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Dynamic Random Arching in the Flow Field of Top-Coal Caving Mining

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Abstract: The large mining height fully mechanized top-coal caving mining technique has developed rapidly and become the most extensively used mining method for ultra-thick coal seams. The arching of coal/gangue and the drawing out of gangue are peculiar phenomena in the process of fully mechanized top-coal caving mining, which not only affects the recovery of top-coal, but also affects the quality of the coal. This paper studies the arching phenomenon in top-coal caving mining process of ultra-thick coal seam. A series of laboratory granular material simulation experiments were performing and a top-coal arching model in the framework of mechanics was established to explore the formation characteristic of arches and their effects to top-coal loss. Then the countermeasures against the arches and technology path of intelligent mining based on improving top-coal recovery were put forward and performed in practice. The results show that the recovery ratio of top-coal has increased nearly 6%, and increased the production efficiency at the same time. The research on arching mechanism and removing strategies of dynamic random arches effectively improves the efficiency of fully mechanized top-coal caving mining in ultra-thick coal seams, and provides the foundation for the realization of intelligent top-coal caving mining technology.

Keywords: top-coal caving mining; arching mechanism; dynamic random arch; granular material; intelligent mining

1. Introduction

In China, fully mechanized top-coal caving mining in ultra-thick coal seams (especially in 14–20 m ultra-thick coal seams) has developed rapidly in the past 10 years [1–4]. Studies in topics such as equipment matching, wall stability, strata control technology, safety guarantee technology for low gas occurrence and high gas emission have made important progress [5–11].

Intelligent mining is the development direction of coal mining. The application of intelligent working faces has been studied in China, which will greatly promote the development of coal intelligent mining technology, especially in the research of fully mechanized top-coal caving intelligent mining [12–17]. At the same time, it is necessary to consider the characteristics of fully mechanized caving mining process and its influence on the intelligent top-coal caving [18–20].

The caving of top-coal in ultra-thick coal seam is a complicated process, and the drop-flow state will directly affect the recovery ratio of top-coal [21–23]. Due to the different fragment dimensions of the top-coal and immediate roof rock, different fragment dimension of top-coal in the direction of top-coal thickness, combined with the change of coal caving space, it is difficult to master the coal gangue flow law and the top-coal loss condition in top-coal caving [5,24].

Field practice shows that the arching of coal/gangue and the drawing out of gangue are peculiar phenomena in the process of fully mechanized top-coal caving mining, which not only affect the recovery ratio of the top-coal, but also affect the quality of the coal [6,22]. With the increase of top-coal thickness, the space of the caving flow field and fragment dimensions of coal and gangue are increased, which not only increases the mixing process of the top-coal and gangue, but also increases the arching probability of top-coal [24–26]. Especially, under consideration of top-coal caving mining in 14–20 m ultra-thick coal seams, many issues need to be further researched. The main issues are the arching law, arch structure characteristics, the influence of arches to the smoothness of coal/gangue flow and loss of top-coal. It is of great significance for improving the recovery ratio of top-coal and solving the key problem in fully mechanized intelligent top-coal caving mining in ultra-thick coal seams [21,23].

Arching is one of the most universal phenomena encountered in the flow and storage of granular materials in hopers and silos. The form of arch may prevent the flow of materials [27]. Vivanco, Rica and Melo found that an arch can be built following the principal compression orientation of the stress tensor [28]. Perry and Handley researched the dynamic arch in free flowing granular material discharging from a model hopper [29]. Duran et al. analyzed the relationship between the static friction and arch formation in granular materials [30]. Peralta-Fabi et al. find a qualitative agreement with Janssen's phenomenological result of arching [31]. Bai et al. established a discrete element numerical simulation model for top coal to discuss the top-coal arching mechanism [24]. Yu et al. proposed a top-coal analytic model formed by arching blocks in face contact [25].

Based on the above research, with the aim of improving the recovery ratio of top-coal caving in ultra-thick coal seams, this paper studies the type and arching probability of arches through physical simulation experiment. A top-coal arching mechanical model was established to study the characteristics of arches and their effect to top-coal loss. Countermeasures against the arches and technologies of intelligent mining were then performed in practice to test the feasibility.

2. Physical Granular Simulation Experiment

2.1. Engineering Background

The 8103 Panel of Tashan Colliery employs the fully mechanized full seam top-coal caving mining method. The main mined coal seam, 292–339 m deep, is 14.5 m thickness and 4° dip angle on average. The mining height is 4.2 m and the caving height is 10.3 m. Therefore, the mining height to top-coal caving height ratio is 1:2.45. The immediate roof, about 3.49 m thick, is comprised of magmatic rock, mudstone and silica. It is overlain by silt sandstone, fine sandstone and coarse sandstone with 22.93 m in thickness. The advance web of the working cycle is 0.8 m, and the top-coal caving interval is 0.8 m. In the mining process of Panel 8103, caving-outlet blocking or inadequate flowing often occurred and caused low recovery and efficacy. In order to find out the reason, holes were drilled to the oblique rear zone of the gob through the intermediate gap of supports. The infrared drilling camera system and three-dimensional laser scanner were used to observe the structure of top-coal upper the caving-outlet. And it was found arches were formed in the top-coal.

2.2. Experiment Design

According to the Fragment Dimension Theory [21,32], the granular simulation experiment was carried out based on the geological condition of 8103 Panel in Tashan Colliery. The top-coal caving simulation experiment system was self-developed and carried out for laboratory testing. This system is mainly composed of control system, simple self-moving hydraulic support, power system and model frame. The model frame is 300 cm in length, 15 cm in width and 220 cm in height. The height of the self-moving hydraulic support is 40 cm, and the geometrical similarity ratio of the simulation experiment is C = 40/420 = 1:10.5. The operations, such as moving hydraulic support and controlling the caving-outlet, can be carried out automatically by setting the parameters of the caving interval.

Theoretical analysis and field measurements show that the fragment dimension of top-coal is decreased along the thickness direction [21,23,32], so different colors and sizes of stones were selected to simulate each layer of coal and rock. Clay was added to simulate coal/rock powder with a smaller particle size. In the model, the top-coal seam of Panel 8103 was divided and simulated by the upper, middle and lower layers along vertical direction. The immediate and main roof were simulated by granular material in different sizes. The thicknesses and fragment dimensions of different layers in the simulation experiment model are shown in Table 1 and Figure 1.

