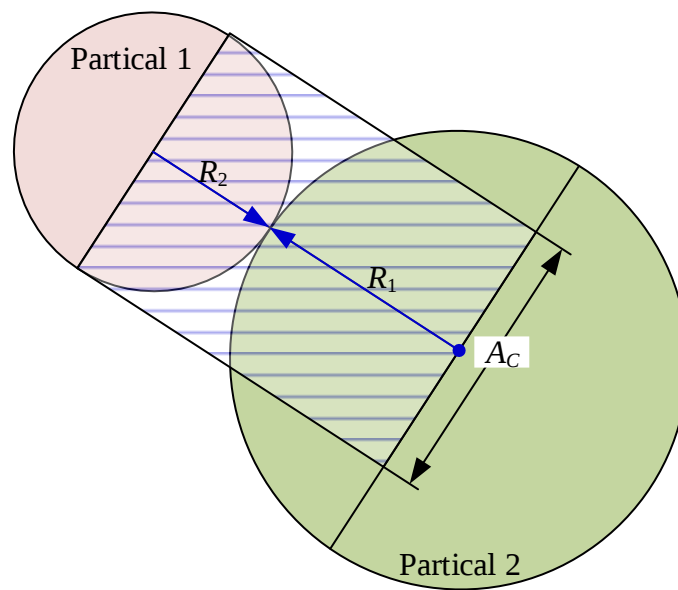


Figure 2. The linked bar model.

The contact forces and momentum between two contact particle elements is calculated by:

$$\begin{cases} F_i(t + \Delta t) = F_i(t) - K_i \Delta u_i, i = 1, 2 \\ M_i(t + \Delta t) = M_i(t) - K_i J_i \Delta \theta_i / A_c \end{cases} \quad (2)$$

where $F_i(t + \Delta t)$ and $F_i(t)$ are the contact forces at the time of $t + \Delta t$ and t , respectively; $M_i(t + \Delta t)$ and $M_i(t)$ are the moments at the time of $t + \Delta t$ and t , respectively; J_i and $\Delta \theta_i$ are the moment of inertia and incremental angle difference between two contact particle, respectively; Δu_i is the contact displacement increment.

According to the Mohr-Coulomb criterion and maximum tensile stress criterion, the contact forces is calculated by:

$$\begin{aligned} &\text{If } F_1 - TA_c \geq 0, \text{ then } F_1 = F_2 = 0, T = C = 0; \\ &\text{If } F_2 - F_1 \tan(\varphi) - CA_c \geq 0, \text{ then } F_2 = F_1 \tan(\varphi) = 0, T = C = 0 \end{aligned} \quad (3)$$

If any of the inequality in Equation (4) is satisfied, the contact between particles will no longer transmit the moment:

$$\begin{aligned} &\left(\frac{-F_1}{A_c} + \frac{M_2}{I} R_{ave} \right) - T \geq 0; \text{ or} \\ &\left(\frac{|F_2|}{A_c} + \frac{M_1}{I} R_{ave} \right) - [F_1 \tan(\varphi) + C] \geq 0 \end{aligned} \quad (4)$$

where $R_{ave} = (R_1 + R_2)/2$; T , C and φ are the tensile strength, cohesion and internal friction angle, respectively; I is the moment of inertia.

In a 2-D numerical model, the contact state between rigid boundary and particle element is determined by the relative position between particle center and rigid wall edge. The contact pair will be created when the distance between particle center and rigid wall edge is less than or equal to the radius of the particle, that is:

$$d = |V_{kl} \cdot n| \leq R \quad (5)$$

where d is the distance between particle center and rigid wall, l is the endpoint of the rigid wall, V_{kl} is the relative position vector for the particle center k to the endpoint l , n is the unit normal vector of the rigid wall, and R is the radius of the particle element. The method of determining contact between particle and rigid wall boundary is shown in Figure 3. Once the contact pair between particle and rigid wall is established, the normal and tangential contact behaviors will be automatically generated.

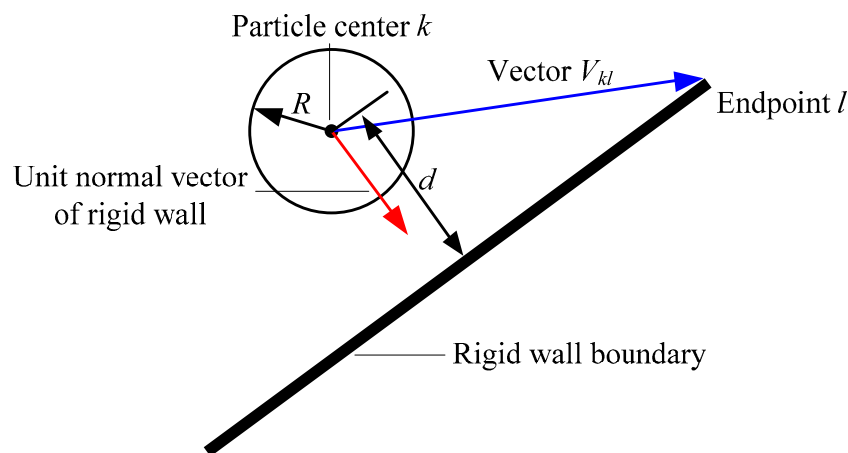


Figure 3. Schematic for determining the contact between a particle and a rigid wall boundary.

2.2. Theoretical Model of Top-Coal Drawing

Top-coal masses are crushed into fragments by the overburden pressure and the cyclic support force of hydraulic support, and then flow out through drawing openings. Because the structure of hydraulic supports does not significantly affect the coal drawing process on the cross section parallel to the working face, the Bergmark-Roos model can be adopted to analyze the top-coal drawing process under single drawing opening condition [26,27].

2.2.1. The Hypotheses of the Bergmark-Roos Model

- (1) Fragments move along straight lines from their initial location points to drawing opening, and then are removed continuously from model.
- (2) Fragments are only controlled by gravity and frictional forces between fragments.
- (3) The acceleration of each fragment is constant during the whole moving process.

2.2.2. Top-Coal Motion Equations

The schematic of Bergmar-Roos model is illustrated in Figure 4.

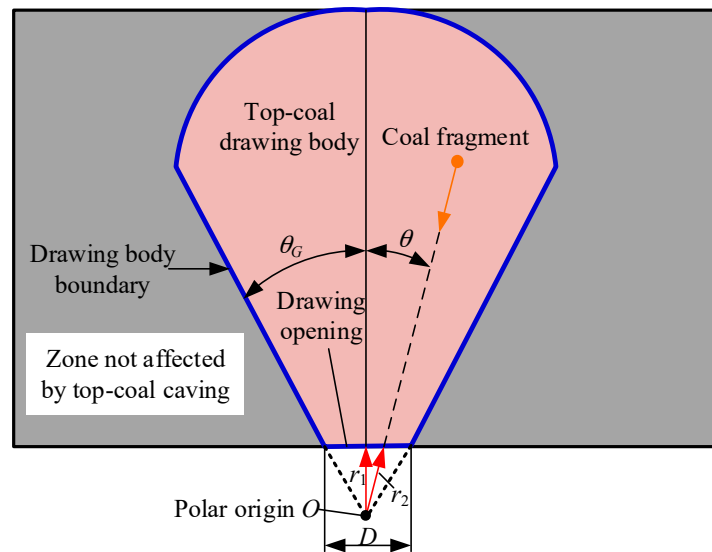


Figure 4. The schematic of the Bergmark–Roos model.

