Research Article

Study and Application of Roof Cutting Pressure Releasing Technology in Retracement Channel Roof of Halagou 12201 Working Face

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The retracement channel roof cutting (RCRC) technology can change the overburden structure actively by cutting off the roof of channel along the direction of working face tendency and make use of the gangue collapsing from roof cutting range to fill the goaf and weaken the mining pressure during the retracement process of working face. In order to solve the problems of high stress in surrounding rock and serious deformation of retracement channel in Halagou coal mine, it is the first time that the pressure releasing test is carried out on the 12201 working face by the method of the directional presplitting roof cutting in retracement channel. First, according to statics theory and energy theory, the stress state of hydraulic support and roof deformation mechanism of retracement channel are analyzed. Then the roof cutting design of retracement channel is determined according to the geological conditions of 12201 working face, and the cutting effect is analyzed by numerical simulation. Finally, the field test is carried out on the 12201 working face to verify the effect of pressure releasing by roof cutting. The result shows that, with the roof cutting design including the roof cutting height being 8m and roof cutting angle being 45°, the roof subsidence of the 12201 working face retracement channel in Halagou mine is reduced to 132.5mm, and the hydraulic support resistance is maintained at 1361KN. And there is no hydraulic support crushed; the deformation of the retracement channel is also small; namely, the effect of roof cutting for pressure releasing is obvious.

1. Introduction

The coal mining method of wall system can realize continuous coal mining and has the advantages of high yield, high efficiency, high production efficiency, and strong adaptability, so it has been widely popularized all over the world [1]. In China, Russia, Poland, Ukraine, Britain, Germany, France, Japan, and other coal mining countries, the coal production with wall system all accounts for more than 80% of the whole underground mining production [2, 3]. But in the application of wall system coal mining method, the stopping and withdrawing process of working face is always the key link restricting its production succession and safety level [4].

There are two main ways regarding the retracement of fully mechanized mining working face in China. One is excavating the retracement channel in advance, that is, excavating 1 or 2 auxiliary lanes parallel to the mining face before the end of the mining work at the stopping line of the mining face, and is used for the retracement of the working face. The other is excavating the retracement channel by the coal mining machine; namely, when the mining face is pushed to the stopping line, the coal mining machine cuts coal wall to form the retracement channel by itself [5, 6]. No matter which method of retracement is adopted, the control of the working face surrounding rock at the end of the mining stage is an unavoidable problem. Particularly, the way of excavating the

TABLE 1: Parameters of each rock layer.

Lithology	Density/kN/m ³	Tensile Strength/MPa	Internal Friction Angle/°	Cohesion/MPa	Bulk Modulus/GPa	Shear Modulus/GPa
Siltstone	22	4.3	28	0.8	2.11	1.86
Fine sandstone	23	7.3	30	1.0	3.81	3.05
Mudstone	20	3.2	28	0.2	0.20	0.15
Coal	13	3.3	29	0.2	0.35	0.18

retracement channel in advance has a higher demand of the roof support, because the channel will be influenced by the stress concentration caused by the advance of mining face [7, 8].

In view of the above problems, many scholars have carried out a large number of studies. Xi Long, taking the 2505 working face of Yongcheng coal mine as an example, studies the mechanical structure and motion state of the overlying rock mass upon the retracement channel and puts forward the reinforcement support measures of the retracement channel under different overburden fracture structures [9]. Kang Jichun points out that the instability process of retracement channel contains three stages, namely, the influence stage of the channel excavation, the influence stage of the mining work, and the influence stage of the main roof's instability. And, on the basis of this, the support design and process of the retracement channel are optimized according to the different stages of the instability [7, 10]. Through the deformation observation of the retracement channel of a broken roof working face, Zhang Jinhu finds out that the movement of its roof can be divided into three processes: relative stability, mutational motion, and significant motion. And, increasing the working resistance of the chock supports in the retracement channel under the relatively stable stage, the final deformation of channel can be controlled effectively [11]. The above research results provide good references for the mechanism exploration of the retracement channel's deformation and the design of the supporting countermeasures. However, in the current research, the deformation control of the retracement channel is still mainly realized by the passive reinforcement of support. While controlling the deformation of the surrounding rock, the support cost and workload also increase, and the retracement and succession of working face are also affected.