Table 1. Parameters of simulation experiment model.

Layer	Parameters	
	Thickness (mm)	Dimension (mm)
Middle main roof	600	90
Lower main roof	400	75
Immediate roof	332	70
Upper top-coal layer	378	55
Middle top-coal layer	300	45
Lower top-coal layer	300	27

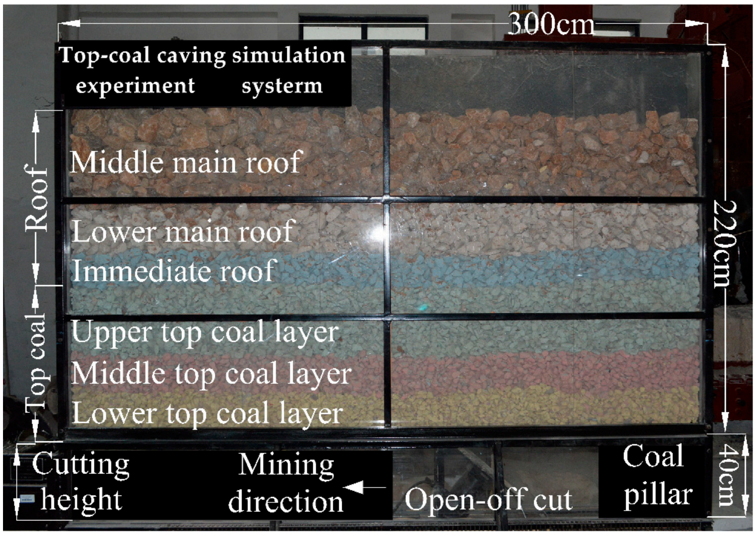


Figure 1. Simulation experiment model of top-coal caving mining.

Because of the balanced structures of overlying strata formed upon the top-coal caving face, the gravity of the overlying strata above the immediate roof is no longer transferred to the granular top coal, so it is only necessary to add the granular with the thickness of immediate roof in the granular model. Therefore, the simulation model does not take into account the stress distribution of the surrounding rock. At the same time, due to the limitation of the model, only the arching characteristics of the mining direction can be monitored.

3. Experiment Result and Analysis

3.1. Types of Arches

The top-coal/gangue arches were formed in different spaces (lower, middle and upper) of caving flow field behind the supports. And the span, arching form and composition of the arches were different in different spaces. The types of arches are as follows:

(1) Lower arch. The lower arch is located at the bottom of the flow space near the caving-outlet with a small span, big arching probability and high stability. That's because the flow space decreases

along the vertical direction. The smaller the flow space is, the larger arching probability would be. The lower arch can be formed by coal blocks only (as shown in Figure 2a), or coal and gangue blocks (as shown in Figure 2b). The front skewback of the arch is generally located at the tail beam of the support, while the rear skewback of the arch is located on the gangue of gob.

(2) Middle arch. The middle arch is located at the middle of the flow space (behind the shield beam in horizontal). The span of the middle arch is usually longer than that of the lower arch. The middle arch can be formed by coal blocks only (as shown in Figure 3a) or coal and gangue blocks (as shown in Figure 3b). The front skewback of the arch is generally located on the shield beam or tail beam of the support, the rear skewback of the arch is located on the gangue of gob.

(3) Upper arch. The upper arch is located over the support with a large span, small arching probability and low stability. The front skewback of the arch is generally located on the top beam of the support, the rear skewback of the arch is located on the gangue of gob. The upper arch can be formed by coal blocks only (as shown in Figure 4a) or coal and gangue blocks (as shown in Figure 4b), too.

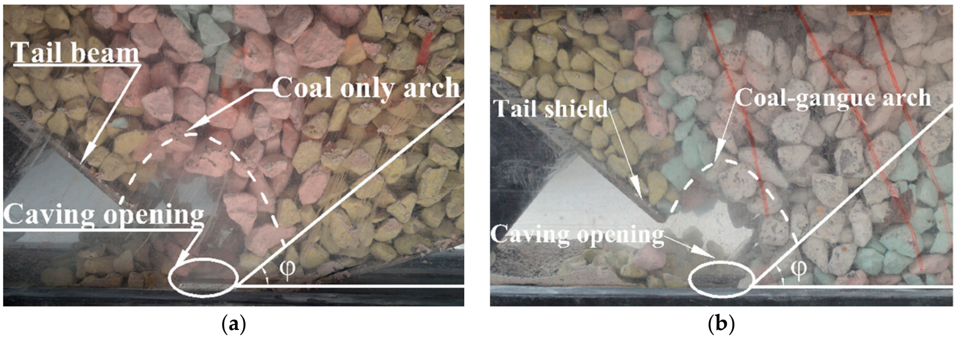


Figure 2. Lower arch. (**a**) Lower coal only arch; (**b**) Lower coal-gangue arch.

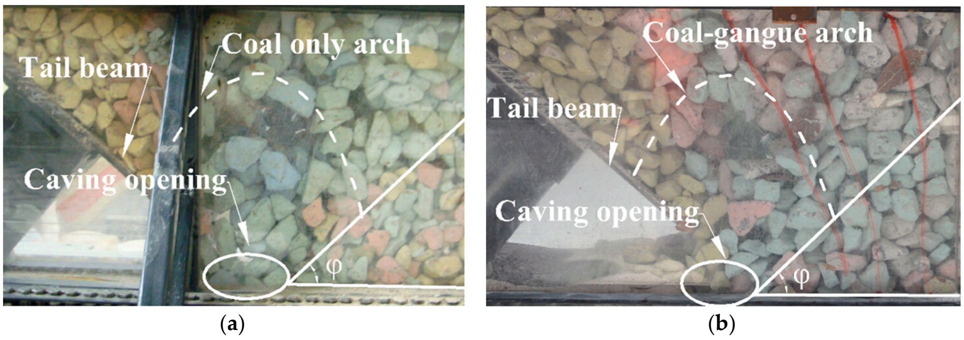


Figure 3. Middle arch. (**a**) Middle coal only arch; (**b**) Middle coal-gangue arch.