The acceleration of single top-coal fragment is:

$$\begin{cases} a_r(\theta) = g(\cos \theta - \cos \theta_G) \\ \theta_G = 45^\circ - \theta_0/2 \end{cases} \quad (6)$$

where $a_r(\theta)$ is the acceleration of single top-coal fragment, g is the gravity acceleration, θ is the angular coordinate of coal particles in r - polar coordinate system shown in Figure 4, θ_G is the boundary angle at which the friction force component in vertical direction equals particle weight and the broken coal fragment does not flow, and θ_0 is internal friction angle of coal fragments.

The location function of the top-coal fragment in drawing process is:

$$r(\theta, t) = r_0(\theta, t) - a_r(\theta)t^2/2 \quad (7)$$

When the top-coal fragment moves to the drawing opening, the moving time is t_1 , so the initial coordinate of the top-coal fragment is:

$$r_0(\theta) = r_2 + a_r(\theta)t_1^2/2 \quad (8)$$

When $\theta = 0$, by substituting Equation (6) into Equation (8), the largest distance from the polar origin to the drawing body boundary $r_{\max}$ can be calculated as:

$$r_{\max} = r_1 + g(1 - \cos \theta_G)t_1^2/2 \quad (9)$$

where r_1 is the vertical distance from the polar origin to the drawing opening, as illustrated in Figure 4.

Obviously, according to Equation (9), t_1 can be represented as:

$$t_1 = [2(r_{\max} - r_1)/g(1 - \cos \theta_G)]^{1/2} \quad (10)$$

By substituting Equations (6) and (10) into Equation (8), the initial coordinate of the top-coal particle is obtained by:

$$r_0(\theta) = r_2 + 2(r_{\max} - r_1)(\cos \theta - \cos \theta_G)/(1 - \cos \theta_G) \quad (11)$$

As shown in Figure 4, the distance from the coordinate origin to any point on the drawing opening is:

$$r_2 = r_1 / \cos \theta = D/2 \tan \theta_G \cos \theta \quad (12)$$

By substituting Equation (12) into Equation (11), the boundary of the drawn top-coals can be obtained by:

$$r_0(\theta) = (r_{\max} - \frac{D}{2 \tan \theta_G}) \frac{\cos \theta - \cos \theta_G}{1 - \cos \theta_G} + \frac{D}{2 \tan \theta_G \cos \theta} \quad (13)$$

where D is the drawing opening size, which equals the width of the tail canopy of hydraulic support.

3. Numerical Model and Simulation Scheme

3.1. Numerical Model

In this study, the Tongxin coal mine is chosen as an engineering background. The top-coal drawing is performed in every mining cycle (one cutting with one drawing), and the cutting height to caving height is 1:3. The length of the working face is 200 m, the average thickness of the coal seams is about 15 m, the advancing length of the longwall panel is 2184.5 m, and the service life of the panel is 21.1 months. 3-D numerical modeling of automated top-coal drawing in extra-thick coal seams is a huge and complex task. Therefore, the automated top-coal drawing process is studied by decomposing into two directions, the cross sections parallel and perpendicular to working face, respectively. Coordinating the multiple drawing openings to obtain more coal resources as conveniently as possible is the main purpose of our current research, so a 2-D particle element model is established to investigate the drawing process of top-coal on the cross section parallel to longwall working face, as shown in Figure 5. The rigid wall boundary is used to collect the drawn top-coal particles in automated top-coal drawing process. This study assumes that all the top-coals have been broken and accumulated above the drawing openings. There are only the resistances generated by the interaction between coal fragments, so the strength parameter values of top-coal particles are set to 0, as shown in Table 1.

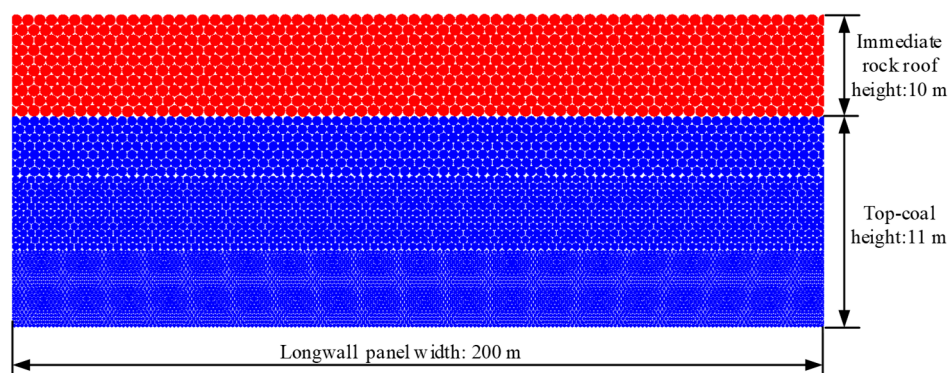


Figure 5. Particle model of top-coals and immediate rock roof.

Table 1. The mechanical parameter values of coal and rock used in this study.

Rock Layer Type	Density (kg/m ³)	Elastic Modulus (Pa)	Poisson's Ratio	Tensile Strength (Pa)	Cohesion (Pa)	Internal Friction (°)
Coal Seams	1373	2×10^8	0.29	0	0	44.82
Immediate Roof	2542	4×10^8	0.23	0	0	33.6

3.2. Simulation Scheme

First, the coal drawing process under single drawing opening is simulated to verify the numerical approach according to top-coal drawing theory (the Bergmark-Roos model). From the drilling histogram of Tongxin coal mine, the top-coal thickness ranges from 9 m to 23 m. Large variation in top-coal thickness may significantly affect the final top-coal recovery rate, so secondly, the top-coal drawing simulations under different top-coal thicknesses are conducted. Finally, the top-coal height with 11 m is kept as a constant condition for simulating the top-coal drawing process under multi-openings cooperation and for optimizing the automated top-coal drawing technique.

To comprehensively compare with different top-coal drawing techniques, some statistics about drawn top-coal amount need to be collected and calculated. As the top-coal drawing process is simulated by a 2-D model, the drawn top-coal amount from each drawing opening is measured in area unit m² as the statistical unit. The average amount of drawn top-coal indicates the total amount of the working face, and m² is also used as its statistical unit. The variance of drawn top-coal amount represents the difference in drawn top-coal amount for 100 drawing openings, so its statistical unit is m⁴, which reflects the transport efficiency of scraper conveyer. These statistics are obtained by:

$$\bar{X} = \frac{1}{m}(x_1 + x_2 + \cdots + x_m) \quad (14)$$

$$s^2 = \frac{1}{m}\{(x_1 - \bar{X})^2 + (x_2 - \bar{X})^2 + \cdots + (x_m - \bar{X})^2\} \quad (15)$$

where $x_1, x_2, \cdots, x_m$ are the amount of drawn coal from each drawing opening, respectively; m is the number of drawing openings for top-coal drawing; $\bar{X}$ is the average amount of the drawn top-coal; and s^2 is the variance of the drawn top-coal.