In 2009, academician He Manchao of the Chinese Academy of Sciences proposed the roof cutting pressure releasing gob-side entry retaining (RCPRGER) non-pillar mining technology [12]. The core of this technology is cutting off the stress transfer between goaf roof and entry roof through directional presplitting blasting implemented on the goaf side of entry roof. Then, after the working face mining, the roof of goaf area will collapse, the mined area adjacent to the retaining entry will be filled up with the broken fallen rocks, and the roadway will be retained automatically with no coal pillar or filling material [13, 14]. At present, the technology has been successfully carried out in many mines to retain the gob-side entry, and the effect of pressure release by roof cutting is obvious. Therefore, taking this as a reference, this paper studies the application of the roof cutting pressure releasing (RCPR) technology in the retracement

channel firstly, namely, through the blasting cutting of the retracement channel roof to cut off the partial stress transfer in the roof and improving the stress environment of the channel surrounding rocks actively, relieving the roof support pressure.

2. Project General Situation

This paper takes the 12201 working face of Halagou coal mine as an engineering example to carry out the research of the retracement channel roof cutting (RCRC) technology. Halagou coal mine is located in the boundary region between Inner Mongolia and Shaanxi provinces in China (as shown in Figure 1(a)), and the 12201 working face is the first mining face of the No.2 panel in Shendong group. The working face is about 747m long in the strike length and 320m long in the tendency length. The thickness of the coal seam ranges from 1.6m to 2.4m, and the average thickness is 2.0m. The buried depth of the working face is about 60m to 100m, and the dip angle of the coal seam is between 1° and 3°. The roof of this working face is a typical coal containing composite roof, its stratigraphic column is shown in Figure 1(b), and the relevant parameters of each rock layer are listed in Table 1.

The layout of 12201 working face is shown in Figure 1(c). The 560m length section before the stopping line of this working face's haulage entry is used to carry out the RCPRGER technology, and the retained entry can be used as the air return entry of 12202 working face. The 12201 working face takes the method of excavating two retracement channels in advance to realize the working face retracement. The length of the retracement channels is 320m, and the tunnel sections are rectangular. Among them, the main retracement channel is 5.2m wide and 2.0m high, and the auxiliary retracement channel is 5.5m wide and 2.0m high. In the working face retracement of adjacent panel, the maximum load of hydraulic support reached 60MPa, and the dynamic load coefficient reached 2.08. Some hydraulic supports were compressed severely, and a part of them were damaged (as shown in Figure 2). Besides, the reinforce support of main retracement channel was difficult, usually needing two rows of chock supports. Therefore, in order to alleviate this phenomenon, this paper takes the 12201 working face as an engineering example to carry out the research about the RCRC technology.

3. RCRC Pressure Releasing Technology

On the basis of the analysis of the overburden strata structure at the final mining stage, this paper puts forward the RCRC

FIGURE 1: Layout and roof lithology of 8304 working face.

FIGURE 2: Overloaded and damaged hydraulic support.

FIGURE 3: Structure diagram of overlying strata at stop line.

FIGURE 4: Breaking process under roof cutting condition.

technology and then combines it with the bidirectional concentrated tension blasting (BCTB) technology to change the structure of the overburden strata actively and improve the pressure environment of hydraulic supports in the retracement channel.

3.1. Analysis of Roof Structure at the Final Mining Stage. Firstly, the roof structure of the working face at the final mining stage under the traditional condition is analyzed. When the retracement channel is formed and connected with the working face, the overburden strata structure at the stopping line, according to the fault line position of the main roof, can be divided into three types: breaking behind the stopping line, breaking upon the retracement channel, and breaking upon the coal wall (as shown in Figures 3(a)–3(c)) [15].

When the main roof is breaking behind the stopping line, the last periodic weighting has completed, and next periodic weighting has not occurred. So the hydraulic supports in retracement channel are mainly subjected to the static load of the overlying rock mass, and the surrounding rock structure is more stable. When the main roof is breaking upon the retracement channel, the suspension length of main roof has reached the weighting step, and this periodic weighting is happening. So the hydraulic supports in retracement channel are affected by the rotation and sinking of main roof, and the surrounding rock structure is unstable. Under this condition, the large deformation of the retracement channel and the damage of hydraulic support are easy to occur during the retracement process of the working face. When the main roof is breaking upon the coal wall, although the suspension length of main roof has not reached the weighting step, the main roof has been breaking upon the coal wall crossing over the retracement channel and this periodic weighting has begun. So, under the disturbance of the retracement of hydraulic supports, the main roof is prone to further break and rotation. Then, during the retracement of the working

face, there are also the risks of the retracement channel deformation and the hydraulic supports overload.

Through the above analysis, it can be found that the structure of the surrounding rock is relatively stable when the main roof is breaking behind the stopping line. But, under the traditional long wall mining condition, the three kinds of main roof breaking forms are random. Therefore, the RCRC technology is put forward. Namely, before the connection of retracement channel and working face, the BCTB technology is used to cut off the retracement channel roof along the direction of working face tendency and change the overburden structure actively. Then when the working face is connected with the retracement channel, a part of roof behind the working face can fall down along the cutting slit and fill the goaf firstly (as shown in Figure 4(a)). Next, when the hydraulic supports have been withdrawn, the roof in the cutting range can collapse and fill the goaf further to weaken the mining pressure and load of hydraulic support in the working face retracement process (as shown in Figure 4(b)).

