Characteristics of Roof Movement and Ground Pressure Behavior of Gob-side Entry Retaining by Roof Cutting in Continuous Mining

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Abstract: Gob-side entry retaining by roof cutting (GERRC) technology has been widely used in China, but application research of the entry-retaining technology in continuous mining is relatively scarce. Based on the analysis of the technology of continuous mining and GERRC, this study adopted the methods of theoretical analysis and in-field monitoring of ground pressure and behavior to obtain the roof movement characteristics and ground pressure distribution law during the entire process of roof directional pre-splitting, entry retaining, and entry reusing. Using the engineering geological conditions and analysis of field data of Dianping coal mine in Shanxi Province, the principal design parameters and technological process of GERRC in continuous mining were obtained. The structure model of the retained roadway roof in continuous mining was constructed to study roof movement patterns and the mechanism of stability control of the retained roadway. The movement regularity of the overlying strata in the mining and entry-retaining stage was obtained, enriching the theory of roof structure evolution and stress transfer under the condition of continuous mining with GERRC. The research results provide significant support for further popularization and application of the technology of GERRC.

1. Introduction
Traditional longwall mining usually adopts the layout of one working face and two roadways
with interval coal pillars, causing a series of problems, such as low recovery rate, a large amount of tunneling workload, and dilemmas between simultaneous mining and tunneling. The mining method of non-pillar entry retaining is an effective way to avoid the problems above \cite{1}. Since the 1970s, China has conducted technical research on gob-side entry retaining, laying a solid foundation for the research of non-pillar mining. The traditional gob-side entry-retaining technology predominantly uses gangue, high water materials, reinforced concrete, and other filling materials to construct an artificial wall beside the entry to support the entry roof, achieving the goal of maintaining the roadways \cite{2}. Nevertheless, large nonlinear deformation resulting from the joint action of high ground stress and intensive mining disturbance brings significant challenges to the maintenance of gob-side entry \cite{3}. To avoid the problems above, a new generation of gob-side entry retaining by roof cutting (GERRC) has been developed and widely used.

The principle of this new technology is that automatic roadway formation and non-pillar mining are realized by implementing roof directional pre-splitting, cutting off the transmission path of ground pressure from overlying strata to the retained roadway roof, and accomplishing the roof caving and gangue pilling automatically \cite{4,5}. This technology avoids the problem caused by constructing gob-side artificial walls in traditional gob-side entry retaining and has a broad application prospect.

Based on the technology of constant resistance and large deformation anchor cable (CRLDAC) and roof directional pre-splitting, He Manchao et al. proposed the theory of short cantilever beam and GERRC technology. As the roadway roof becomes a cantilever beam with a span of roadway width after roof cutting, the roadway is retained under the joint action of roof reinforcement support with CRLDAC and roadway temporary support, such as single prop and bulking gangue support in the gob. This technology is first applied to the condition of the composite roof of a medium-thick coal seam \cite{6}. Zhang Guofeng et al. conducted indoor static and dynamic tensile tests on the self-developed CRLDAC. The results show that CRLDAC can maintain a working resistance of 350 kN under static tension, and the elongation can reach 300 mm–950 mm. Under the action of the dynamic impact load, the elongation limit of CRLDAC can reach 1.6 m, and the working resistance can be maintained at 280 kN–375 kN. After field application, the outstanding advantages of CRLDAC, such as high pre-tightening force, high constant resistance, and large elongation, are summarized, which could meet the requirements of roadway support under various geological conditions \cite{7}.