The top-coal recovery rate is also an important indicator for evaluating top-coal drawing technology. In this study, the recovery rate is determined by referring to the 'Tongxin coal mine practice', which is obtained by the ratio of the total drawn top-coal amount to the total coal amount above all the hydraulic supports. To ensure safe support on both sides of the working face, there are three and four hydraulic supports at the two ends of working face which does not draw out top-coals, respectively. In numerical simulation, the total number of coal drawing openings is 100, and the width of each drawing opening is 1.75 m, so the width of all coal drawing openings used for top-coal caving is 175 m. To obtain the top-coal recovery rate that can characterize the engineering significance, the width of 12.25 m of the seven hydraulic supports without coal drawing is also considered.

4. Numerical Simulation Results

4.1. Verification of Numerical Approach

The top-coal drawing process under a single drawing opening is simulated to verify the numerical approach, by compared to the Bergmark-Roos model. The coal drawing termination condition is "rocks appear, close the opening". With the top-coal being drawn out gradually, the interface between coal and rock gradually moves down. Figure 6a shows the final state of the interface which is like a hopper. The ID numbers of all the released particles are counted and to back analyze their initial space

locations (i.e., the drawn body shape). As shown in Figure 6b, the drawn body is an approximate ellipsoidal body.

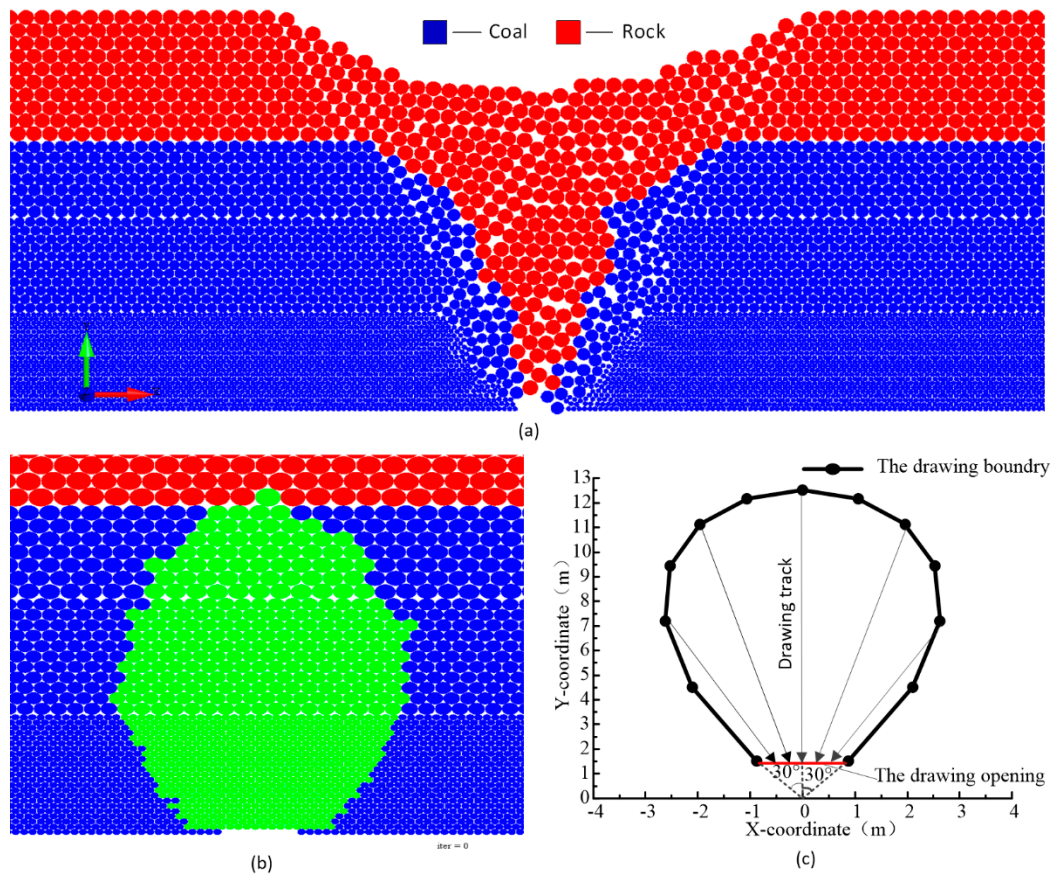


Figure 6. The drawn coal body shape under single drawing opening, (a) the coal-rock interface after coal drawing; (b) the numerical result of drawn coal body; and (c) the theoretical solution of drawn coal body.

The Bergmark–Roos model is adopted to verify the numerical approach. The initial position of drawn coal fragments in polar coordinate system can be described by Equation (13) in Section 2.2.2.

In this study, $r_{\max}$ is regarded as the thickness of the top-coal, taken as 11 m, $\theta_G = 30^\circ$, and D equals the width of the tail canopy of the hydraulic support, taken as 1.75 m. Under this condition, Equation (13) is simplified to:

$$r_0 = \frac{11(2 \cos \theta - \sqrt{3})}{2 - \sqrt{3}} + \frac{7\sqrt{3}}{8 \cos \theta} \quad (16)$$

According to Equation (16), the drawn coal body shape is plotted in Figure 6c, which also shows an approximate ellipsoid shape. Comparing Figures 4 and 6a, after the top-coal is drawn out, the interface between coal and rock shows a hopper, which indicates that the movement tracks of top-coal particle during the drawing process accord with the hypothesis of the Bergmark–Roos model. Comparing Figure 6b,c, the initial space distribution of drawn top-coal by numerical simulation inversion also conforms to the solution of Bergmark–Roos model, which proves that the numerical approach is suitable for simulating top-coal drawing process.

4.2. Effect of Top-Coal Thickness

Large variations in top-coal thickness will significantly affect the final top-coal recovery rate. To study the effect of top-coal thickness on the coal drawing mechanism under multiple drawing

openings, the top-coal thickness is set to 11 m, 16 m and 21 m, respectively. The length of working face is 200 m and the drawing opening width of each hydraulic support is 1.75 m (see Figure 5). The coal drawing operation for 100 drawing openings is executed in sequence from one end of working face to another. The coal drawing termination condition of “rocks appear, close the opening” is adopted. When top-coal is extra thick, a coal arch structure above the drawing opening may be formed by large coal blocks from the upper coal seams, which will cause coal drawing process to be forced to stop, thus, the naturally formed coal arch structure is also a coal drawing termination condition.

The coal-rock interfaces under different top-coal thickness are shown in Figure 7. From Figure 7, in each case, the coal and rock are periodically mixed into each other. The mixing degree of coal-rock interface increases with top-coal thickness, and the amount of residual top-coal also increases. When the top-coal thickness is 11 m, most of the top-coal are released. When the top-coal thickness is 16 m, a part of the top-coal cannot be drawn out. When the top-coal thickness is 21 m, a large amount of top-coal cannot be released.