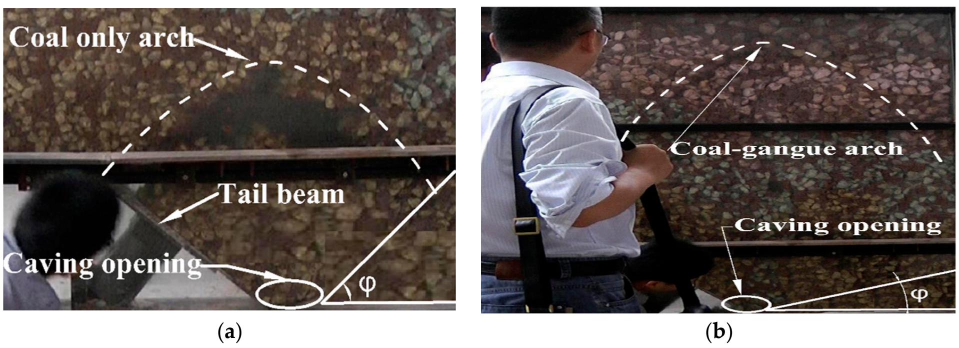


Figure 4. Upper arch. (**a**) Upper coal only arch; (**b**) Upper coal-gangue arch.

According to the arching position and characteristics, the flow space of the arch structure formed can be divided into the lower arch area, middle arch area and upper arch area. The formation probability, arching medium, arch span size, stability and their impact on top-coal caving flow, and recovery of different arches are also different. The different arch areas are shown in Figure 5.

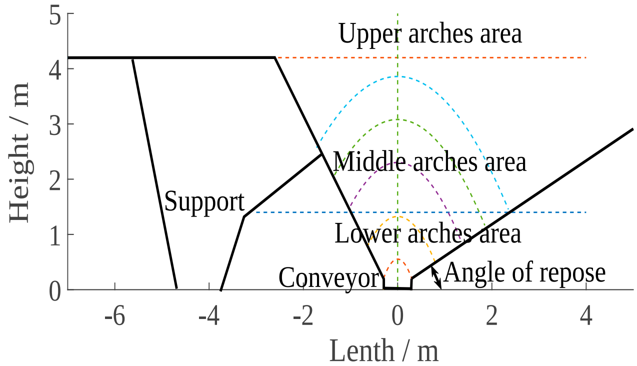


Figure 5. Region of different arch areas in the top-coal caving flow space.

3.2. Arching Probability and Effect on the Top-Coal Recovery of DRA

In the process of the experiment, the arching times and arching probabilities of different types of arch and their effects on the top-coal recovery ratio in 20 caving cycles were analyzed, and the results are shown in Table 2.

Table 2. The arching times and arching probability of different types of arch structures.

Type of Arches		Times	Arching Probability (%)	Arch Ratio (%)	Recovery Ratio (%)
Upper arch	Coal only arch	1	5	1.04	60.30
	Coal-gangue arch	2	10	2.08	78.80
Middle arch	Coal only arch	9	45	9.38	51.34
	Coal-gangue arch	7	35	7.29	63.23
Lower arch	Coal only arch	56	280	58.33	24.14
	Coal-gangue arch	21	105	21.88	82.23

From Table 2, the arching probability of lower, middle and upper arch structure are 3.12%, 6.67% and 80.21%, respectively. The arching probability of the lower arch is the highest. In the same arching area, the effect of the coal only arch on recovery ratio is greater than that of the coal-gangue arch. The recovery ratio of top-coal is only 24% when the coal only arch is first formed in the lower arch area, so removing of the coal only arch structure in the lower top-coal is an effective way to improve the recovery ratio of top-coal. However, the recovery ratio has a high value (82.23%) when the coal-gangue arch is first formed in the lower arch area. If the coal-gangue arch is mainly made up of gangue, more gangue will reach the caving-outlet once the arch structure is destroyed, resulting in high refuse content. The middle arch structure has a great influence on the recovery ratio, removing means need to be applied. The arching probability of upper arch structures is low and have little effect on the recovery ratio, so nothing needs to be done to them.

3.3. Characteristics of Arches

According to the conditions of the arches formed in different arching areas, the characteristics of arches can be obtained as followings:

(1) Arching positions. The arch can be formed in any position in the caving flow space. And the shape and position of the arch may change with the flow of coal and gangue in the flow field. In other words, the arching position is dynamic.
(2) Arching probability. The arching probability of arches in different positions is different. With the contraction of the coal flow field, the probability of arching increases. In other words, the arching probability is random.
(3) Arching materials. The arching materials are not only just coal blocks but also coal and gangue blocks.

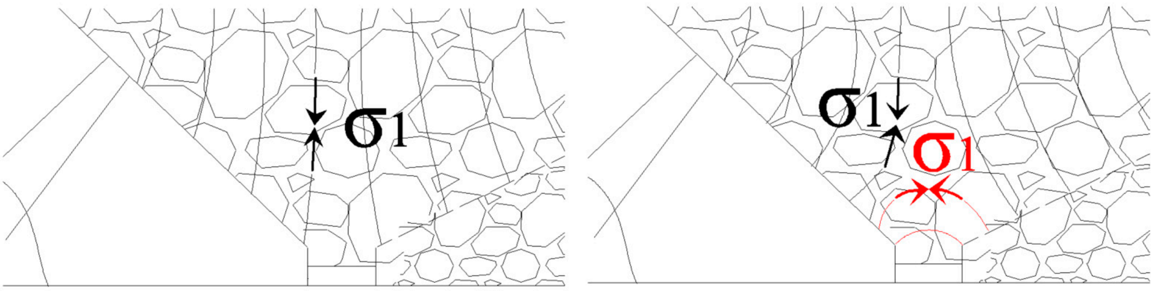
To sum up, the formation time, position and shape of the arch structure have dynamic and random characteristics, so they can be called dynamic random arched (DRA) which are formed by different fragment dimension of the coal and gangue in top-coal caving process. According the characteristics and types of DRA, the arching conditions are as follows.

(1) Uneven or relative displacement needs to occur.
(2) The support points or constraints should exist to act as the skewback.