Through theoretical analysis and calculation, Gao Yubing et al. revealed that pre-splitting blasting was achieved by propagating cracks guided by the original penetrated crack, and obtained the calculation formula of crack propagation depth and the distance between roof drilling holes. By using discrete element simulation software, the influence of the roof-cutting height and angle on roadway ground pressure behavior was also studied, and the research results were applied to a thick coal seam successfully \cite{8}. Sun Xiaoming determined that the principal factors affecting the effect of GERRC on the thin coal seam are roof-cutting height, roof-cutting angle, and the distance between roof drilling holes. The reasonable roof-cutting height and cutting angle of 1,610 the thin coal seam working face in Nantun Coal Mine were calculated by numerical simulation, and the reasonable distance between roof drilling holes was determined by field blasting tests. After adopting the above parameters, the technology of GERRC was successfully applied in the thin coal seam \cite{9}. 
Ma Xingen et al. summarized the principal parameters of GERRC in the medium-thick coal seam as roof-cutting height, roof-cutting angle, the crack rate, explosive consumption of each single blasthole, blasthole spacing, and the number of initiation boreholes at a time. After applying the above parameters to 8,304 working face of Tashan Coal Mine, it was found that after roof cutting, the periodic weighting length of the main roof near the roof-cutting side increased, and at the same position, the average pressure and peak pressure of hydraulic support were decreased [10]. Therefore, the pressure-relief effect caused by roof cutting is remarkable. Zhen Enze et al. compared and analyzed the influence of traditional gob-side entry retaining with artificial wall and GERRC on roadway surrounding rock. The results showed that the technology of GERRC significantly optimizes the stress distribution of the surrounding rock and controls the deformation of the roadway [11]. Based on the self-bearing theory of bulking rocks and stability principle (S-R) of surrounding rock in the deeply buried coal seam, Chen Shangyuan et al. derived formulas for calculating the roof-cutting height and angle. Based on the mechanical model construction of energy-cumulation blasting, the reasonable distance between roof drilling holes was then obtained by numerical simulation and field blasting tests [12]. Yang Jun et al. studied the stress evolution characteristics and surrounding rock movement of the retained roadway by roof cutting when there is an above-normal fault using mechanical analysis, numerical simulation, and field engineering test. They suggested that the range of 70 m before and after the normal fault is significantly affected by the fault activity; therefore, the corresponding support and monitoring should be strengthened here [13]. Guo Zhibiao et al. obtained the calculation principle of lateral pressure of gangue by constructing a structural mechanical model of the overlying strata during the roof caving and gangue compaction in the gob under the condition of fractured roof in the medium-thick coal seam [14]. This provided a basis for the design of gangue-retaining support besides the roadway. Zhang Guofeng et al.

Based on the mechanical model of short cantilever beam structure formed by GERRC, He ManChao et al. proposed the idea of controlling the stability of roadway surrounding rock by artificially constructing the structure of the upper strata of the main roof, bulking gangue at the gob, and cantilever beam of the entry roof. The stability of the roadway roof predominantly depends on CRLDAC and the temporary support in the roadway and gangue bulking. The support at the gob is induced by roof cutting and then controlled by the gangue-retaining structure [15]. Given the above research, Zhu Zhen et al. constructed the surrounding rock structure model of GERRC and derived the calculation formula and influencing factors of roof support resistance. Depending on the intensity of the roof movement, the retained roadway is divided into three zones, namely the dense support zone, the zone in which support has been withdrawn at intervals, and the non-temporary support zone to provide more targeted support countermeasures [16]. Ma Xingen et al. divided the entire process of GERRC into three periods, namely the coal support, dynamic pressure affected, and stable periods. The corresponding mechanical models of roadway surrounding rock were established for different periods, respectively, and the deformation law of roadway roof and the requirement of roadway support were obtained [17].

Currently, most research of GERRC, at home and abroad, predominantly focuses on the identification and optimization of key parameters of non-pillar mining and the characteristics and laws of ground pressure behavior. However, a few studies have included the entire
process of the surrounding rock movement, the stope structure model, and the law of ground pressure behavior of continuous mining with roof-cutting and pressure-relief technologies. Much research is still needed in this field.

In conclusion, currently, the development of GERRC belongs to the initial stage of popularization and application. Studies predominantly focus on the optimization of key technical parameters and the mechanical structure of the overlying strata in single working face mining under different geo-mechanical conditions. Although research on the ground pressure distribution law and stope structure of continuous mining with roof cutting and pressure relief has just started, with the further popularization and application of GERRC technology, continuous mining will receive increasing attention and has a broad application prospect.