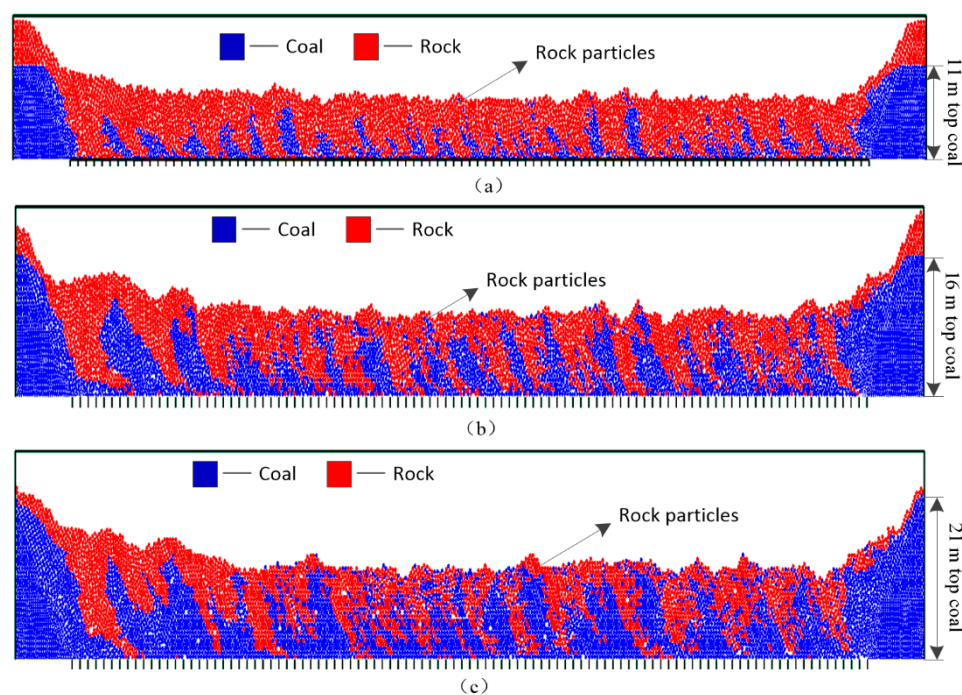


Figure 7. The coal-rock interfaces after coal drawing under different top-coal thicknesses. (a) 11 m, (b) 16 m, and (c) 21 m.

A concept of effective thickness of drawn coal is proposed to evaluate quantitatively the influence of top-coal thickness on coal drawing, which is the drawn top-coal amount divided by the length of working face. The results of the coal drawing under different thicknesses are shown in Table 2. As the top-coal thickness increases, the top-coal recovery rate is gradually reduced from 81.6% to 68.8%, and the effective thickness of coal drawing is continuously increased, indicating that the top-coal is not easy to be drawn out if top-coal is too thick. Table 3 shows the average and variance of drawn top-coal amount of 100 drawing openings. From Table 3, it can be found that with the increase of the top-coal thickness, the average amount of coal drawing increases but the difference in the amount of coal drawing also increases.

Table 2. Comparison of drawn top-coal amount under different top-coal thicknesses.

Top-Coal Thickness	Total Coal Amount (m ²)	Drawn Top-Coal Amount (m ²)	Top-Coal Recovery Rate (%)	Effective Thickness of Coal Drawing (m)
11 m thick top-coal	1839.9	1500.5	81.6	8.01
16 m thick top-coal	2727	1990	72.97	10.63
21 m thick top-coal	3605	2481	68.8	13.25

Table 3. The average and variance of the drawn top-coal amount under different top-coal thicknesses.

100 Drawing Openings	11 m Thick Top-Coal	16 m Thick Top-Coal	21 m Thick Top-Coal
Drawn top-coal amount average (m ²)	15.01	19.86	23.57
Drawn top-coal amount variance (m ⁴)	67.69	135.42	172.92

When the top-coal thickness is 11 m, the top-coal will be fractured and drawn out under the tail canopy disturbance of hydraulic support and the mining-induced pressure. If the top-coal thickness is thicker than 11 m, part of top-coal cannot be drawn out. The thicker the top-coal is, the larger amount of top-coal cannot be drawn out, and the difference in the drawn coal amount of 100 drawing openings is also greater, because the possibility of top-coal arching is higher, which prevents the release of top-coal. For extra thick coal seams, the arch structure is formed frequently during coal drawing process, so the top-coal recovery rate of entire working face is relative low. The difference of drawn top-coal amount from every drawing opening is larger, which have a negative impact on the transportation efficiency of scraper conveyer.

4.3. Optimizing of Automated Top-Coal Caving Technology

4.3.1. Automated Top-Coal Caving Time

In fact, the coal drawing time of each hydraulic support is an input parameter for the automated control device which determines the opening and closing states of drawing opening. To determine the automated coal drawing time, considering the relationship between the equipment at working face, top-coal recovery rate and coal transportation efficiency is important and necessary. Because traditional top-coal caving technology is widely used in coal mines, large corresponding information on some in-site observations and statistic is significant on determining automated coal drawing time. To make our research valuable for a practical mining, the simulation should be also better correlated with the practical operation in field. The number of iterative steps in CDEM is equivalent to the time in real coal drawing practice. Therefore, the time-based automated coal drawing simulation can be realized indirectly by controlling the number of iteration steps of each drawing opening in each drawing round. Therefore, the coal drawing time is converted to the iteration steps of automated top-coal drawing in numerical simulation. The total iteration steps can be estimated by referring to the simulation steps in traditional top-coal caving adopting the criterion of “rocks appear, close the opening”.

Some specific details are as follow. First, the coal drawing simulation of single drawing opening is carried out in the middle of working face (see Figure 6a), the coal drawing process is allowed to continue until the waste rock particles appear at the drawing opening, then the drawing opening is closed and the drawing process is terminated. At this time, the number of iteration steps in the coal drawing simulation is 159,190, which is taken as the upper bound value of coal drawing time for each coal drawing opening. For the situation of using traditional top-coal drawing technique in 11 m thickness of top-coal, the total number of iteration steps is 5,471,291. Thus, the average coal drawing time for each drawing opening is about 54,713 iteration steps. Considering the time allocation of multi-round coal drawing, the total number of iteration steps for each coal drawing opening is set to 60,000 in the automated coal drawing simulation. In automated multiple-round coal drawing

simulation, the coal drawing steps of single drawing opening for each round is calculated by the total drawing steps and the number of coal drawing rounds.

4.3.2. Automated One-round Coal Drawing

The top-coal drawing sequence is from the first drawing opening at one end of the working face to last drawing opening at another end, as illustrated in Figure 8. The number of coal drawing iteration steps for each coal drawing opening is 6000. At any time, only one drawing opening is allowed to be opened for coal drawing (Figure 8a). The next adjacent drawing opening can only be opened when the previous one is closed. During the automated coal drawing process, rock particles are also drawn out because time is a control factor. Coal and rock particles are collected in the rigid tubes under 100 drawing openings to analyze the rock mixed rate and top-coal recovery rate, as listed in Table 4.