3.4. Arching Mechanism of DRA and Its Effect on Top-Coal Caving Process

3.4.1. Arching Mechanism

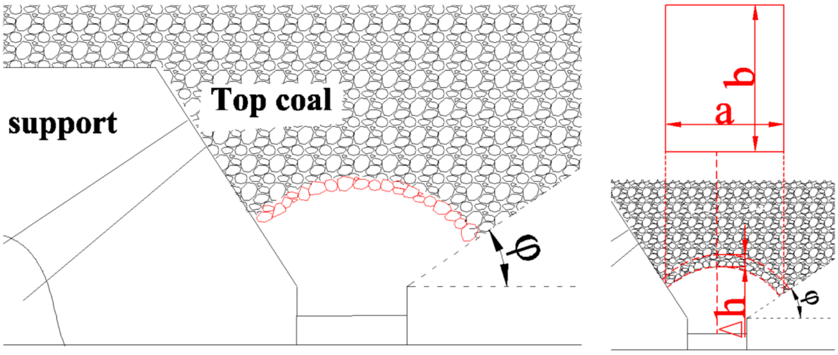
In a stationary state, the trajectories of the major principal stress of the loose coal and gangue behind the support are almost perpendicular and bends slightly toward both sides, as shown in Figure 6a. When the caving-outlet is opened, the static loose coal and gangue loses the support force, and the coal and gangue near the caving-outlet begins to flow and discharge out. The shape and size of broken coal/gangue are irregular and uneven, causing large friction between particles. During the discharge phase, the flow of the coal gangue is blocked, so the movement of the coal and gangue in higher position will lag than lower ones. In addition, the coal caving space is gradually shrinking from top to bottom, the trajectories of the major principal stress of coal/gangue near the coal-caving port will become horizontal, while the one of the coal/gangue in the higher position is gradually reduced, but still vertical, as shown in Figure 6b.



(**a**) (**b**)

Figure 6. Trajectories of major principal stress during (**a**) stationary state and (**b**) discharge state.

The support tail beam and the gangue in the gob form a sloping boundary, providing horizontal extrusion force for the top coal flowing. Because of the horizontal extrusion force between the particles, the particles will produce vertical shear stress. When the vertical shear force surrounding the entire coal-caving outlet is sufficient to withstand the weight of loosed coal and gangue at top of the coal-caving outlet, the top coal will be arched. At the same time, the contour of the arch will coincide with the maximum major principal stress trace. The arching model is shown in Figure 7a. The shape of the top-coal caving-outlet is rectangular, assuming the area of the hole is A, the circumference of the orifice is L, and the edges of the orifice are a and b, respectively, as shown in Figure 7b.



(a) (b)

Figure 7. The top coal arching (**a**) model and (**b**) size.

Under the condition of arching, an arbitrary height of ΔH is taken, according to the balance of force:

$$A\Delta h\rho g = L\Delta h\tau, \quad (1)$$

because the critical radius of the arch hole is:

$$R = \frac{A}{L}, \quad (2)$$

so:

$$R = \frac{\tau}{\rho g}, \quad (3)$$

in which:

$$\tau = \frac{h_0 \rho g cos\varphi}{2}, \quad (4)$$

therefore:

$$R = \frac{h_0 cos\varphi}{2}, \quad (5)$$

in which h_0 is the vertical wall height of coal, which is affected by factors such as the broken degree, shape and water content of the top coal, and its range is 0.3–3 m. The range of internal friction angle is determined as φ = 15–45°. Therefore, it can be calculated that the critical arch radius is 0.106–1.448 m. The width of the caving outlet is 0.6–0.8 m. In the case of high broken degree of top coal or even powder, the phenomenon of arching in the process of coal caving will not occur. For the ultra-thick coal seam with high strength, low broken degree, barge internal friction angle and large straight wall height, the critical arch radius is larger than the width of the caving-outlet, so it is inevitable to be arching.

3.4.2. Affecting Factors

The arch is considered as a whole, and the front skewback on the tail is recorded as A, the angle between the tail beam and the horizontal plane is β, the vertex of the angle is set to E, the rear skewback on the gangue in the Gob is recorded as B, the resting angle of the gangue is α, the vertex of the rest angle is F, the uniform pressure from coal gangue above the arch is q, the skewback is supported and the frictional force respectively, The support force is decomposed into two forces in horizontal and vertical directions, and the force analysis is shown in Figure 8.

A plane coordinate system is established with origin at the center point of the coal seam, and the width of the caving-outlet is $2a$. The vertex of the arch is C, the vertical distance of point C and point A is h, the vertical distance of point C and point B is $(h + \triangle h)$, the ordinate of point A is set to h_1, the ordinate of point B is set to h_2, then the coordinates of point A, B, C, D, E and F are $(-(\frac{h_1}{tan\beta} + a), h_1)$, $(-(\frac{h_2}{tan\alpha} + a), h_2)$, $(0, h_1 + h)$, $(0, h_1 + h)$, $(-a, 0)$ and $(a, 0)$, respectively.

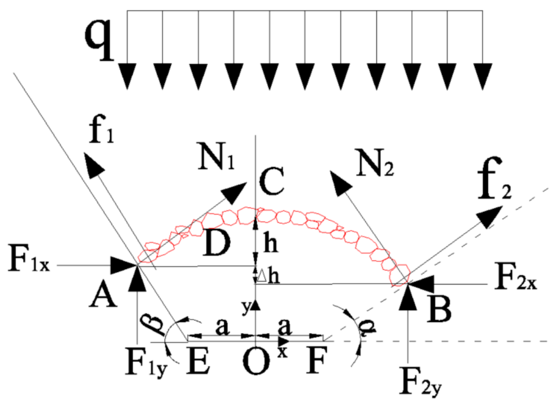


Figure 8. The stress analysis of the top coal arch rear support.