2. Technical process of continuous mining with GERRC

In some mines, the lateral abutment pressure caused by working face mining is too intensive to maintain the stability of adjacent roadways after driving. Therefore, people excavate the roadway and working face far away from the gob to avoid the influence induced by adjacent working face mining. However, the lateral abutment pressure will then affect all the roadways of the last working face, resulting in the pressure concentration in the roadways and working face, which significantly influences the safety and efficiency of mining. By implementing GERRC, the stress environment of roadway surrounding rock is improved, and the roadway of the current working face is retained as a mining roadway of the next working face to realize the continuous mining of the working face in the mining area. Because of two adjacent working faces are mined sequentially, a significant difference exists between the process of continuous mining and traditional interval mining; therefore, it must be studied.

2.1. Preparations for the first entry retaining

2.1.1. Strengthen the roof support during the roadway excavation

In the entire process of continuous mining with GERRC, the roadway to be retained will be influenced by advancing abutment pressure during the mining of the first working face, intensive dynamic pressure after mining the first working face, and advancing abutment pressure during the mining of the subsequent working face. Therefore, higher requirements for roadway roof support is necessary. The final support form of the roadway roof is anchor, cable, and mesh.

The driving speed can be maintained by conducting the roadway support twice during the excavation. The head-on support ensures the stability of the roadway roof during excavation, and the subsequent support lagging the head-on face strengthens the support of key parts of the roadway roof before roof cutting.

When energy accumulation blasting is adopted for roof directional pre-splitting, the adjacent roadway roof will inevitably be disturbed. During the process of entry retaining by roof cutting, the gob-side roof is the key part of roadway deformation and failure (Figure 1). Moreover, after the working face is mined, the stress concentration before roof breaking and the impact of roof collapse on the roadway roof are all located here. From the perspective of support mechanics, roof support at this position is most conducive to the stability of the roof. Therefore, based on the original head-on support of the roadway roof, the support for this key
part must be strengthened to prevent breakage of the roof anchor cable caused by blasting impact and mining-induced disturbance. CRLDAC incorporates constant resistance, and a large allowable deformation is suitable for high pretension and high-strength roof support. Figure 1 shows the situation of using CRLDAC to reinforce the gob-side roof.

**Figure 1.** Reinforcing the key part of the roadway roof using CRLDAC

Applying CRLDAC reinforces the gob-side roof. The integrity and anti-deformation ability of roof strata are improved, effectively preventing bed separation and roof dislocation. The increase in anti-deformation ability of the roadway roof can limit the rotation of roof strata to gob, reduce the extrusion pressure of the main roof on the immediate roof of the roadway to avoid crushing the immediate roof of the retained roadway, and prevent the occurrence of roof collapse of the retained roadway. Simultaneously, CRLDAC can resist the blasting impact disturbance caused by pre-splitting blasting on the gob-side roof, absorb the blasting energy, ensure the integrity and stability of the key parts of the roof to avoid damage of the bearing structure, and guarantee the stability of the surrounding rock of the retained roadway.

2.1.2. Roof directional pre-splitting is accomplished before the working face mining

Through directional pre-splitting blasting, the stress transmission from the overlying strata of the working face to the roadway roof is cut off within a certain height range, significantly reducing the roof pressure of the roadway. Based on conventional blasting technology and using a new type of energy accumulation device, the energy accumulation tube, a more efficient energy accumulation and controlled blasting technology was invented, namely, bilateral tensile and energy-cumulated blasting. When the explosive is installed and blasted in the energy accumulation tube, the pressure-relief groove cuts the rock directionally. That is, the explosive gas first passes through the pressure-relief groove and forms an initial crack toward energy accumulation, whereas the rock in other directions is uniformly compressed. Under this joint action, the initial crack will continue to extend until the cracks generated by the two adjacent blastholes are connected.

**Figure 2.** Roof directional pre-splitting blast and roadway support with CRLDAC
2.1.3. The formation of the ventilation system

Before retaining the roadway, the retained roadway and working face must form a ventilation system. Therefore, the preparation of two working faces might be accomplished before entry retaining to form the Y or W-type ventilation system. Figure 3 shows that fresh air flows into the two roadways of the first working face, and dirty air is discharged from the roadway of the second working face.