3.2. BCTB Technology. In order to realize the directional presplitting cutting in the roof of retracement channel along the direction of working face tendency, the BCTB technology is used to carry out the roof cutting. As a kind of directional presplitting blasting, this technology can realize the directional transmission of explosive energy along the leading direction of the energy gathering pipe through the combined use of energy gathering pipe and explosive and then realize the directional breaking of the overburden strata along the direction of roof cutting. The schematic is as shown in Figure 5 [16].

The structure and blasting control mechanism of energy gathering pipe are shown in Figure 6. Some pipes can be connected and installed by connecting sleeves according to the requirement of blasting depth, and the locked groove can maintain the energy gathering pipe towards a certain angle at the time of installation. When cutting the roof, a certain

FIGURE 5: Mechanics model of BCTB.

FIGURE 6: Device and principle of BCTB.

amount of explosive rolls is loaded into the energy gathering pipes, followed by putting them into the blasting hole in the roof and sealing the holes. The design of the energy hole can make the blasting energy produce the accumulation effect in a setting direction, which can form a tensile presplitting in the rock mass along the direction of energy gathering and protect the integrity of the rock mass in the energy nongathering area.

In order to achieve the ideal effect of presplitting cutting, the explosive charge structure and the blasting hole spacing should be rationally designed. In the application of the RCPRGER technology, the size of the energy gathering pipe is usually $\phi 36.5\text{mm} \times 1500\text{mm}$. Combined with the previous experience, the explosive charge structure of single hole should be determined by the field test according to the specific lithology of the roof. And a reasonable explosive charge structure of single hole can make two continuous cracks on the hole wall after blasting and cannot make the blasting hole collapse. Besides, the blasting hole spacing

depends on the influence range of blasting. If the spacing is too large, the presplitting cracks cannot penetrate the roof rock completely; if the spacing is too small, some explosion energy will be wasted.

In addition, in the application of RCRC releasing technology, in order to avoid the roof leakage of the working face during the connection process of retracement channel and working face, only charging the explosive in the section of blasting hole which is behind the hydraulic supports when the working face stops mining and the other section of the hole is only treated as sealing section, that can make the roof upon the hydraulic supports have a certain integrity.

4. Analysis of the Roof Cutting Effect in Retracement Channel

The RCPRGER has been successfully tested in many mines, and its schematic is shown in Figure 7. According to the

FIGURE 7: Simple diagram of roof cutting principle.

previous experiences about roof cutting, it can be seen that the roof cutting not only can affect the horizontal collapse of the roof but also has some influences on the roof vertical structure [17, 18].

In the horizontal direction, the roof presplitting cutting can cut off the stress transfer in the roof and can change the roof collapse form actively. Then the breaking and collapse of roof can turn to a human controlled process. In the vertical direction, part of main roof in the roof cutting affecting range can be converted to the immediate roof through the reasonable design of roof cutting height. Then the thickness of immediate roof will increase, and the gangue pile formed by immediate roof's collapsing and expansion can support main roof and other overlying strata much better. That can reduce the subsidence deformation of the overburden strata effectively. According to the structural evolution characteristics of the cutting roof, the roof cutting effect in retracement channel can be analyzed from two aspects of the hydraulic support pressure and channel deformation.

The working face is usually long under long wall mining, and the analysis emphasis is the working face advance section in this study. Based on the rock mass mechanical property of poor tensile capacity, the influence of both ends of the working face can be neglected, and the stress analysis of retracement channel can be simplified into 2D plane problem. Besides, during the retracement of working face, the retracement channel is supported well by various support types, so it can be regarded as a deformable body within a certain deformation range. Then, based on the classical assumptions in typical materials mechanics and elastic mechanics, such as continuity hypothesis, homogeneity hypothesis, small deformation hypothesis, the field problem can be solved by mathematical method in a certain content, and the analysis results can provide certain references to the engineering application.