The force of the arch is analyzed, and the force of the arch in the x direction is zero:

$$\sum F_x = 0,\ F_{1x} = F_{2x} = F_x, \tag{6}$$

the force of the arch in the y direction is zero:

$$\sum F_y = 0, F_{1y} + F_{2y} - q\left(\frac{h_1}{tan\beta} + \frac{h_2}{tan\alpha} + 2a\right) = 0, \tag{7}$$

the torque of the arch AC segment of arch is zero:

$$\sum M_C = 0, F_{1y}\left(\frac{h_1}{tan\beta} + a\right) - F_{1x}h - \frac{q}{2}\left(\frac{h_1}{tan\beta} + a\right)^2 = 0, \tag{8}$$

the torque of the arch BC segment of arch is zero:

$$\sum M_C = 0, F_{2y}\left(\frac{h_2}{tan\alpha} + a\right) - F_{2x}(h + \Delta h) - \frac{q}{2}\left(\frac{h_2}{tan\alpha} + a\right)^2 = 0, \tag{9}$$

any section D in the AV segment of arch:

$$\sum M_D = 0, F_{1y}\left(\frac{h_1}{tan\beta} + a + x\right) - F_x(y - h_1) - \frac{q}{2}\left(\frac{h_1}{tan\beta} + a + x\right)^2 = 0, \tag{10}$$

and take the extreme value at the C point of the arch, that is $y'_{x=0} = 0$.

So:

$$F_x = \frac{q}{2h}\left(\frac{h_1}{tan\beta} + a\right)^2, \tag{11}$$

$$F_{1y} = q\left(\frac{h_1}{tan\beta} + a\right), \tag{12}$$

$$F_{2y} = q\left(\frac{h_2}{tan\alpha} + a\right), \tag{13}$$

$$y = \frac{h\left[\left(\frac{h_1}{tan\beta} + a\right)^2 - x^2\right]}{\left(\frac{h_1}{tan\beta} + a\right)^2} + h_1 \tag{14}$$

According to the Theory of Blandarakov [33], there is a relationship among the height h, width D of dynamic drop arch and the internal friction coefficient f of the material:

$$f = D/2h, \tag{15}$$

in this paper:

$$\frac{D}{2} = \frac{h_1}{tan\beta} + a, \tag{16}$$

so:

$$h = \frac{\frac{h_1}{tan\beta} + a}{f} \tag{17}$$

Equation (12) is introduced into Equation (9) to get the curve equation of the arch

$$y = \frac{\left(\frac{h_1}{tan\beta} + a\right)^2 - x^2}{\left(\frac{h_1}{tan\beta} + a\right) \times f} + h_1 \tag{18}$$

For the granular arch, the steeper of the arch is, the more difficult it is to destroy, and the steeper arch can be obtained by the slope of the arch curve. Derivation of equation of parabola for the tangent equation:

$$y' = \frac{-2x}{\left(\frac{h_1}{tan\beta} + a\right)f} \tag{19}$$

Take $2a$ = 0.8 m, h_1 = 1, tail beam angle range is 30–60°, then therange of horizontal coordinate of front arch skewback is (1/tan30 + 0.4, 1/tan60 + 0.4), namely (−2.13, −0.98) in the first half of the arch to take a point G, and ordered x_G = −0.8, then he slope at the point G is:

$$y'_{x\,=\,0.8} = \frac{-1.6}{\left(\frac{1}{tan\beta} + 0.4\right)f} \tag{20}$$

It is concluded that the slope of point G is related to the inclination angle of the tail beam and the internal friction coefficient of the top coal, and the relationship among them is shown in Figure 9.

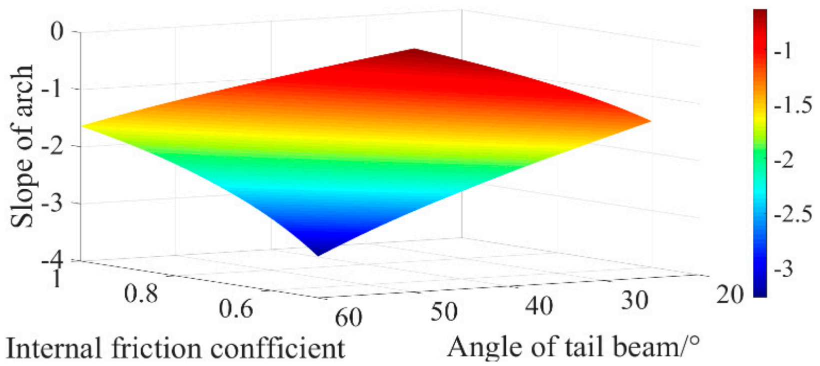


Figure 9. The relationship among slope of arch, internal friction conffícient and angle of tail beam.

From Figure 9, the steep degree of arch is influenced by the internal friction coefficient of the coal/gangue and the angle of tail beam. For the top-coal caving mining, the smaller the top coal fragmentation, the smaller the inner friction coefficient and the smaller the slope of the arch. Therefore, reducing the crushing block size of the top coal and increasing the angle of tail beam can reduce the chance of arching. From the above, although the formation of the dynamic arch has randomness, the factors which affect the formation of DRA are as follows.

(1) Fragment dimension. Mutual contact and extrusion would have had to occur between the top-coal and gangue in the process of top-coal caving mining. The larger the top-coal/gangue is, the easier it is to squeeze to form a more stable hinge structure, thus forming a stable arch structure. So the coal/gangue fragment dimension and distribution have great influence on the formation of arch structure.
(2) Arch span. The span of the arch structure determines the number of coal/gangue blocks in the arch structure. Usually, the arch structure is relatively stable, once one block in the arch structure is unstable, the whole arch structure is damaged and unstable, so the larger the span of arch structure, the lower stability and higher position of the arch would be.
(3) Horizontal binding force. Because the arch structure usually belongs to the parabolic curve. The constraint of the horizontal force is an important factor to stabilize the arch structure. Usually, the horizontal force can provide the constraint for the skewbacks. And the horizontal binding force can also increase the extrusion between blocks in the arch structure, thus increase of the stability of the whole arch structure.

Therefore, in the process of fully mechanized top-coal caving mining, the lower arch structure span is small. Because the flow field range decreases from top to bottom, the binding force in horizontal direction increases, the arching probability of the lower arch structure is the highest, and the arching probability of the upper arch structure is the lowest.

3.5. Removing Strategies of DRA and Technology Path of Intelligent Top-Coal Caving Mining

3.5.1. Removing Strategies of DRA

The concrete measures taken in the top-coal caving working face are as follows.

(1) Top-coal water softening

Dynamic pressure combined with static pressure water injection was used in long boreholes to softening the top-coal of the Panel 8103, that is, the boreholes were bored in both gateways in opposite directions along the coal seam. The water injection boreholes move with the recovery schedule and keep a 30 m distance from the working face. Fragment dimension of the top-coal in non-water injection and water injection zone were observed, and the observation result as shown in Figure 10a, the fragment dimension as shown in Figure 10b,c.