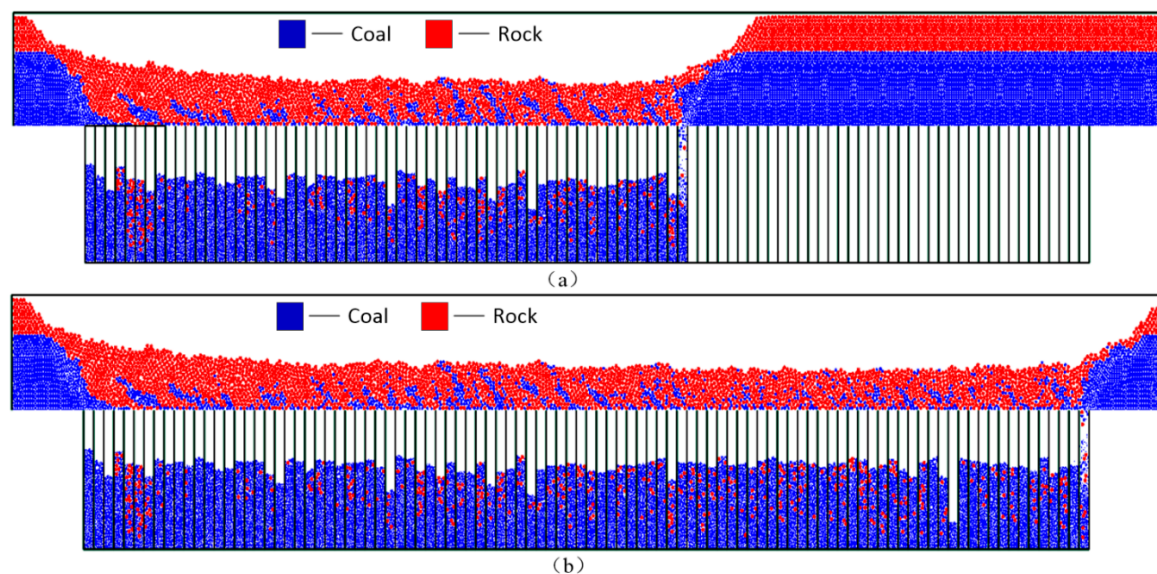


Figure 8. The numerical results of automated one-round coal drawing, (a) a coal drawing state in the drawing process, and (b) the final coal drawing state.

Table 4. Comparison of drawn top-coal amount in traditional and automated coal caving technologies.

Top-Coal Caving Technology	Total Coal Amount	Drawn Top-Coal Amount (m ²)	Rock Drawing Amount (m ²)	Top-Coal Recovery Rate (%)	Rock Mixed Rate (%)	Drawn Top-Coal Amount Variance
Automated coal caving	1839.9 m ²	1538.78	125.1	83.7	7.52	3.35
Traditional coal caving	941.6 m ²	1500.5	0	81.6	0	67.69

According to Figure 8b, the top-coal particles and rock particles are mixed with each other near the coal-rock interface and in the particle collection rigid tube. As shown in Table 4, the recovery rate is 83.7% for the automated one-round coal drawing, which is higher than the top-coal recovery rate (81.6%) of the traditional coal drawing. The drawn top-coal amount variance (3.35) is also less than that in traditional coal drawing (67.69). However, for the automated one-round coal drawing, the rock mixed rate is 7.52%, indicating that a large amount of rocks is mixed into the top-coal drawn. Automated top-coal drawing technique based on time control criterion is good for improving coal recovery rate, but should control the rock-mixed rate. Therefore, it is necessary to find a top-coal drawing strategy to reduce the rock-mixed rate.

4.3.3. Automated Three-round Coal Drawing

To solve the problem of high rock mixed rate of the automated one-round coal drawing technique, an automated three-round coal drawing is modeled to investigate whether increasing the number of top-coal drawing rounds can reduce rock mixed rate. Thus, the coal drawing time for each round is adjusted as 20,000 iteration steps. When the previous round is completed, the next round starts. In each top-coal drawing round, the top-coal drawing sequence is from the first drawing opening at one end of the working face to last drawing opening at another end. Therefore, at any time, only one drawing opening is allowed to be opened for coal drawing, as shown in Figure 9.

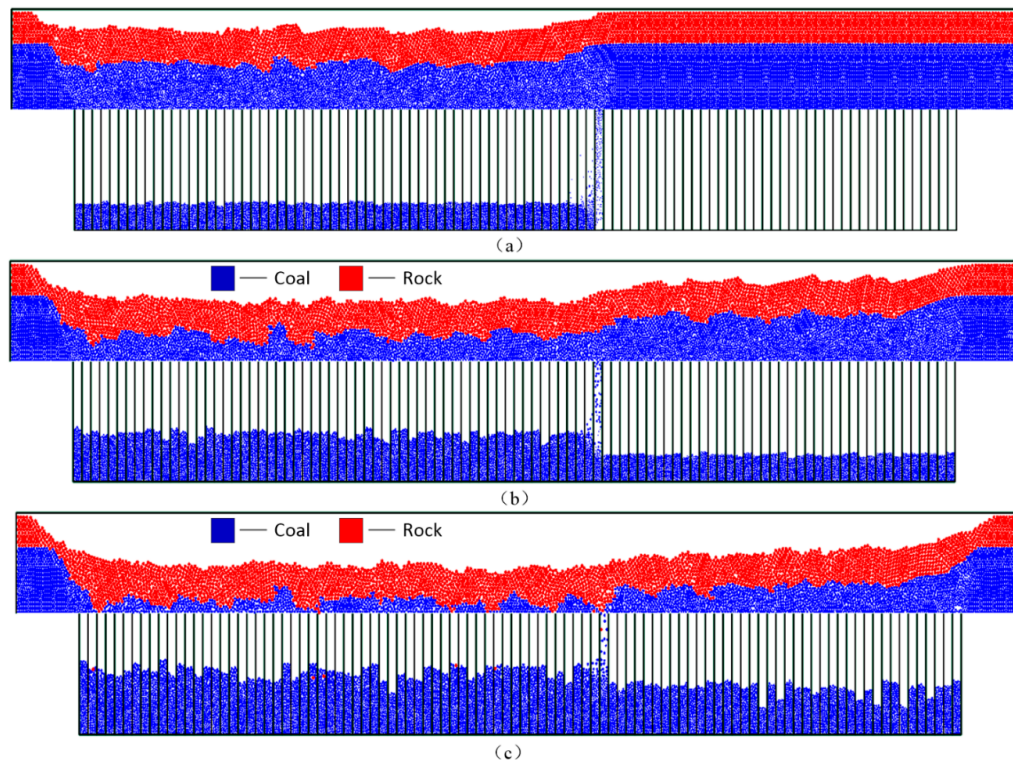


Figure 9. The process of automated three-round coal drawing, (a) the first top-coal drawing round, (b) the second top-coal drawing round, and (c) the third top-coal drawing round.