4.1. Pressure Analysis of Hydraulic Support. Based on the stress balance theory of loose medium, Professor Hou Chaojong and Professor Ma Nianjie combined the stress differential equilibrium equation to find the stress of the coal seam interface and the width of the limit equilibrium area of the coal stress. On this basis, the limit equilibrium area width

and the support force of the plastic zone in the protective coal pillar at the stopping line can be solved as follows [19, 20]:

$$x_0 = \frac{mk_a}{x} \ln \left(\frac{k\gamma H + c' / \tan \varphi}{c' / \tan \varphi + p_x / k_a} \right), \quad (1)$$

$$\sigma = \left(\frac{c'}{\tan \varphi} + \frac{p_x}{k_a} \right) e^{2x \tan \varphi / mk_a} - \frac{c'}{\tan \varphi}, \quad (2)$$

where c' and φ are the cohesive force (MPa) and internal friction angle ($^\circ$) of the interface between the coal seam and surrounding rock; m is the coal seam thickness, m; k_a is the lateral pressure coefficient; k is the maximum coefficient of stress concentration; γ is the average density of coal seam, KN/m^3 ; H is the mining depth, m; p_x is the support strength of coal wall, MPa.

On this basis, the pressure of hydraulic support under four overburden strata structures is calculated, respectively [21, 22].

The mechanical models of the overburden strata breaking upon retracement channel are shown in Figure 8, where q is the resultant force of main roof weight and pressure of other overburden strata; q_0 is the average pressure caused by immediate roof; T_A is the horizontal thrust to rock block A; N_A is the shear force to rock block A; M_A is the bending moment to rock block A at point A'; T_B , N_B , and M_B have the same meaning as T_A , N_A , and M_A ; M_0 is the limit bending moment of direct roof; x_0 is the lateral width of limit equilibrium area in coal wall; σ is the support of coal wall plastic zone; F_G is the support of gangue wall; P_1 , P_2 , P_3 , and P_4 are the support force of the hydraulic support under four conditions; a is the width of the retracement channel; b is the support length of the hydraulic support; c is the horizontal distance between retracement channel and point A'. Taking Figure 8(a) as an example, the stress state of main roof rocks can be analyzed by static equilibrium method:

To rock B,

$$\begin{aligned} \sum F_x &= 0 \\ \sum F_y &= 0 \\ \sum M_{B'} &= 0, \end{aligned} \quad (3)$$

FIGURE 8: Mechanics model of main roof breaking upon retracement channel.

and then

$$\begin{aligned} T_A &= T_B \\ N_A &= N_B + qL \\ M_B + T_B(h - \Delta S_C) - N_B L - \frac{qL^2}{2} &= 0, \end{aligned} \quad (4)$$

and therefore

$$N_B = \frac{M_B + T_A(h - \Delta S_B) - qL^2/2}{L}, \quad (5)$$

$$N_A = \frac{M_B + T_A(h - \Delta S_B) + qL^2/2}{L}. \quad (6)$$

To rock A,

$$\sum M_A = 0, \quad (7)$$

and then

$$\begin{aligned} M_A + M_0 + P_1 \left(c + a + \frac{b}{2} \right) + \int_0^c \sigma(c-x) dx \\ + T_A(h - \Delta S_A) - M_B - \frac{qL^2}{2} - \frac{q_0(c+a+b)^2}{2} \\ - N_A L = 0. \end{aligned} \quad (8)$$

The horizontal thrust can be calculated as follows:

$$T_A = T_B = \frac{qL}{2(h - \Delta S_B)}, \quad (9)$$

where h is the thickness of main roof, m; L is the lateral breaking span of basic roof, m; ΔS_A is the subsidence of rock A at point B'; ΔS_B is the subsidence of rock B at point C'. Then P_1 can be solved as follows:

$$P_1 = \frac{[2M_B + qL^2 + q_0(c+a+b)^2/2 + qL(\Delta S_A - \Delta S_B) / [2(h - \Delta S_B)] - M_A - M_0 - \int_0^c \sigma(c-x) dx]}{(c+a+b/2)}. \quad (10)$$

In the same way, according to the mechanical models shown as Figures 8(b)–8(d), P_2 , P_3 , and P_4 can be solved as follows:

$$P_2 = \frac{[2M_B + qL^2 + q_0(a'+b)^2/2 + qL(h - \Delta S_C) / [2(h - \Delta S_B)] - M_A - M_0 - q'L/2]}{(a' + b/2)}, \quad (11)$$

$$P_3 = \frac{[2M_B + qL^2 + q_0(c+a+b)^2/2 + qL(\Delta S_B - \Delta S_C)/[2(h - \Delta S_B)] - M_A - M_0 - \int_0^c \sigma(c-x)dx]}{(c+a+b/2)}, \quad (12)$$

$$P_4 = \frac{[M_B(L+c+a+b) + q(c+a+b)^2/2 + qL(c+a+b)/2 + q_0(c+a+b)^2/2 + q(c+a+b)/2 - F_G(c+a+b) - M_A - M_0 - qL/4 - \int_0^c \sigma(c-x)dx]}{(c+a+b/2)}. \quad (13)$$

Comparing formula (11) and formula (12), $P_3 < P_2$ is easy to get. Because the residual bending moment at the fracture of rock beam is usually very small, which can be regarded as 0, $M_B=0$ in Formula (10) and $M_A=M_B=0$ in formulas (11) and (12). Then, through the subtraction between formula (12) and formula (10), it can be got that $P_1 < P_3 < P_2$. Generally, the roof suspension length behind the hydraulic supports under roof cutting condition is shorter than the no cutting condition, and $F_G \geq 0$. So $P_4 < P_1 < P_3 < P_2$ can be got through the subtraction between formula (13) and formula (10), which shows that the working pressure of hydraulic support decreases obviously after roof cutting.