Water was infused into the top-coal seam of Panel 8103 for softening. Then, the fragment dimension of the top-coal decreased in the top-coal caving process, and the arching probability reduced synchronously.

(2) Improve the working resistance of the supports and oscillate the caving beam

The zf-15000/28/52 low top-coal caving supports were laid in the Panel 8103 whose shield beam had two jacks installed (the max working force is 2000 KN). So the large resistance supports were used to block the top-coal through the support in the mining process to decrease the fragment dimension of the top-coal repeatedly. The shield beam can swing up 19.5° and down 41°. In the process of coal caving, the lower arch structure near the caving outlet would be removed by the telescopic motion of the tail beam, and the middle arch structure would be removed by the swinging of the shield beam. The strong oscillation of the jacks decrease the fragment dimension of the top-coal and increase the fluidity of the caving flow.

(3) Multi-cycles/multi-outlets top-coal caving

In view of the occurrence of different DRA in the process of top-coal caving, group multi-cycles and multiple-outlet caving method were adopted. If the upper arch structure is formed behind No. 1 support during the top-coal caving process, the collapse of the arch structure would be caused by the top-coal caving behind adjacent support because of the large span of the upper arch. So, when the upper arch is formed in the flow space behind No. 1 support, the caving outlet of No. 1 support would be closed and caving the top-coal behind the adjacent support subsequently, the caving outlet should be re-opened when the top-coal caving behind the No. 2 support was finished to draw out all top-coal behind the No. 1—multi-cycles method. Or, adjacent 2 caving outlets of supports, i.e., Nos. 1 and 2 are one group and Nos. 3 and 4 is another group, would be opened synchronously for one group to increase the flow space and decrease the arching probability of top-coal–multi-outlet method.

According to the measured results, through the above measures, the recovery of top coal in the fully mechanized top coal caving mining of ultra-thick coal seam has increased nearly 6%, from the original 80.77% to 86.67%, and increased the production efficiency at the same time.

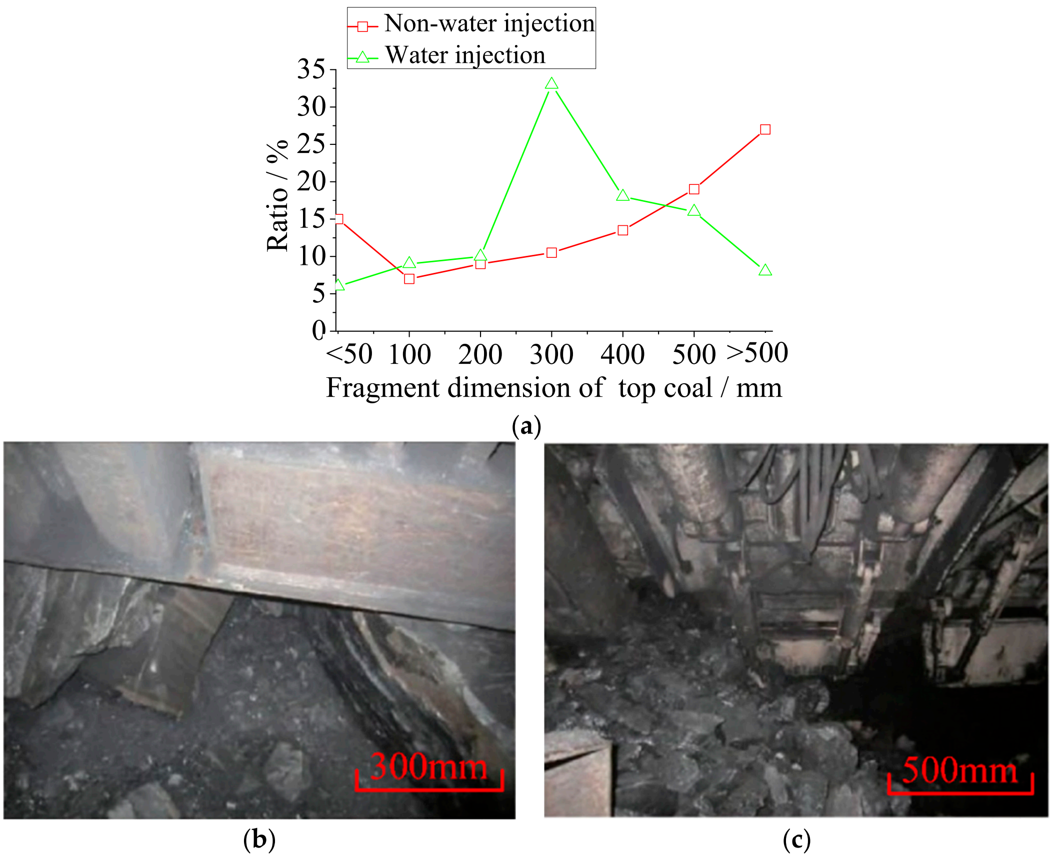


Figure 10. Fragment dimension of top-coal in non-water injection and water injection zone. (**a**) Fragment dimension ratio; (**b**) Top-coal fragment dimension before water injection; (**c**) Top-coal fragment dimension after water injection.

3.5.2. Technology Path of Intelligent Top-Coal Caving Based on the Removal Strategies of DRA

DRA in top-coal caving mining not only affects the caving smoothness and recovery ratio of the top-coal but also affects the coal caving time. Therefore, these factors must be taken into account in the research of fully-mechanized intelligent top-coal caving mining, especially the function of intelligent analysis to judge the exiting of arches and removal of them. Meanwhile, the top-coal caving mining technology, support controlling technology, smoothness of top-coal and the coordination of all mining processes should be done to realize the intelligent control of the top-coal caving mining. To this end, the technical path is presented as shown in Figure 11.