The coal-rock interfaces of each round are shown in Figure 10. For the automated three-round coal drawing, the coal-rock interface has a layered distribution basically, and coal and rock appear slightly mixed into each other. In first and second rounds, there is no rock mixed into the top-coal drawn. The coal and rock appear obviously mixed into each other in the third round, and there is only a little of rocks mixed into the top-coal drawn. Comparing to the coal-rock interfaces by one-round coal drawing technique, the coal-rock interfaces by automated three-round coal drawing technique show an obviously layered distribution, which greatly reduces the drawing amount of rocks. Therefore, the automated three-round coal caving technology is superior to the automated one-round coal caving technology.

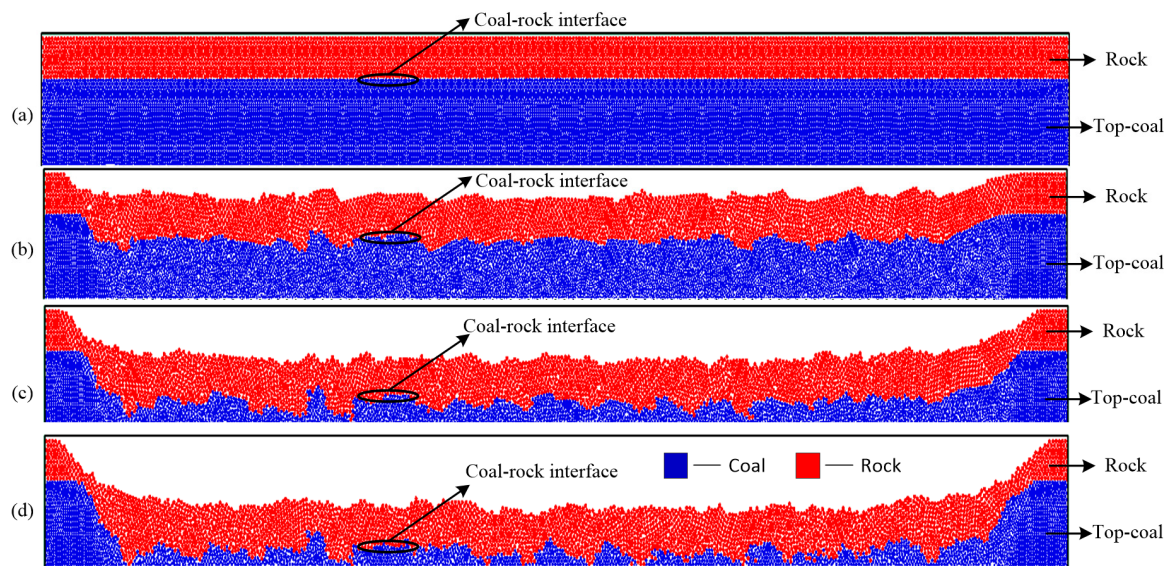


Figure 10. The coal-rock interfaces after different coal drawing rounds, (a) before coal drawing; (b) after the first round coal drawing; (c) after the second round coal drawing; and (d) after the third round coal drawing.

4.3.4. Automated Three-Round Equal Time Coal Drawing

In the above automated three-round drawing technique, there is only one coal drawing opening to draw out the top-coal in the working face at the same moment, so the total coal drawing time is very long and unacceptable for engineering project. To reduce the total drawing time, a new automated three-round drawing technique is proposed. Three coal drawing openings corresponding to the three rounds are opened to draw out the top-coal at the same time, and the coal drawing time of each drawing opening in each round is still 20,000 steps. In each round, the working order of 100 drawing openings is also from the first one to the last one in sequence, but the three rounds are carried out simultaneously, as shown in Figure 11a. The first drawing opening of the second round is opened from the end of working face when the 10th drawing opening of the first round is opened. As the 10th drawing opening of the second round is opened, the first drawing opening of the third round of coal drawing is opened from the end of working face. Thus, there are three hydraulic supports to draw out the top-coal of the working face at the same moment, and the interval between two adjacent drawing opening is the width of 10 drawing openings. For the convenience of description, this new technique is named automated three-round equal time top-coal drawing technique.

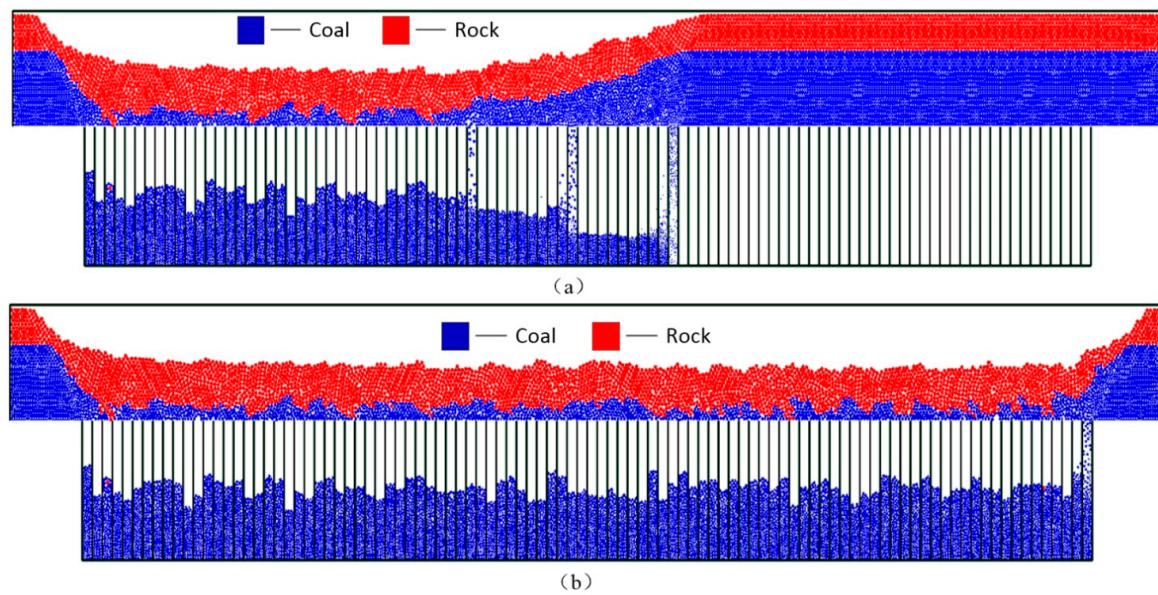


Figure 11. The automated three-round equal time coal drawing technique, (a) a coal drawing state in drawing process; and (b) the final coal drawing state.

The final coal-rock interface and rock mixed in drawn top-coal are shown in Figure 11b. Results show that few rock is drawn out, and the coal-rock interface shape is very similar to that under the automated three-round drawing technique in which only one opening is opened at any time. The total coal drawing time is greatly shortened, so the automated three-round equal time coal drawing technique is superior to the automated three-round coal drawing.

The drawn top-coal amount of each drawing opening is counted, as shown in Figure 12. The amount of coal in the first round, second round and third round is reduced in order, while the difference of drawn top-coal amount of 100 openings increase in turn. Overall, for the automated three-round equal time coal drawing technique, the difference of the top-drawn top-coal amount of each round is great, which leads to the large weight difference on the scraper conveyer in each round and the unbalanced and lower transport efficiency.