![Figure 3. The ventilation system for entry retaining during continuous mining](image)

2.2. Technical process of GERRC in the first working face

2.2.1. Gangue prevention support

With the promotion of the working face, the roof of the mined-zone will cave behind the hydraulic support. Gangue can be prevented from flowing into the retained roadway by implementing several gangue prevention structures and gangue prevention and gob-side roof support equipment. The surrounding rock deformation of roadways in the thin coal seam is usually small; therefore, joist steel is adopted as the main structure in a non-contractible prop and mesh system. The purpose of gangue prevention is usually accomplished using joist steel, single prop, steel mesh, or rhombic steel mesh.

The horizontal force of gangue in gob on the support device besides the roadway is small. The failure is predominantly caused by the gangue prevention and gob-side roof support device is the high vertical pressure between the roadway roof and floor, which increases significantly with the increase in thickness and buried depth of the coal seams. When the vertical resistance of rigid support such as joist steel exceeds its bending strength, it begins to bend and deform. Once the bending deformation of joist steel emerges, its anti-lateral pressure capacity will be significantly reduced until it is unable to control gangue.

The structure of contractible stress relief U-shaped steel (CSRUS) is a new type of gangue control device in which two U-shaped steel constitute as integrity by staples to support the gangue wall of the retained roadways. When the vertical pressure on CSRUS exceeds its sliding friction force, the two U-shaped steel slide to release the pressure, maintaining anti-lateral pressure and achieve a good support effect for the gangue wall. Figure 4 illustrates the structure of CSRUS.

The construction safety and support effect of CSRUS can be ensured by locating the face-end hydraulic support inside the roof-cutting line and out from the roadway, and CSRUS should be installed beside the face-end hydraulic support to protect the safety of workers.
2.2.2. Temporary support of the roadway roof

After the working face is mined, although the roof movement is violent, the roof collapse in the gob is insufficient and the piled gangue cannot provide effective support for the overlying strata. The main roof will break at a certain distance and subside in the form of rotation. Simultaneously, the bolt (cable) support structure cannot achieve self-stability under rotary subsidence of the lateral fractured main roof. The influence of roof movement on the roadway and maintaining the stability of the roadway surrounding rock can be reduced by conducting temporary passive reinforcement on the roadway roof, especially the gob-side roadway roof. When the movement of the overlying strata tends to be stable and the gangue in gob provides effective support for the overlying strata, which means that the GERRC is in a stable state, the temporary reinforcement support in the roadway can be removed.

The traditional support method of a single hydraulic prop is incapable of providing high-support strength for the roadway roof and floor; therefore, it is used in roadway support of thin coal seam or shallow buried coal seam. The surrounding rock stress of gob-side entry retaining is concentrated, and the roadway deformation is large from medium-thick and thick coal seam; therefore, the single hydraulic props cannot be the main support under these conditions. To solve this problem, the gob-side roof is reinforced by hydraulic support, and a structure with one beam and two props is added in special sections of the retained roadway. The hydraulic support has the characteristics of high strength and stiffness, strong support capacity and large support area, provides a large roof-cutting resistance, effectively reduces the influence of the lateral roof rotary subsidence on the retained roadway, and ensures the stability of the retained roadway during the process of strata movement. In the deformation period of the surrounding rock in GERRC, roof subsidence and floor heave often occur simultaneously. The base of hydraulic support has a large supporting area and enough rigidity. Therefore, it can restrain the floor heave while supporting the roof, and realize the double control of roof and floor deformation.

2.2.3. Sealing and air leakage prevention of the roadway gangue wall

In the initial stage of GERRC, a cloth of ventilation tube is adopted and hanged between the metal mesh and gangue to prevent air from flowing into gob. When the distance between the retained roadway and working face exceeds 60 m, the intensity of roof strata movement is significantly weakened, so the gangue wall can be sealed by shotcrete with a thickness of 40 mm. The results of ground pressure monitoring show that the second shotcrete with a
thickness of 60 mm could be adopted when the surrounding rock of the retained roadway tends to be stable. Shotcrete materials can be selected from mine-used polymer spraying materials or concrete spraying materials.