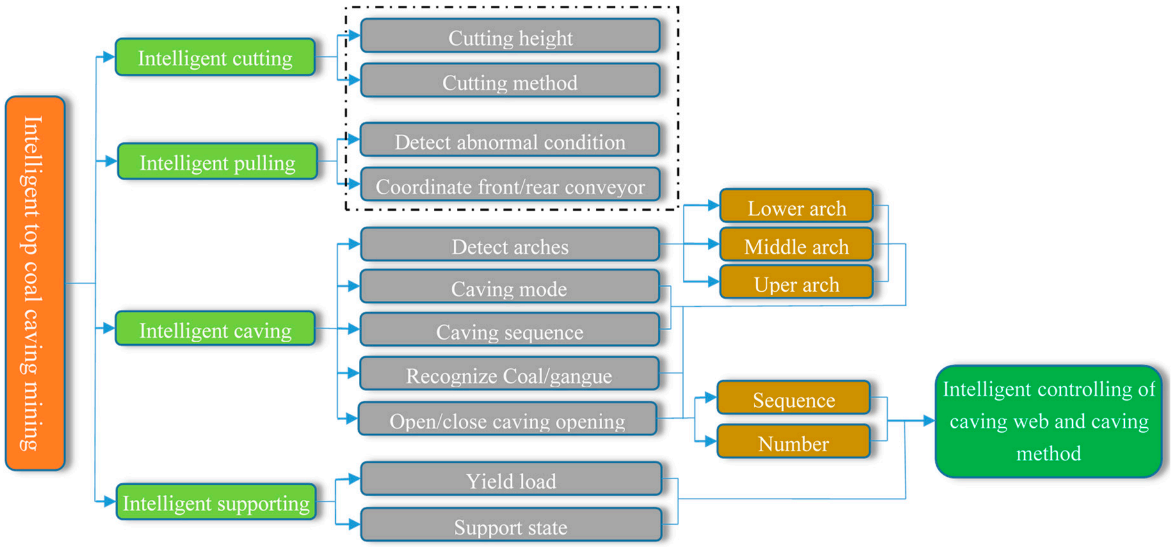


Figure 11. The technology path of intelligent top-coal caving mining.

4. Discussion

In this paper, the types, arching probability, and effect on top coal caving mining of arch formed in top coal caving process in fully mechanized top-coal caving mining is studied by means of laboratory physical simulation test. Three different arch structures were recognized according to the arching stratum characteristics. And the arch medium was determined. The DRA characteristics were described and their effects are found. The mechanism of arching and factors influencing arching are analyzed through mechanical analysis, and combined with the above research, the related measures are put forward through field practice. The above measures can effectively improve the recovery rate of top coal.

In terms of on-site operation, the top-coal water softening project is a huge and complex construction, which also effects the production efficiency of the working face. In the later stage, water injection equipment and hydraulic support can be integrated together to make water injection as a function of the hydraulic support, which will increase the convenience of the operation and improve the efficiency. And the production efficiency of the working face has a greater impact on equipment arrangement in advance. Water injection equipment and hydraulic support integration can increase the convenience of operation.

Besides the arches in top coal caving mining, there are many other factors affect the recovery ratio of top-coal, the calculations for the ellipsoid of relaxation zones would be taken into account in future studies.

5. Conclusions

(1) According to the layer characteristics and medium composition, the arches are divided into lower, middle and upper arch layers in fully mechanized top coal caving mining of ultra-thick coal seam. The coal and gangue are the medium composition of arches. And there are different arching probability and stability in different layers.

(2) The arch has dynamic and random characteristics. The stability of DRA was influenced by the fragment dimension, arch span and the horizon binding force. The arching probability of the lower arch is higher than others. The arches can be damaged by destabilizing the skewback and adopting the composing sequence.

(3) In the process of top coal caving, the arching probability is reduced and the recovery ratio is improved by means of top coal water softening, improving the working resistance of the supports, oscillating the caving beam, and multi-cycles/multi-openings top coal caving.

(4) The intelligent fully mechanized top coal caving should consider the influences of the arch structure during the caving process. To ensure the maximum recovery of top-coal, the caving technology and support action should be combined to realize the intelligent detecting and removing arches.

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References

1. Huang, B.X.; Wang, Y.Z.; Cao, S.G. Cavability control by hydraulic fracturing for top coal caving in hard thick coal seams. *Int. J. Rock Mech. Min. Sci.* **2015**, *74*, 45–57. [CrossRef]
2. Li, M.; Zhang, J.X.; Huang, Y.L.; Gao, R. Measurement and numerical analysis of influence of key stratum breakage on mine pressure in top-coal caving face with super great mining height. *J. Cent. South Univ.* **2017**, *24*, 1881–1888. [CrossRef]
3. Li, S.; Fan, C.J.; Luo, M.K.; Yang, Z.H.; Lan, T.W.; Zhang, H.F. Structure and deformation measurements of shallow overburden during top coal caving longwall mining. *Int. J. Min. Sci. Technol.* **2017**, *27*, 1081–1085. [CrossRef]
4. Wang, X.F.; Wang, Y.; Zhang, D.S.; Wang, H.Z.; Zhang, Y.; Qin, D.D.; Zhang, C.G. Characteristics of strata behavior during thick seam mining by fully-mechanized top coal caving in a loess-covered gullied region. *Minerals* **2017**, *7*, 63. [CrossRef]
5. Chi, M.B.; Zhang, D.S.; Fan, G.W.; Zhang, W.; Liu, H.L. Prediction of top-coal caving and drawing characteristics by the analytic hierarchy process-fuzzy discrimination method in extra-thick coal seams. *J. Intell. Fuzzy Syst.* **2017**, *33*, 2533–2545. [CrossRef]
6. Kong, D.Z.; Wang, Z.H.; Li, X.M.; Wang, Y.L.; Wang, C. Study of reasonable width of full-mechanized top-coal caving with large mining height. *Rock Soil Mech.* **2014**, *35*, 460–466.
7. Liu, Y.J.; Wang, X.M. Technology Research on the Fourth Panel Mining Large Height Fully-Mechanized Caving Mining in Shangwan Coal Mine. In Proceedings of the International Conference on Engineering Technology and Application, Xiamen, China, 29–30 May 2015; Li, J.Y., Liu, T.Y., Deng, T., Tian, M., Eds.; EDP Sciences: Les Ulis, France, 2015; Volume 22.
8. Li, H.M.; Peng, S.; Li, H.G.; Xu, Y.X.; Yuan, R.F.; Yue, S.S.; Li, K. Trial of small gateroad pillar in top coal caving longwall mining of large mining height. *Int. J. Min. Sci. Technol.* **2016**, *26*, 139–147. [CrossRef]
9. Wang, J.H. Demonstration project of safe and efficient mining operations in extra-thick coal seam. *Front. Eng. Manag.* **2016**, *3*, 264–274. [CrossRef]
10. Guo, J.S.; Ma, L.Q.; Wang, Y.; Wang, F.T. Hanging wall pressure relief mechanism of horizontal section top-coal caving face and its application—A case study of the Urumqi coalfield, China. *Energies* **2017**, *10*, 1371. [CrossRef]
11. Li, Z.; Xu, J.L.; Yu, S.C.; Ju, J.F.; Xu, J.M. Mechanism and prevention of a chock support failure in the longwall top-coal caving faces: A case study in Datong coalfield, China. *Energies* **2018**, *11*, 288. [CrossRef]
12. Ren, P.; Qian, J.S. A power-efficient clustering protocol for coal mine face monitoring with wireless sensor networks under channel fading conditions. *Sensors* **2016**, *16*, 835. [CrossRef] [PubMed]
13. Xie, J.C.; Yang, Z.J.; Wang, X.W.; Wang, S.P.; Zhang, Q. A joint positioning and attitude solving method for shearer and scraper conveyor under complex conditions. *Math. Probl. Eng.* **2017**, *2017*, 3793412. [CrossRef]
14. Wang, J.H.; Huang, Z.H. The recent technological development of intelligent mining in China. *Engineering* **2017**, *3*, 439–444. [CrossRef]
15. Yang, Y.S.; Li, X.W.; Zhang, L.Z. Research on Hydraulic Support Selection of Unmanned Fully-Mechanized Coal Mining Face. In Proceedings of the 2016 7th International Conference on Mechatronics, Control and Materials (ICMCM 2016), Changsha, China, 29–30 October 2016; Volume 104, pp. 295–301.