4.2. Deformation Analysis of Roof. When the retracement channel is stable under various support types, the roof can be regarded as a deformable body that accumulates a certain amount of elastic energy, and the subsidence of it can be solved according to energy principle and variational method [23, 24]. The simplified mechanical model of retracement channel's immediate roof is shown in Figure 9. The left boundary is fixed; the right boundary is suffered pressure P_{z2} ; the upper boundary is given certain deformation; the lower boundary is suffered support P_{z1} of anchor cables and support P of hydraulic supports; θ is the rotation of basic roof. The strain energy can be calculated as follows:

$$U = \iiint \Delta U dx dy dz = \frac{1}{2} \iiint \sigma \varepsilon dV, \quad (14)$$

where dV is an elastic element; σ and ε are the stress and strain of elastic body. The immediate roof deformation of retracement channel can be regarded as a plane strain problem, so the strain energy can be expressed by displacement component:

$$U = \frac{E}{2(1+\mu)} \iiint \left[\frac{\mu}{1-2\mu} \left(\frac{\partial \mu}{\partial x} + \frac{\partial \mu}{\partial y} \right)^2 + \left(\frac{\partial \mu}{\partial x} \right)^2 + \left(\frac{\partial \mu}{\partial y} \right)^2 + \frac{1}{2} \left(\frac{\partial \mu}{\partial x} + \frac{\partial \mu}{\partial y} \right)^2 \right] dV, \quad (15)$$

where u and v are the displacement components.

Assuming that the direct roof elastic body becomes stable after a slight deformation caused by external force, the Lagrange displacement variational equation can be obtained as follows:

$$\delta U = \iiint (X\delta u + Y\delta v) dx dy + \iint (\bar{X}\delta u + \bar{Y}\delta v) ds, \quad (16)$$

where X and Y are the components of bulk force; $\bar{X}$ and $\bar{Y}$ are the components of surface force.

According to the boundary conditions of retracement channel, the displacement component on y -axis can be expressed as follows:

$$v = \frac{a}{l} \left[\frac{(4\mu-1)l\theta/16(1-2\mu)^2 - p_{z2}h'(1+\mu)/4E(1-2\mu)}{[(2l/3h')((1-\mu)/(1-2\mu)) + 2h'/3l][(2h'/3l)((1-\mu)/(1-2\mu)) + 2l/3h'] - 1/16(1-2\mu)^2} + \frac{[(2h'/3l)((1-\mu)/(1-2\mu)) + 2l/3h'] [\theta h'/6 - (2l^2\theta/3h')((1-\mu)/(1-2\mu)) + ((1+\mu)/E)[(p_{z1}a - h'\rho gl)/2 + (b/a + 2b)p]}{[(2l/3h')((1-\mu)/(1-2\mu)) + 2h'/3l][(2h'/3l)((1-\mu)/(1-2\mu)) + 2l/3h'] - 1/16(1-2\mu)^2} \right], \quad (17)$$

where $l=a+b$; E is the modulus of elasticity; μ is the Poisson ratio.

It can be seen that the main parameters affecting the roof deformation of retracement channel are the channel section size, the working resistance of hydraulic supports, the strength of channel support, the immediate roof rotation angle, and the immediate roof thickness. Under the same conditions of the channel section size, the working resistance of hydraulic supports, and the strength of channel support, the immediate roof thickness increases after the roof cutting. Then the gangue pile formed by immediate roof's collapsing and expansion can support

main roof and other overlying strata much better, and the rotation angle of main roof also decreases. So the roof subsidence of the retracement channel should also be reduced.

5. Roof Cutting Design of Retracement Channel

5.1. Key Parameters of Roof Cutting. The key parameters of roof cutting mainly contain roof cutting height and roof cutting angle.

FIGURE 9: Mechanics model of retrace channel direct roof.