2.2.4. Recycling and reuse of the temporary support
When the roof subsidence speed is less than 1 mm/d for three consecutive days, the temporary support equipment can be recycled. The roof support equipment is withdrawn one-by-one from the stable section of the retained roadway to the working face and recycled in turn. To maintain the stability of the gangue wall during the mining of the subsequent working face, CSRUS does not withdraw in this period.

2.3. Reuse of the retained roadway and continuous entry retaining

2.3.1. Advancing support of retained roadway during the mining of subsequent working face
By monitoring the ground pressure, the distribution of advancing abutment pressure and deformation law of surrounding rock are obtained, and the reasonable advancing support strength and length are calculated.

2.3.2. Removal of the roof support during the mining of subsequent working face
When the roof belongs to the hard rock stratum, which is not easy to collapse, anchor cables and CRLDAC must be uninstalled to promote the collapse of the roadway roof before mining of the subsequent working face. When the deformation of CRLDAC is too large to uninstall, extra measures, such as forced caving, must be adopted to ruin the cable structure and loosen the roof strata.

2.3.3. Parameter optimization of continuous entry retaining
When retaining the roadway in the subsequent working face, the design scheme should be optimized according to the effect of GERRC in the previous working face to achieve technical reliability and economic rationality.

3. Structural changes and movement characteristics of retained roof

3.1. Roof structure before retaining entry
The directional pre-splitting of the immediate roof before mining must be completed so that the existence of the fracture plane will not affect the structural stability of the roof. First, because the directional pre-splitting and energy-cumulation blasting technology is used, only contact cracks are produced in the roof. Second, the fracture plane produced by blasting has a certain angle, ensuring that the roadway roof is still supported by the rock strata below the fracture plane. Finally, CRLDAC is installed in the roof to strengthen the support, and the high pretension of CRLDAC ensures the stability of the roof. Therefore, the roadway roof will not be affected by implementing directional pre-splitting.
3.2. Roof structure after entry retaining

In the entry-retaining stage, the roof structure should be studied, respectively, in two stages according to characteristics of roof movement. One is the dynamic pressure-influenced stage induced by the strata caving of the gob roof, and the other is the static pressure-influenced stage induced by the continuous subsidence deformation of the overlying strata.

In the dynamic pressure-influenced stage, the dynamic pressure influence on the roadway surrounding rock comes from the immediate roof collapses along the crack plane, and the influence degree predominantly depends on the roof lithology. The fractured roof will collapse soon after mining, which has a relatively small impact on the stability of the roadway. The collapse of the composite roof lags the working face by no more than 3 m, which has a certain impact on the stability of the roadway. The collapse of hard and rigid roofs could lag the working face by 3 m–10 m, and the impact of roof collapse on the roadway is strong. Furthermore, the periodic break of the main roof will also have a dynamic pressure impact on the roadway. Therefore, the stability of the surrounding rock in this stage can be ensured by adopting the temporary support form of single pros and sheds for fractured or composite roof support, while the U-shaped support or hydraulic unit support with greater working resistance is needed for hard roof.

After the immediate roof of the gob completely collapses and the gangue fills the post-mining space, the subsidence deformation of the main roof and overlying strata develops with gangue compaction. It then forms the periodic break of the rock stratum, which is the static pressure-influenced stage. Now, the compressed gangue in the gob supports both the immediate and main roofs, forming a stable pressure arch structure, ensuring the stability of the roadway roof. The temporary support can be withdrawn and CSRUS should be maintained so that the subsequent working face can continue to use this roadway.
3.3. Roof structure of the retained roadway during the subsequent working face
When the second working face goes into service, the retained roadway enters the reuse stage. Under the action of the advancing abutment pressure, the immediate roof rotates and subsides toward the gob with bed separation developing in the roadway roof. Now, the advancing temporary support of the roadway roof must be strengthened compared with the advancing temporary support of the previous working face to prevent further development of deformation. The length of advancing support should be obtained and optimized by monitoring the ground pressure. The conventional advancing support form with single props and sheds is usually adopted in GERRC. Under the combined control structure of solid coal, reinforced anchor cable, and advancing temporary support, the roadway roof of the retained roadway can maintain a stable state in the reuse stage.