16. Li, X.S.; Lu, J. Design and Application of Interface Circuit of Coal Mine Equipment Intelligent Management System TCP/IP Module. In Proceedings of the 2016 6th International Conference on Machinery, Materials, Environment, Biotechnology and Computer (MMEBC), Tianjin, China, 11–12 June 2016; Volume 88, pp. 1869–1874.
17. Yu, G.H.; Wang, S.Y. The Design of Gas Monitoring System Based on the Prediction Model. In Proceedings of the 2016 6th International Conference on Machinery, Materials, Environment, Biotechnology and Computer, Tianjin, China, 11–12 June 2016; Zhang, L., Xu, D., Eds.; Atlantis Press: Paris, France, 2016; Volume 88, pp. 1910–1915.
18. Song, Q.J.; Jiang, H.Y.; Zhao, X.G.; Li, D.M. An automatic decision approach to coal-rock recognition in top coal caving based on MF-score. *Pattern Anal. Appl.* **2017**, *20*, 1307–1315. [CrossRef]
19. Zhang, G.X.; Wang, Z.C.; Zhao, L.; Qi, Y.Z.; Wang, J.S. Coal-rock recognition in top coal caving using bimodal deep learning and hilbert-huang transform. *Shock Vib.* **2017**, *2017*, 3809525. [CrossRef]
20. Zhang, G.X.; Wang, Z.C.; Zhao, L. Recognition of rock-coal interface in top coal caving through tail beam vibrations by using stacked sparse autoencoders. *J. Vibroeng.* **2016**, *18*, 4261–4275.
21. Zhang, N.B.; Liu, C.Y.; Yang, P.J. Flow of top coal and roof rock and loss of top coal in fully mechanized top coal caving mining of extra thick coal seams. *Arab. J. Geosci.* **2016**, *9*, 465. [CrossRef]
22. Guo, W.B.; Tan, Y.; Bai, E.H. Top coal caving mining technique in thick coal seam beneath the earth dam. *Int. J. Min. Sci. Technol.* **2017**, *27*, 165–170. [CrossRef]
23. Zhang, N.B.; Liu, C.Y.; Pei, M.S. Effects of caving-mining ratio on the coal and waste rocks gangue flows and the amount of cyclically caved coal in fully mechanized mining of super-thick coal seams. *Int. J. Min. Sci. Technol.* **2015**, *25*, 145–150. [CrossRef]
24. Bai, Q.; Tu, S.; Wang, C. Numerical simulation on top-coal arching mechanisms. *J. Min. Saf. Eng.* **2014**, *31*, 208–213.
25. Yu, B.; Xia, H.C.; Meng, X.B. Top coal arching mechanism and arch removal strategies in fully mechanized top coal caving mining of ultra-thick coal seam. *J. China Coal Soc.* **2016**, *41*, 1617–1623.
26. Bychkov, I.V.; Vladimirov, D.Y.; Oparin, V.N.; Potapov, V.P.; Shokin, Y.I. Mining information science and big data concept for integrated safety monitoring in subsoil management. *J. Min. Sci.* **2016**, *52*, 1195–1209. [CrossRef]
27. Guo, P.J.; Zhou, S.H. Arch in granular materials as a free surface problem. *Int. J. Numer. Anal. Methods Geomech.* **2013**, *37*, 1048–1065. [CrossRef]
28. Vivanco, F.; Rica, S.; Melo, F. Dynamical arching in a two dimensional granular flow. *Granul. Matter* **2012**, *14*, 563–576. [CrossRef]
29. Perry, M.G.; Handley, M.F. Dynamic arch in free flowing granular materialdischarging from a model hopper. *Trans. Inst. Chem. Eng.* **1967**, *45*, T367.
30. Duran, J.; Kolb, E.; Vanel, L. Static friction and arch formation in granular materials. *Phys. Rev. E* **1998**, *58*, 805–812. [CrossRef]
31. Peralta-Fabi, R.; Malaga, C.; Rechtman, R. Arching in confined dry granular materials. *Europhys. Lett.* **1999**, *45*, 76–82. [CrossRef]
32. Liu, C.Y.; Huang, B.X.; Wu, F.F. Fragment dimension theory and its application in fully mechanized top coal caving. *J. Min. Saf. Eng.* **2006**, *23*, 56–61.
33. Lu, Z.H. The mechanism analysis of flowing agricultural particle material arching in hole. *Trans. Chin. Soc. Agruc. Eng.* **1991**, *7*, 78–85.