5.1.1. Roof Cutting Height. In the haulage entry retaining process of Halagou coal mine, the roof cutting height is designed by the roof rock's crushing expansion coefficient. In order to ensure the effective filling of the goaf by the gangue after the collapse of the roof in the roof cutting range, the minimum roof cutting height can be calculated as follows [25]:

$$H_F = \frac{(H_M - \Delta H_1 - \Delta H_2)}{(K - 1)}, \quad (18)$$

where H_F is the minimum roof cutting height, m; H_M is the coal seam height, m; ΔH_1 is the roof subsidence volume, m; ΔH_2 is the floor heave volume, m; K is the roof rock's expansion coefficient. According to the weight calculation of the thickness of each rock layer in the roof cutting range (as shown in formula (19)), the roof rock's expansion coefficient K is 1.31. Then, ignoring the roof subsidence and floor heave, the minimum roof cutting height is calculated approximately to be 6.5m based on the coal seam height, which is 2m.

$$K = \sum_{i=1}^n K_i \frac{D_i}{H_M}, \quad (19)$$

where, assuming that the number of the rock layer in the roof cutting range is n ($n \geq 1$), the thickness of each rock layer is D_i ($1 \leq i \leq n$), and the rock's theoretical expansion coefficient K_i ($1 \leq i \leq n$) can be determined by indoor test.

In the practice of entry retaining test, the 6.5m roof cutting height can make the certain goaf zone adjacent to the retained entry be filled well and can form a gangue wall on one side of the retained entry, which can support upon main roof effectively. However, according to the roof lithologic histogram, the top of the roof cutting slit is located in the middle of the fine sand rock layer. When the entry is retained with the mining advance of working face, the immediate roof breaks along the roof cutting surface periodically with a certain suspension length affected by the dynamic mining pressure. But when the mining face reaches the stopping line after the roof cutting of retrace channel, the immediate roof of whole working face will break along the roof cutting surface basically at the same time under the affection of static pressure. So, in order to further reduce the tension of the roof breaking, the roof cutting height is raised to 8.0m in the roof cutting height design of retrace channel, namely, cutting off the fine sand rock layer completely as shown in Figure 12.

5.1.2. Roof Cutting Angle. The design of the roof cutting angle should meet two requirements. One is that the friction of the roof cutting surface should be small when the goaf roof collapses, and the other is that the goaf roof in the roof cutting range can collapse in time behind the hydraulic supports when the working face stops mining [26].

In general, the collapse of the goaf roof in the roof cutting range has two forms. One is the broken falling of lower immediate roof firstly, and the other is the rotary breaking of upper immediate roof then (as shown in Figure 10) [27]. At this condition, the rotary breaking process of upper immediate roof is the key to reduce the frictional effect to roof cutting surface caused by the collapse of goaf roof, and its geometric description is shown in Figure 11, where H_F is the roof cutting height and H_Z is the thickness of the lower immediate roof; the key rock block $OABN$ of upper immediate roof is subjected to a torque m with an axis O point. In order to ensure that the rotation with point O as axis of rock block $OABN$ has no extrusion and friction on the cutting face BM , the line segment OA needs to be longer than the line segment OB ; namely, $L_{OA} \geq L_{OB}$.

According to the geometric relationship shown in Figure 11, the length of L_{OA} and L_{OB} can be calculated as follows [18]:

$$\begin{aligned} L_{OB} &= \sqrt{L_S^2 + (H_F - H_Z)^2} \\ \frac{L_{OA}}{\sin \angle 3} &= \frac{L_{OB}}{\sin \angle 4} \\ \angle 4 &= \angle 1 = \pi - \angle 2 - \angle 3 \\ \angle 2 &= \arctan \frac{H_F - H_Z}{L_S} \\ \frac{L_{OB}}{\sin \angle 5} &= \frac{L_{BM}}{\sin \angle 6} = \frac{L_{MO}}{\sin \angle 3} \\ L_{BM} &= H_F - \frac{K \cdot H_Z - H_M}{\cos \beta}. \end{aligned} \quad (20)$$

During the entry retaining process of 12201 working face in Halagou coal mine, the lower mudstone layer can collapse directly when it is behind the hydraulic supports and exposed in the goaf, but the upper layers in the roof cutting range usually break with rotation. According to the above formulas, the minimum roof cutting angles of upper coal layer, mudstone layer, and fine sandstone layer are calculated to be 23° , 17° , and 12° , respectively.