4. Strata behavior regularity of retained roadway by roof cutting during continuous mining

4.1. General situation of the engineering
Dianping coal mine is in the Liliu mining area, Shanxi Province, China. Three working faces are arranged in the second mining area of the main mineable coal seam 9#. The 9-202 working face is the first working face to be mined in the second mining area. Its 9-202-1 roadway was retained using the technology of GERRC and became the 9-204-1 roadway of the 9-204 working face after mining. The reuse of retained roadway 9-204-1 and entry retaining by roof cutting of roadway 9-204-2 are conducted simultaneously with the second working face mining. Figure 8 shows the layout of the working faces and location of the reused roadway.
Figure 8. The working faces layout and situation of roadway retaining by roof cutting

The average thickness of the coal seam in the second mining area is 3 m, the immediate roof is fine sandstone with an average thickness of 6.7 m, and the main roof is sandy mudstone with an average thickness of 5.6 m. The roof stability is good, and the fracture development degree is low. The immediate floor is sandy mudstone with an average thickness of 6.2 m and has low expansion and softening ability when encountering water.

Figure 9. Engineering site and lithology of the overlying strata

4.2. Design of the key parameters

4.2.1. Parameter design of reinforced cable support (CRLDAC)

The first column of CRLDAC is installed in the roadway roof 600 mm away from the gob side of the roadway, and the row spacing of CRLDAC is 1,000 mm. The first column of anchor cables is connected as integrity using 3,400 × 300 × 3 mm W-shaped steel strip parallel to the roadway strike. The second column of CRLDAC is 1,100 mm away from the gob side of the roadway, and row spacing is 1,000 mm. CRLDAC in the second column is staggered with the first column toward the roadway strike. The third column of the CRLDAC is arranged in the middle of the entry roof with a row spacing of 2,000 mm. CRLDAC adopts a steel strand with a diameter of 21.8 mm and length of 13.3 m. The pretension force of CRLDAC should not be less than 250 kN, and the constant resistance value is 330±20 kN.

4.2.2. Parameter design of roof directional pre-splitting

The parameters of roof directional pre-splitting blasting predominantly include two aspects, namely drilling and charge structure parameters. The key parameters of drilling are drilling depth, drilling angle, and the spacing of adjacent boreholes. The key parameters of the charge structure contain charge quantity and structure.

The drilling angle should not be too small to ensure the stability of the roadway roof before mining and collapse of the gob roof after mining. Similarly, the drilling angle should not be too large to enhance the filling effect of gangue in the gob and improve the stress condition of the short arm beam. For a medium-thick coal seam, the general drilling angle α is 10°–20°, according to the field tests. The drilling angle of this engineering is 71° and inclines to the gob side.

Regardless of the influence of the drilling angle, calculating the drilling depth is based on the
mining height and gangue-bulking factor. The critical design formula of drilling depth \((H_c)\) is illustrated as

\[
H_c = \frac{(H_m - \Delta H)}{(K - 1)},
\]

where \(H_m\) represents the mining height of the working face, \(\Delta H\) represents the roof-to-floor convergence, and \(K\) represents the coefficient of gangue bulking.

Because the immediate roof of the working face is fine sandstone, the fragmentation of the collapsed rock block will be large, so the minimum value of \(K\) is 1.3. The average thickness of the coal seam is 3.0 m and the roof-to-floor convergence is 300 mm. The calculated value of the drilling depth is 9 m.

The distance between the drilling hole and the gob side of the roadway is designed to be 100 mm, and the distance between two adjacent drilling holes is 500 mm. The mine-used explosive with a diameter of 35 mm and a length of 200 mm is adopted for roof directional pre-splitting blasting. The charge structure of the explosive is 7-6-6-4-3, the explosive consumption per hole is 5.2 kg, and the length of the sealing mud is 1.5 m.