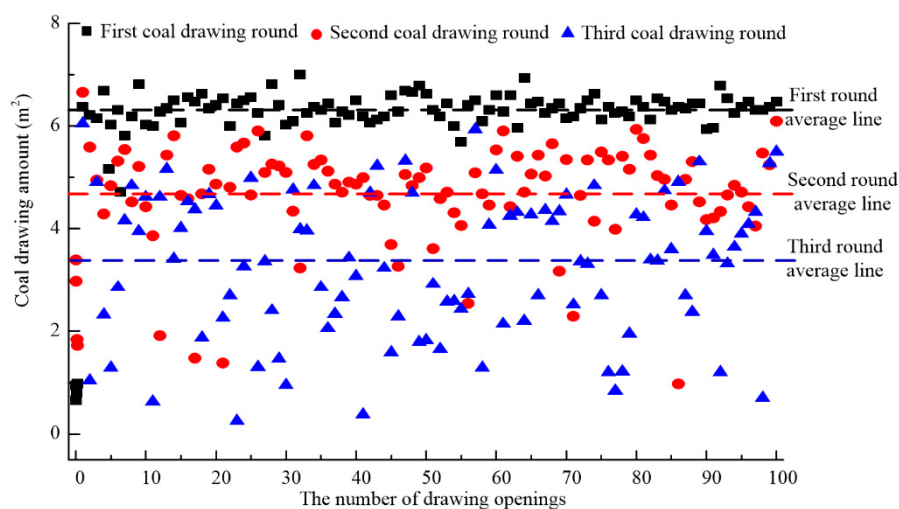


Figure 12. The drawn top-coal amount of each drawing opening in each round by the automated three-round equal time coal drawing technique.

In the multi-round coal drawing process, the top-coals in the lower part of coal seams are almost fractured and their sizes commonly are small, so they easily flow out. However, the dimension of top-coal block in the upper coal seams is large, so the friction resistances between the large top-coal blocks in the upper coal seams are greater than those in the lower coal seams, which leads that the coal blocks in the upper coal seams need more time to reach the drawing openings. In order to make the amount of drawn coal in each round as equal as possible, the coal drawing time of each round should be adjusted according to the variation of the top-coal recovery rate, rock mixed rate and the shape of coal-rock interface.

4.3.5. Automated Three-Round Unequal Time Coal Drawing

An automated three-round unequal time coal drawing technique is proposed to solve the problem of large drawn coal amount difference of each drawing round. The top-coal drawing process is the same as the automated three-round equal time coal drawing process, and the total drawing time is also kept as 60,000 iteration steps, but the drawing time for the three round is changed. The iteration steps for the first, second and third rounds are 15,000, 20,000 and 25,000, respectively. To clearly express the mining sequence of this technique, a coal drawing state is shown in Figure 13a.

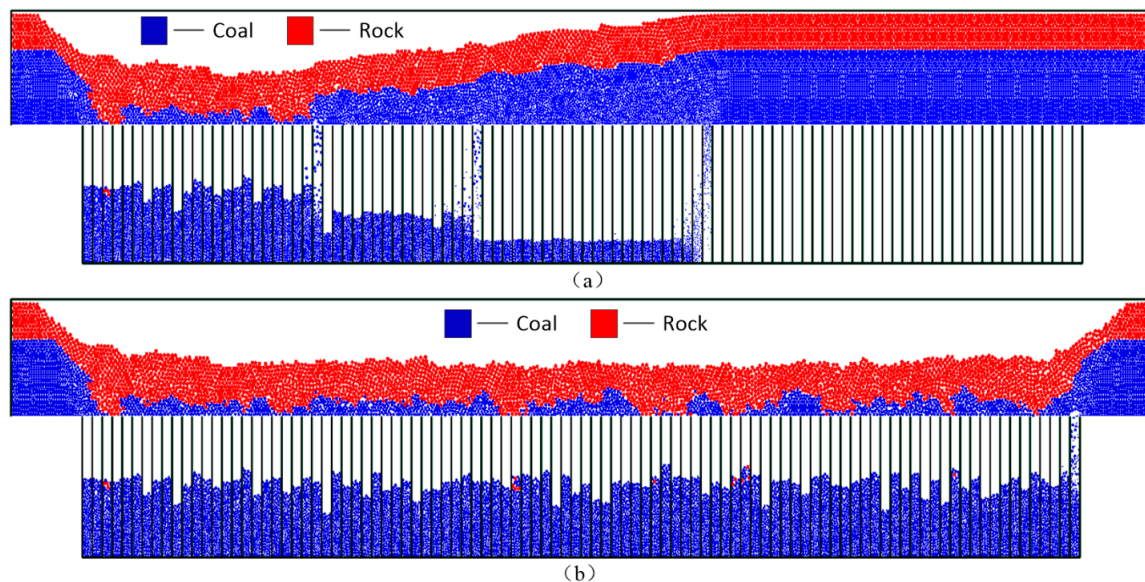


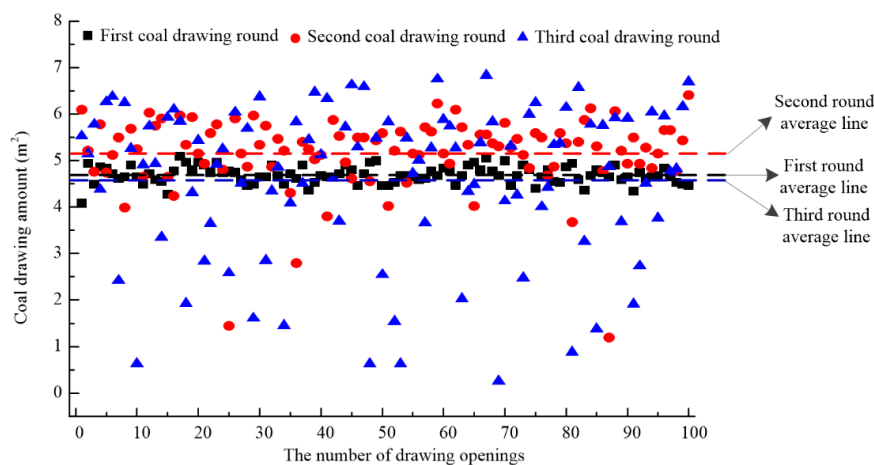
Figure 13. The automated three-round unequal time coal drawing technique, (a) a coal drawing state in drawing process; and (b) the final coal drawing state.

The final coal-rock interface and rock mixed in drawn top-coal are shown in Figure 13b. The coal-rock interface is basically identical with that of automated equal time drawing, in which most of the top-coal are efficiently drawn out and few rocks are mixed into the top-coal drawn.

To specifically compare the above two techniques, the top-coal recovery rate and the rock mixed rate are counted in Table 5. The top-coal recovery rates of the two techniques are both high ($>78\%$) and the rock mixed rates are both lower ($<0.3\%$). Figure 14 shows the drawn top-coal amount of each round. From Figure 14, the periodic fluctuation degree of drawn top-coal amount from every drawing opening of the 1st, 2nd and 3rd rounds increases gradually. However, by comparing Figures 12 and 14, it can be found that the total drawn top-coal amount in every round is more uniform than that of the automated three-round equal time coal drawing. Therefore, the stability and efficiency of scraper conveyor conveying drawn top-coal are greatly improved.