In addition, the hydraulic support type of 12201 working face is TAGOR10660/11.3/22.3, the top beam length of this support is 4.8m, and the support maximum length is 5.8m. And, through field observation, the maximum suspension length of the immediate roof behind the hydraulic supports is 2m in the mining process. So, in order to ensure that the roof in the roof cutting range can collapse in time when the working face stops mining, the roof cutting slit should extend 2m behind the hydraulic supports at least (as shown

FIGURE 13: Numerical calculation model.

in Figure 12). Then the roof cutting angle can be calculated as follows:

$$\theta_F \geq \arctan \frac{L_D + L_J + d}{H_F}, \quad (21)$$

where L_D is the maximum suspension length of immediate roof, m; L_J is the maximum length of the hydraulic support, m; d is the distance between the cutting holes and the retracement channel principal wall, which is 200mm in this study. Taking relative parameters into formula (21), the result can be got as $\theta_F \geq 45^\circ$. At the same cutting height condition, the larger the cutting angle is, the deeper the cutting hole is and the larger the workload of roof cutting is. And if the roof cutting angle is too large, the roof leakage of working face during the connection process of retracement channel and working face may happen easily. So the roof cutting angle is designed as 45° finally, as shown in Figure 12.

5.2. Analysis of the Roof Cutting Effect. In view of the above roof cutting design, the relevant parameters can be taken into the formulas in Section 4 to verify the design effect. At the same time, according to the geological conditions of 12201 working face in Halagou coal mine, the design results can also be verified through the numerical simulation by the software FLAC 3D. So, in this study, we use two ways of mechanical analysis and numerical simulation to analyze the roof cutting effect in retracement channel.

5.2.1. Calculation Analysis. According to the field geological conditions of 12201 working face, the relevant parameters are assigned as follows: $c=0.1\text{MPa}$, $\varphi=18^\circ$, $k=2$, $\gamma=25\text{KN/m}^3$, $H=80\text{m}$, $p_X=0.04\text{MPa}$, $m=2\text{m}$, and $L=19\text{m}$. Then the width of the limit equilibrium area of the mining stopping protected coal pillar is calculated to be 4.6m. Taking the relevant parameters about the size of the retracement channel and the specifications of hydraulic support into formulas (10)-(13) and in order to get the minimum value of P_1 , P_2 , P_3 , and P_4 , let $a'=0$ in the value range of $0 \leq a' \leq a$ and $c=x_0$ in the value range of $0 \leq c \leq x_0$. The calculation results of P_1 , P_2 , P_3 , and P_4 are 2.284MN, 4.028MN, 3.146MN, and 1.594MN, respectively; it can be seen that pressure of hydraulic support reduces significantly after roof cutting. In

addition, according to the support design of the retracement channel, the strength of the channel support $P_{zl}=0.6\text{MPa}$, and the strength of the hydraulic support $p=1.2\text{MPa}$. Taking the relevant parameters under no cutting condition into formula (17), the roof subsidence is calculated to be 0.26m. Meanwhile when considering the relevant parameters under roof cutting condition, the calculation result is 0.11m. Namely, the subsidence of roof also reduces obviously after roof cutting.

5.2.2. Numerical Simulation Analysis. The numerical model is built by the FLAC 3D software based on the geological conditions of 12201 working face in Halagou coal mine. The model size is $100\text{m} \times 50\text{m} \times 50\text{m}$, which contains the 30m thick roof, the 18m thick floor, the 60750 grid units, and the 70677 nodes (as shown in Figure 13). After the completion of the model, the working face mining simulation is carried out, and the vertical stress distributions of the retracement channel surrounding rock under roof cutting and no cutting conditions are analyzed comparatively.

As shown in Figure 14, when the mining face is far away from the retracement channel, the stress distribution of the surrounding rock is symmetrical and the stress is relatively higher under no cutting condition. But the stress distribution is obviously changed after roof cutting, and the surrounding rock of the retracement channel presents the pressure relief state. In this condition, the stress distribution is asymmetrical, and the vertical stress of the channel vice wall is greater than that of the channel principal wall. With the advance of mining face, when the mining working face is closer to the retracement channel (5m), the channel principal wall and the mining wall are all in the high stress state under no cutting condition. So the rib spalling and large deformation phenomena can easily take place in the working face and retracement channel, which is bad to the working face retracement process. Meanwhile, under the roof cutting condition, the channel principal wall and the mining wall are all in the low stress state. Although there is a stress concentration area in the left pillar of the retracement channel, it is far from the channel vice wall. So the retracement channel is relatively stable under this condition. When the mining face is connected with the retracement channel, the channel

FIGURE 14: Numerical calculation results of vertical stress distributions.

vice wall is in the high stress state under either the no cutting condition or the roof cutting condition. But, under the roof cutting condition, the stress concentration area is smaller, the peak value is lower, and the distance between the stress peak and retrace channel is longer. So the retrace channel has a better stability under the roof cutting condition.