To enhance the cutting effect of the shallow hard roof strata, deep and shallow holes are arranged alternately, ensuring that roof strata are completely cut within the cutting height. The depth of the shallow hole is 3 m, and the spacing between adjacent shallow holes and the deep hole is 250 mm. The charge structure of the shallow hole is 4-3, the explosive consumption of a shallow hole is 1.4 kg, and the length of the sealing mud is 1.0 m.

\[\text{Figure 10. The charge structure of deep and shallow holes and effect of roof pre-splitting}\]

4.2.3. Design of the temporary roof support

To provide sufficient support strength and cutting force, ZMX 420/310 self-circulation \(\Pi\)-shaped hydraulic support is used in the 9-204-1 roadway for temporary support. The working resistance of this support is 2,040 kN, and the designed spacing between them is 1,500 mm. Figure 11 shows the support effect of this \(\Pi\)-shaped hydraulic support.
4.3. Ground pressure and behavior of the entire process

From tunneling to entry retaining, reuse, and final abandonment, the deformation process of the roadway can be divided into six stages. Figure 12 shows that the first three stages are included before entry retaining, and the remaining three stages are included after entry retaining.

Stage I: Roadway tunneling. The surrounding rock stress will redistribute, with simultaneous roadway deformation emerging.

Stage II: The stable stage before mining. The surrounding rock stress of the roadway reaches a new equilibrium, and the surrounding rock is in a stable state.

Stage III: Advancing abutment pressure-influenced stage. Because of the influence of advancing abutment pressure, roadway deformation and deformation rate increases rapidly.

Stage IV: Dynamic pressure-influenced stage. The intensity of dynamic pressure changes from strong to weak, and the overlying strata movement gradually tends to be stable.

Stage V: The stable stage of the retained roadway. The surrounding rock of the retained roadway secondarily reaches the stress balance state.

Stage VI: Advancing abutment pressure-influenced stage during subsequent working face mining. Affected by advancing abutment pressure produced by the second working face mining, the surrounding rock deformation increases rapidly and reaches a maximum until roadway destruction.

Figure 12. The entire process of roof deformation of the retained roadway

The roof subsidence in Dianping coal mine is 50 mm during roadway driving because of the influence of advancing abutment pressure induced by working face mining. In the stage of roadway retaining, the subsidence of the roof is 200 mm, and the influence of dynamic pressure lasted for ~1 month; that is, the roadway tends to be stable when it lags the working face more than 160 m. During the reuse period, the roadway roof began deforming 30 m ahead of the subsequent working face, and the final subsidence in this period is ~50 mm.
4.4. Effect of entry retaining

The effect of the retained roadway is good, the surrounding rock deformation is less than 10% of the entry geometry scale, which can meet the needs of pedestrians, transportation, and ventilation. During the reuse period, the surrounding rock is well-controlled until the roadway fulfilled its mission.

![Image](a)

![Image](b)

Figure 13. The effect of entry retaining

Figure 14. The effect of entry reuse

5. Conclusions

1. Continuous non-pillar mining is a critical technical means to realize safe and efficient mining. Continuous mining with GERRC can be realized essential systemic preparations are accomplished, such as the roof cutting, reinforced support, and complete ventilation system construction before mining. After mining, temporary roof support, gangue-retaining support, and gob-sealing measures are conducted to maintain the stability of the roadway. During subsequent working face mining, the reuse of the retained roadway and entry retaining for the third working face are simultaneously conducted. Simultaneously, the roof support and ground pressure monitoring of the retained roadway should be strengthened, ensuring roof stability and optimizing the design parameters.

2. The entire process of GERRC includes four stages, namely roof directional pre-splitting blasting impact before mining, dynamic pressure influence induced by mining, static pressure influence, and dynamic pressure influence induced by mining the subsequent working face. Although roof movement is intensive, under the joint action of roof strengthening support, advancing temporary support, and post-mining temporary support, the roadway roof structure remains stable, the stress distribution of the surrounding rock is optimized, and the surrounding rock deformation is always acceptable.
3. Depending on the condition of the hard roof, the method of staggered deep and shallow blastholes and energy-cumulation blasting is adopted to increase the crack rate of the roadway shallow roof. The analysis of ground pressure and GERRC behavior in the entire process show that the deformation velocity of the surrounding rock reaches the maximum at the stage of dynamic pressure influence because the roadway roof severely subsides, and the floor heave deformation is also intensive. The high-strength support structure such as the \( \mathbb{I} \)-shaped support has a large support area and can provide high-cutting force, effectively ensuring the stability of the roadway surrounding rock during violent roof movement.

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