Table 5. Comparison of drawn top-coal amount in equal time and unequal time in every coal drawing round.

Top-Coal Caving Technology	Total Coal Amount (m ²)	Drawn Top-Coal Amount (m ²)	Rock Drawing Amount (m ²)	Top-Coal Recovery Rate (%)	Rock Mixed Rate (%)
Equal time in every round	1839.9 m ²	1437.3	0.57	78.08	0.04
Unequal time in every round	941.6 m ²	1448.34	3.96	78.61	0.27

**Figure 14.** The unequal time drawn top-coal amount of each drawing opening.

5. Discussion

5.1. Different Top-Coal Caving Techniques

In a coal drawing cycle, the final coal drawing results of entirely working face are determined by the collaborative coal drawing work of all openings. For the traditional coal drawing in which the “rocks appear, close the opening” is set to the coal drawing termination condition, top-coals are drawn from an ellipsoidal space and form a large gangue funnel above the drawing opening, then the gangue funnel will significantly affect the top-coal drawing of the next opening. The next opening can only draw out the top-coals in a smaller ellipsoid range. Therefore, the space of the top-coal caving body is arranged alternately in the form of large and small ellipsoids along the direction of working face, and the drawn top-coal amount of each opening is very uneven, resulting in low transport stability and efficiency of scraper conveyer. However, for automated coal drawing techniques, the time of each top-coal drawing round is regarded as a control variable and can be adjusted according to the number of top-coal drawing rounds, which makes the size of the caving ellipsoid above each opening close to each other and realizes that top-coals move down evenly, so the difference in coal amount of each drawing opening is smaller, and the transport efficiency of scraper conveyer is improved.

For the automated one-round coal drawing technique, the coal drawing time of every drawing opening is relatively larger, so some rocks are mixed into the drawn coal. For the automated three-round coal drawing technique, the coal drawing time in every round is smaller, so that only a small amount of rocks is drawn out in the third round of coal drawing, which implying that the rock mixed rate decreases as the drawing rounds increases.

For the automated three-round coal drawing technique, there is only one drawing opening to be opened for coal drawing in entire working face, so the total drawing time is too long to meet the production requirements in unit time. For the equal and unequal time top-coal drawing techniques, there are three drawing openings to be opened for coal drawing at the same time, which reduces

the total top-coal drawing time by $2/3$ and is more suitable for practical mining to meet the coal production requirements.

The top-coals in lower part of coal seams are almost completely broken with a small fragment. During the drawing process of lower coal seams, the frictional resistance between the loose coal particles is smaller, so the top-coals can be easily drawn out. However, the size of top-coal blocks in the upper part of coal seams is larger, causing that the flow resistance of coal particles is also larger. As a result, the upper coal blocks need more time to be drawn out, which indicates that the drawing time of each round should be different and be determined by the fragmentation degree of top-coal. Numerical simulation results also prove that the unequal time top-coal drawing technique which prolongs the drawing time of the third round for the upper coal seams is better than the equal time top-coal drawing technique, and improves the transport stability and efficiency of the scraper conveyor by making the top-coal more evenly drawn out.

5.2. Automated Coal Drawing Time

The coal drawing time is an important control variable in automated coal drawing technique, which affects the top-coal recovery rate, rock mixed rate, the uniformity of drawn coals and drawing rounds, etc. The real time of top-coal drawing in field can be equal to the iteration steps. In numerical simulation, the coal drawing time for one drawing opening can be estimated according to the simulation of traditional coal drawing. Moreover, the numerical inversion result of iteration steps, which comprehensively considers the movement of coal-rock interface, rock mixed rate, top-coal recovery rate and transport efficiency of the scraper conveyor, can be used for real top-coal drawing time estimation and automated drawing process design to achieve a better top-coal drawing effect of entirely working face. However, because the shapes of coal-rock blocks, top-coal thickness, mechanical properties of coal-rock masses and boundary conditions in field are different from the particles in simulation, the top-coal drawing time in simulation cannot be directly transferred to the coal drawing time in the practical operation. Numerical simulation result suggests the top-coal drawing time should be extended properly in the later drawing rounds, but the exact time for each drawing round still needs to be corrected by the transport capacity of the field equipment, which not only obtains the highest transport efficiency of top-coal, but also ensures that the armored face conveyor is not overloaded. The total automated coal drawing time also needs to meet the coal production schedule to achieve more efficient and coordinated coal mining. Therefore, determination of the automated coal drawing time for engineering application still needs to be studied further.

6. Conclusions

In this study, CDEM is conducted to evaluate and optimize the automated top-coal drawing techniques in extra-thick coal seams. Numerical models with 100 drawing openings are created according to the field engineering geological conditions of Tongxin coal mine in China. The top-coal drawing under single drawing opening is modeled to investigate the top-coal drawing mechanism and verify the numerical approach accuracy of top-coal drawing according to the top-coal caving theory, the Bergmark-Roos model. An automated coal drawing control approach in numerical modelling based on time criterion is proposed. The rock mixed rate, top-coal recovery rate and the variance of the drawn top-coal amount are counted and set as the statistical indicators to evaluate top-coal drawing techniques in extra-thick coal seams. Conclusions are drawn as follows:

- (1) The traditional top-coal drawing criterion, “rocks appear, close the opening”, leads to low recovery of top-coal and waste of coal resources in extra-thick coal seams. As coal seams thickness increases from 11 m to 21 m, the top-coal recovery rate decreases from 81.6% to 68.8%, and the drawn coal amount variance increases from 67.69 m^4 to 172.92 m^4 , which will significantly weaken the transport stability and efficiency of the scraper conveyor.

- (2) An three-round unequal time top-coal drawing technique is proposed for automated top-coal drawing, in which the top-coals are completely drawn out in three rounds, three drawing openings with an interval of 10 hydraulic supports are working at the same time, and the drawing time of each round is not equal and increases with the round number. This top-coal drawing technique controls the coal-rock interface to move down smoothly, resulting in a top-coal recovery rate of 78.61% and a rock mixed rate of 0.27%. The total drawn top-coal amount in every round is more uniform, so that the stability and efficiency of scraper conveyer conveying drawn top-coal are greatly improved.
- (3) The coal drawing time is an important control variable in automated coal drawing technique, which affects the top-coal recovery rate, rock mixed rate, the uniformity of drawn coals and drawing rounds, etc. The numerical inversion approach of iteration steps can be used for real top-coal drawing time estimation and automated drawing process design to achieve a better top-coal drawing effect of entirely working face. Numerical simulation result suggests the top-coal drawing time should be reduced properly in the later drawing rounds, while the exact time for each drawing round still needs to be corrected by the engineering practice, because the shapes of coal-rock blocks, top-coal thickness, mechanical properties of coal-rock masses and boundary conditions in field are different from the particles in simulation.

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