6. Field Engineering Test

According to the above analysis, the roof cutting angle is 45° , the roof cutting height is 8m, and the depth of roof cutting hole is 11.3m in the field test of RCRC about 12201 working face in Halagou coal mine. The roof of the retrace channel is supported by anchor bolts, anchor cables, and W steel strips. The specification of anchor bolt is $\phi 16\text{mm} \times 1800\text{mm}$, and the layout spacing is $900\text{mm} \times 1000\text{mm}$. The specification of W steel strips is $3\text{mm} \times 230\text{mm} \times 4800\text{mm}$. The anchor cables are installed as 3 columns in total on the roof. The column on the channel vice wall side is common steel strand

anchor cable, whose specification is $\phi 17.8\text{mm} \times 8000\text{mm}$. The other two columns are constant resistance large deformation anchor cable, whose specification is $\phi 21.8\text{mm} \times 8000\text{mm}$. The row spacing of anchor cables is 1500mm. The original temporary reinforcement support of retrace channel needs two rows of chock supports, and only one row can be left along the channel vice wall under the roof cutting condition (as shown in Figure 12) [28].

As shown in Figure 12, in the roof cutting blasting of this test, only charging the explosive in the section of blasting hole which is behind the hydraulic supports when the working face stops mining (upper 4.2m), the other section of the hole is only treated as sealing section (lower 7.1m). That can ensure that the roof upon the hydraulic supports have a certain integrity. Through the field blasting test, the class 2 coal mine permissible emulsion explosive with the specification being $\phi 32\text{mm} \times 200\text{mm}$ is chosen to carry out the roof presplitting cutting, the blasting spacing is 1000mm, and the explosive consumption of each blasting hole is 20 volumes.

FIGURE 15: Field monitoring results.

In the connection process between working face and retracement channel, the working resistance of hydraulic support and the convergence of roof and floor at the middle of retracement channel, where the deformation is the most severe, are observed and recorded as Figure 15. It can be seen that the working resistance of the hydraulic support reaches a peak value of 8741kN when the distance between working face and retracement channel is 38m. Then the working resistance slumps during the distance range of 32m-15m, and the minimum value is 1612kN. In the distance range of 15m-4m subsequently, the working resistance rises slightly, and the maximum value reaches 3782kN. Finally, until the retracement of hydraulic support is completed, the working resistance is maintained at 1361kN. For the convergence of roof and floor, which begins to increase obviously at the distance of working face and retracement channel, is 37m, it increases sharply in the distance range of 28m-13m and then becomes stable. At the last stage, there are two slight rises of the convergence at the distance being 8m and 3m, and the final convergence of roof and floor is 132.5mm.

In addition, through the field observation, it is found that when the working face and the retracement channel are connected, the immediate roof behind the hydraulic support collapses along the roof cutting hole's explosive charged section firstly. Then, after the retracement of hydraulic support, the triangular remnant immediate roof upon the original hydraulic support collapses along the tendency direction of working face with the 2m-3m break step. Through the whole retracement process, the deformation of the retracement channel is small, and the working condition of hydraulic support is good with no overload phenomenon (as shown in Figure 16).

7. Conclusion

(1) According to the fault line position of the main roof, the overburden strata structure at the stopping line can be divided into three types: breaking behind the stopping line, breaking upon the retracement channel, and breaking upon the coal wall, followed by putting forward the RCRC technology. Based on the statics theory and energy theory,

FIGURE 16: Scene of mining stopping.

the stress state of hydraulic support and roof deformation mechanism of retracement channel are analyzed to judge the stability of surrounding rock. According to the calculation and comparison analysis, under the roof presplitting cutting condition, the pressure of hydraulic support is lower than the other three traditional types. And the pressure of hydraulic support and the subsidence of the channel roof are all closely related to the thickness of the immediate roof and the weighting step of the working face.

(2) On the basis of the analysis about the overburden strata structure at stopping line and the roof cutting effect, the key parameters of the RCRC in 12201 working face of Halagou coal mine are designed as follows: the roof cutting height is 8m, the roof cutting angle is 45° , and the depth of the roof cutting blasting hole is 11.3m. Through the verified mechanical calculation and numerical simulation, the working resistance of hydraulic support and the subsidence of channel roof all reduce obviously through the channel roof's presplitting cutting, and the pressure release effect of surrounding rock is remarkable.

(3) According to the field supporting condition and the blasting test conclusion, the spacing of roof cutting blasting hole is 1000mm, the section of the hole which is charged with explosive is the upper 4.2m section, the lower 7.1m section of the hole is treated as seal section, the explosive specification is $\phi 32\text{mm} \times 200\text{mm}$, and the explosive consumption of single hole is 20 volumes. It is verified by the field engineering

test that the working resistance of hydraulic support at the middle of the working face finally remains at 1361KN, and the maximum roof subsidence of retracement channel is 132.5mm during the working face retracement process. Overall, the deformation of the retracement channel is small, and the working condition of hydraulic support is good with no overload phenomenon through the whole retracement process.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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